Institut national de physique nucléaire
et de physique des particules

REACHING FOR THE INFINITIES

A Strategic Plan for French Nuclear, Particle and Astroparticle physics in the 2030 Horizon

CONTENTS

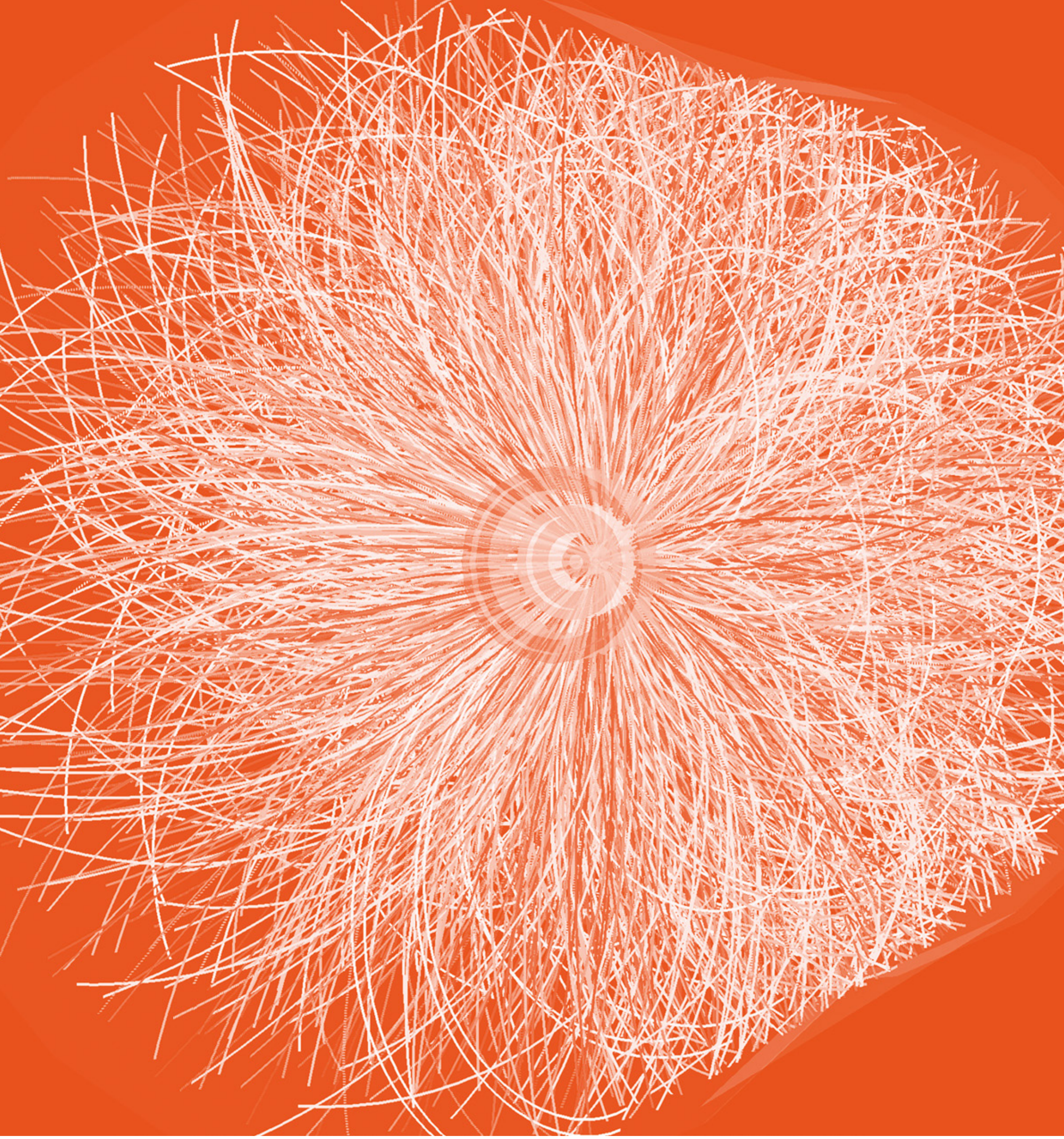
FOREWORD

Research in Nuclear, Particle and Astroparticle physics relies on committing to long-term scientific goals. These goals can be achieved through experimental and theoretical research programs that often require the pooling of multi-national human and financial resources. New projects proposed to explore new ideas (e.g., to detect dark matter) hence compete for resources with the continuation or extension of existing projects which are necessary to deepen and enhance our knowledge (e.g., the study of the Higgs boson), while the latter projects can also enable new discoveries (for example, the observation of significant departures from the Standard Model). Having a national decadal scientific prioritization process involving scientists active in these fields is therefore important to be able to generate a roadmap for French research organizations and universities over that time span. This has been the goal of the nuclear, particle and Astroparticle prospective exercise that started about two years ago and is now completed. The present document summarizes the main findings of this work.

Section 1 introduces the global scientific challenges these scientific domains will face in the next decade and the process that has led to the publication of this strategic plan. The major developments since the previous exercise, along with the new scientific questions which have arisen, are in Section 2, while the most urgent scientific questions for the next decade are expressed through Science Drivers in Section 3. Program-wide scientific priorities together with a prioritized set of projects to be implemented in the next few years are presented in Section 4. The necessary efforts required to advance the technologies needed to achieve the scientific goals, whether in particle detection and accelerator developments or in data processing, simulation and analysis are presented in section 5. Finally, the interplay of these scientific and technical achievements with neighboring disciplines, as well as their impacts on society at large, are summarized in section 6.

The reader who is pressed for time may jump directly to page 33, which gives a summary of project priorities, while Table 1 page 30 shows the timeline of the major projects entering this roadmap and Table 2 page 32 shows how each of these projects address the Science Drivers summarized on page 19.

Paris, December 2022



GLOBAL SCIENTIFIC CHALLENGES

This document presents the French roadmap for Nuclear, Particle and Astroparticle physics, and associated technical developments and applications. The objectives of these fields of research are to study the constituents of matter, describe their interactions, and understand their role in the structuring of space and time and the evolution of the Universe. Particle and nuclear physics are the fundamental sciences studying the infinitely small scales: atomic nuclei, nucleons, elementary particles, and the forces and symmetries that govern their interactions while astroparticle and cosmological physics deal with understanding the physics at the infinitely large scales. In both theoretical and experimental aspects, studies of the elementary constituents of matter on one hand and research on high-energy cosmic rays, neutrinos, dark matter, dark energy and gravitational waves on the other hand, come together to try to answer the same questions of fundamental physics. In that respect, Nuclear, Particle and Astroparticle physics, sometimes dubbed "physics of the 2 infinities", now appears as a unique field. In this broad domain, the recent discoveries of neutrino oscillations, of the accelerated-expansion of the Universe, of the Higgs boson, and of gravitational waves open bright new perspectives of developments for the next decades.

Research in these scientific domains takes place over long periods of time. Between the time a new idea is formulated and the time it can actually be tested experimentally, it often requires decades to develop the needed technologies, to conceive and build the experiment, to record the data and to exploit it scientifically. Two famous examples are the discovery of the Higgs boson in 2012 which occurred nearly 50 years after its prediction by Brout, Englert and Higgs, and the discovery of gravitational waves in 2015, a century after Einstein predicted their existence.

Research in these fields has become an international endeavor. Given the cost of the projects and the limited human and financial resources available in a single country, experimental projects have largely become unique world-class projects managed by large international collaborations. This has been possible thanks to reliable partnerships between scientists and research organizations from many countries with whom a common vision and strategy is shared and implemented, and where contributions are often based on the partner's specific capacities brought to the project on a best effort scheme. The choices that are therefore made involve international coordination and aim at achieving the highest level of excellence to maximize the scientific impact of the funded projects. These experiments are often installed at major international research centers, some of which operated in France or in Europe.

In France, the funding of French participations in these large experiments generally proceeds through Research Infrastructure (RI) budget lines. These RI are listed on the French National RI Roadmap, and for some of them on the European ESFRI list. They can either be of the IR* type (formerly TGIR) if they are supervised directly at the Ministry of Higher Education and Research level (e.g., CTA, DUNE, EGO-VIRGO, FAIR, GANIL-SPIRAL2, HL-LHC) or of the IR type if their funding come from CEA and CNRS general budgets (e.g. AGATA, JUNO, KM3NeT, LSM, LSST, PAO). The funding of other often smaller experiments and projects relies on the research organization and university budgets and also on other funding sources (Europe, ANR…). In addition, space projects are mainly funded by the French space agency CNES, which also provides critical support for their construction, operation and scientific exploitation.

To achieve their objectives, the scientific teams join efforts in international collaborations which are responsible for the construction and operation of the experiment, as well as the scientific exploitation. National contributions to these experiments are often coordinated by national research organizations. In France, IN2P3 (Institut National de Physique Nucléaire et de Physique des Particules) of CNRS is tasked to perform this coordination, in partnership with French universities and CEA. As part of this national mission, IN2P3 organizes and conducts national prospective exercises.

This planning exercise began at the end of 2019, and follows the one carried out in 2012. It has mobilized French actors in these scientific domains, many of whom having also largely contributed to the recently published European roadmaps: the Long-Range Plan 2017 of the Nuclear Physics European Collaboration Committee, the European Astroparticle Physics Strategy 2017–2026 by the Astroparticle Physics European Consortium and the Update of the European Strategy of Particle Physics 2020 (ESPP) led by the European Organization for Nuclear Research (CERN) Council. The exercise has led to the publication of the current roadmap which provides a vision for scientific research in France in Nuclear, Particle and Astroparticle physics for the next 10 years. It identifies priorities in order to plan for the resources, expertise and industrial partnerships that need to be implemented to maximize the impact and visibility of French teams and laboratories in these global projects.

1. Projects fundings according to the "best effort" principle means that it is not based on the financial capacities of each partner, but that each partner invests up to the level of interest that it brings to the project, which allows very strong voluntary contributions.

THE PROSPECTIVE EXERCISE

The objectives of this roadmap, which covers the current decade, are to express nationally European and international strategic priorities in the three domains, Nuclear, Particle and Astroparticle physics, and to define objectives and priorities for national activities and projects in these research fields, as well as objectives and priorities in associated technological developments (detectors, accelerators and computing) and applications.

This document aims at providing a comprehensive view of activities and projects in these scientific fields, as well as an analysis of the strategic positioning of French teams and laboratories and of their impact in the international landscape. The broad vision presented in this roadmap provides near-term (5-10 years) prioritization of the scientific projects, but also anticipates the developments needed for the long-term future in order to preserve the excellence of the French teams in these fields and thus to continue being a major player in preparing for future discoveries.

As part of the process, CEA, partner universities and engineering schools were invited to provide representatives to form a national supervising committee charged with overseeing and validating the implementation of the roadmap exercise. Representatives from the following research entities[2], Aix Marseille Université, Université de Bordeaux, Université Caen Normandie, ENSI Caen, Université Clermont-Auvergne, Université Grenoble Alpes, Université Lyon 1, Université de Montpellier, Nantes Université, IMT Atlantique, Université Paris Cité, Université Paris-Saclay, Institut Polytechnique de Paris, Université Savoie-Mont Blanc and Université de Strasbourg, met and set up twelve thematic working groups and town hall meetings open to researchers from all over France.

The twelve working groups (GTs) scientific and technical themes are listed below. They were selected according to experimental and theoretical techniques while regrouping a large enough research community.

- Particle physics
- Accelerators and associated instrumentation
- Nuclear physics and astrophysics
- Detectors and associated instrumentation
- Hadron physics
- Computing, algorithms and data
- Physics of astroparticles
- Radiation physics for Health
- Inflation Physics and Dark Energy
- Nuclear energy and environment
- Neutrino physics and dark matter
- Geosciences, solar system and interstellar medium

These twelve GTs were led by conveners chosen among researchers holding responsibilities in the corresponding scientific area and including members of the IN2P3 Scientific Council. After collecting a large number of white papers, ten town hall meetings were held in various places in France.

Each working group then issued a report summarizing Science Drivers and recommendations.

The ten town hall meetings were held between October 2019 and June 2020. The white papers and the presentations are available on each event website:

- Lyon - Mar. 12-13, 2020:
  GT01 – Particle physics
- Caen - Jan. 30-31, 2020:
  GT02 – Nuclear physics and astrophysics
- Nantes - Mar. 2-3, 2020:
  GT03 – Hadronic physics
- Annecy - Nov. 12-13, 2019:
  GT04 – Physics of astroparticles
- Grenoble - Dec. 9-10, 2019:
  GT05 – Inflation physics and dark energy
- Bordeaux - Oct. 28, 2019:
  GT06 – Neutrinos physics and dark matter
- Orsay - Jan. 20-21, 2020:
  GT07 – Accelerators and associated instrumentation
- Orsay - Jan. 23-24, 2020:
  GT08 – Detectors and associated instrumentation
- Clermont - Oct. 17-18, 2019:
  GT09 – Computing, algorithms and data
- Strasbourg - Feb. 5-6, 2020:
  GT10 – Radiation physics for Health
  GT11 – Nuclear energy and the environment
  GT12 – Geosciences, solar system
  and interstellar medium

The reports of the GTs are directly accessible on https://prospectives2020.in2p3.fr/?page_id=313.

A 13th GT was setup to address human and financial resources issues with laboratory-director offices and the supervising committee, and a meeting was held on these subjects on Jun. 23, 2020 in Paris.

2. L2IT, the joint laboratory between CNRS-IN2P3 and Université Toulouse III - Paul Sabatier did not exist when this roadmap exercise was initiated.

As an extension of the twelve thematic seminars organized in 2019-2020, two workshops were then organized in June 2021, one focusing on theoretical physics called Theoretical physics of the two infinities and the second on quantum technologies: Quantum technologies for the two infinities.

Then, after several postponements due to the covid pandemic, a restitution colloquium was finally held in Giens in October 2021 (https://indico.in2p3.fr/event/22028/), bringing on site 350 physicists and engineers and 750 online in order to prepare for the final project prioritizations process.

Detailed information about the overall process is available on the dedicated web site (https://prospectives2021.in2p3.fr/), including the composition of the supervising committee and the composition of the GTs steering committees (see also Appendix B).

FUNDING SCENARIO

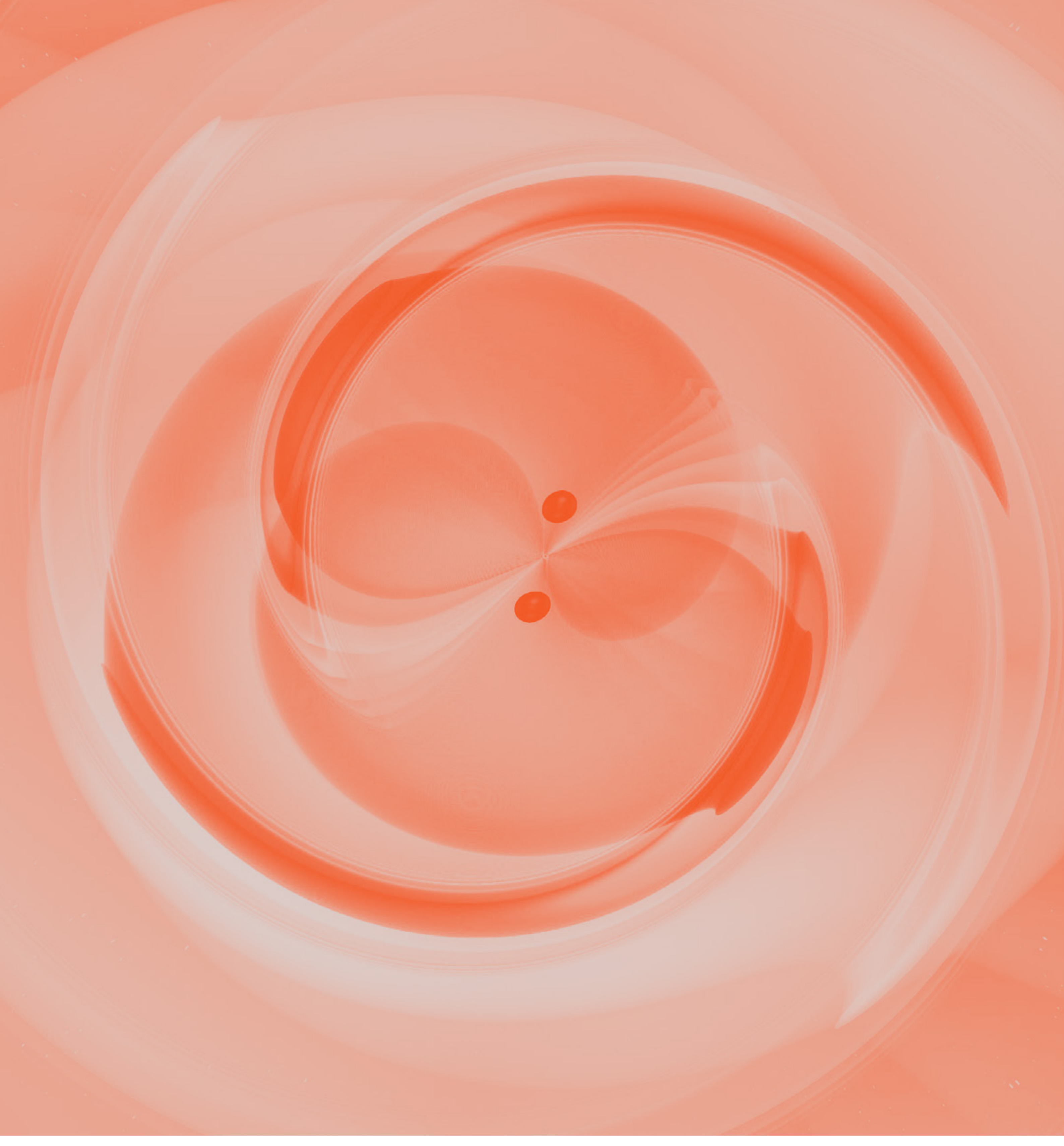
Funding of French laboratories in these scientific domains can be divided into base funding that covers laboratories operation costs, including permanent staff salaries (researchers, administrative and technical staff) and dedicated project funding that accounts for funding projects material and supplies and non-permanent staff salaries (graduates, post-graduates and some temporary technical positions). In addition, not discussed below, is the direct funding by France of the CERN laboratory and of the construction of FAIR in Germany, two research facilities used or to be used by French nuclear and particle physicists.

For IN2P3 led laboratories, base funding is, for most of it (about 85%), provided by CNRS and dominated by salary costs. IRFU (Institut de recherche sur les lois fondamentales de l'Univers), which includes also a department of astrophysics, base funding comes from CEA. The 2010-2020 period, has seen a decrease of IN2P3 laboratories yearly operation funding by an overall 15% and a reduction of the CNRS permanent staff by about 10% (1% per year). In this exercise we have assumed the base funding of IN2P3 laboratories to remain constant in the next decade.

Project funding comes from several sources and has greatly diversified in the last 10 years. For IN2P3 led laboratories, the dominant part comes from CNRS[3] (about 70% in the 2010-2020 period). Projects pursued at IRFU are funded by CEA and through external resources. Large projects funding comes from the national Very Large Research Infrastructure (IR*) funding scheme, from various competitive calls that appeared in the last decade as part of the national Plan d'Investissement d'Avenir (PIA) initiatives and from CNES for space projects. Smaller and medium size projects can be funded through the French national research agency, ANR, and European Union scientific initiatives such as Horizon 2020 and its predecessors (now Horizon Europe). Additional project funding is obtained from regional funding and contracts or joint collaborative project with industries. During the past 10 years, project funding has significantly increased mainly due to increase funding of existing IR* (GANIL/SPIRAL2, EGO/Virgo), funding of IR* accelerator construction projects (XFEL, ESS and FAIR), the launching of two new IR* (detector upgrade for HL-LHC and CTA), several successes at successive PIA calls (S3, DESIR, PACIFICS) and increased successes at European funding calls (mostly INFRADEV and ERC). Recently, funding for several larger projects that will deploy in the next decade has been granted: the IR* DUNE/PIP-II and the PIA4 NEWGAIN and FITS projects.

This project prioritization assumes that CNRS project funding (AP and IR) will remain constant, that more projects funding will be obtained through ANR, whose budget is scheduled to double in the next years, and that European funding will continue to increase as well as funding through joint collaborative project with industry. Funding through the IR* scheme, CNES or PIA is by construction subject to large fluctuations and cannot be easily anticipated. Nevertheless, large projects that will require IR* or CNES funding and projects of intermediate size that could benefit from PIA funding are being proposed and we have assumed new funding through these schemes will remain possible.

3. Project funding from CNRS comes in two categories: CNRS *Action Projet* (AP) for small and medium size projects, CNRS *Research infrastructure* (IR) for large projects.



MAJOR DEVELOPMENTS SINCE THE 2013 ROADMAP AND NEW SCIENTIFIC QUESTIONS

Since the previous planning and roadmap exercise, major advances have revolutionized our understanding of the laws of physics that govern the Universe and pushed further the frontiers of knowledge:

- precision measurements have established with certainty the scalar nature of the Higgs particle, its mass with a per-mil accuracy, and its couplings with vector bosons and the heaviest fermions, all of which being consistent with what is expected for a Standard Model (SM) Higgs boson;
- the impressive agreement of measurements with the SM of particle physics remains, although intriguing deviations persist notably in the flavor sector;
- collective effects in heavy-ion collisions studying quark-gluon plasma physics have also been observed in the collisions of smaller systems and remains unexplained;
- rare and exotic hadron states, such as tetraquarks and pentaquarks, have been observed as predicted by quantum chromodynamics (QCD);
- the long-standing international competition for the discovery of new elements lead to the completion of the 7^{th} period of the Mendeleev table with the discovery of element Z=118;
- with important advances in effective field theories, especially in the low-energy QCD non-perturbative sector, new nuclear interactions have been used that are appropriate for solving the nuclear many-body problem, opening new opportunities in particular to link QCD to low-energy nuclear physics and to perform exact ab-initio calculations;
- gravitational waves have been discovered with the spectacular detections of black holes and neutron star mergers, shading light on the equation of state of nuclear matter in dense stars and confronting general relativity in new ways;
- very high-energy neutrinos have been detected coming from astrophysical objects and the origin of ultra-high energetic cosmic rays is now clearly established as being extragalactic;
- studies of high-energy gamma-ray have confirmed that the supermassive black hole at the center of our Galaxy is a powerful particle accelerator generating cosmic rays with energies of the order of 10^{15} eV;
- multi-probes observations of the expansion of the late Universe, of the early Universe through the cosmic microwave background (CMB), and of the presence of cosmic dark matter, has reinforced a description of today's Universe where the Standard Model of particle physics describes only 5% of all mass and energy. Today's Universe's composition appears dominated by cold dark matter (27%) and dark energy (68%), both defying our current best description of the physics of elementary particles and fields.
- the validity (within uncertainties) of the Standard Model of Cosmology, ΛCDM, seems to confirm the current understanding of galaxy distribution originating from quantum fluctuations of a primordial scalar field during inflation;
- our knowledge of the neutrino sector has greatly improved, notably with the measurement of the large neutrino mixing angle Θ_{13} and the first hint of CP violation paving the way to future tests of leptogenesis as the mechanism generating baryon asymmetry in the early Universe;
- an order of magnitude has been gained using underground detectors, on the cross-section upper-limit of WIMP dark matter particles interacting with ordinary matter.

On the other hand, and despite huge gains obtained in sensitivity, some areas will need increased attention. It is in particular the case for direct dark matter detection and neutrinoless double beta decay (NDBD). Revealing the nature of dark matter which constitutes 85% of the matter of the Universe and testing whether the neutrino is its own antiparticle or not have naturally emerged in this roadmap as strong priorities for the years to come.

These discoveries and major advances could be achieved thanks to major progress in computing, modeling and simulation and the development of new techniques in particle detection leading to major advances in sensitivity, granularity and time resolution. Furthermore, the appearance of promising new techniques, using quantum technologies for computing and detectors is offering new opportunities. In particle acceleration, new highs have also been reached in technological developments of magnets and accelerating cavities, development of high intensity proton linacs, as well as free electron lasers for light sources.

QUARK AND LEPTON PHYSICS

The Standard Model of particle physics describes in a very successful way three of the four known interactions, electromagnetic, strong, and weak forces. Despite its success in describing the properties of fundamental particles, and in predicting with unprecedented precision numerous observables from the electroweak and QCD sectors, the SM, which relies on three fundamental symmetry groups, is not considered the ultimate theory of particle physics. The SM has to be extended for example to account for the baryon asymmetry of the Universe, to provide a suitable candidate for dark matter, to explain the neutrino mass, and to solve theoretical puzzles such as naturalness of the theory, grand unification, or strong CP violation.

The discovery of the Higgs boson (Physics Nobel Prize 2013) at the Large Hadron Collider (LHC) has opened a new era of detailed studies of the properties of this cornerstone of the SM that is the spontaneous breaking of electroweak symmetry which generates the mass of elementary particles. With this discovery, the particle content of the SM is complete, and since the last roadmap exercise, the Higgs boson couplings to heavy-fermions and bosons were firmly established, with measurements in agreement with the minimal theory within the current uncertainties. However, our understanding of the Higgs sector remains embryonic and many questions require dedicated physics programs and instruments to elucidate them, such as the Higgs self-interaction which could have major implications for the understanding of the early Universe.

The scheme and arrangement of quark and lepton masses and mixings, known as the flavor puzzle, are directly related to these open questions on the Higgs sector. Several deviations with the SM predictions have emerged in recent years in flavor physics. The most remarkable examples are in semi-leptonic b→clν and b→sll decays, which question the lepton flavor universality property of the electroweak interaction. Another large group of flavor observables belong to the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which parametrizes the mixing of quark flavors, and displays a clear hierarchical structure that the SM does not explain. The unitarity triangle tests, probing the consistency of the measurements of the matrix elements, are at the moment a remarkable proof of the success of the CKM mechanism within the SM, and impose strong constraints to physics Beyond the Standard Model (BSM). Also, the apparent absence of strong CP violation leaves the phase parameter of the CKM matrix as the unique source of CP violation. Flavor-diagonal CP-violating observables like electric dipole moments are then particularly suppressed and constitute very important precision tests of the SM.

The direct search for new particles and interactions at both high-energy and high-intensity facilities remains one of the priorities of the discipline. The LHC keeps on exploring the energy frontier, pushing further the limits established in the last 10 years. In a very complementary way, exhaustive and precise metrology of the processes already observed, particularly in the electroweak and flavor sectors, is confronted to improving state-of-the-art calculations provided by the theoreticians of the field in order to possibly observe anomalies compared to the SM predictions.

French scientists, who are involved in the four LHC experiments, have major roles in the entire LHC program, from design and construction (accelerators and detectors) to scientific exploitation, as well as now in the preparation of the high-luminosity phase of the LHC (HL-LHC). Furthermore, the IN2P3 Computing Center (CC-IN2P3) located in Lyon is one of the 13 major worldwide centers (Tier 1) of the LHC Computing Grid

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Organisation Européenne pour la Recherche Nucléaire (CERN)

Established in 1954, CERN is a European research organization that operates accelerators dedicated to particle and nuclear physics. It is located near Geneva on the France-Swiss border. With the LHC, CERN became the world leading laboratory for high energy physics, attracting 12,500 international users. French scientists from CNRS, CEA and universities, who represent about 10% of users from the 23 member states, provide key contributions to CERN research programs, whether for physics experiments, technology developments for particle detectors and accelerators or in intensive computing.

(W-LCG). About 70% of CC-IN2P3 resources are used for LHC data processing and simulations, which represent about 12% of LHC Tier 1 computing resources.

At the end of the current phase of detector upgrades, the operation of the LHC is resuming for four years, with the aim of doubling the amount of data collected. An upgrade of the accelerator and new improvements to the ATLAS and CMS detectors will then be installed in order to start by 2029, and for about ten years, the high-luminosity operation phase of the LHC. This phase will increase the amount of data collected tenfold, providing increased sensitivity to SM testing and possible observation of new physics. The challenging measurements of the self-coupling of the Higgs boson and of its couplings to lighter generations of fermions are among the main objectives of the years to come. In view of anomalies that would seem to emerge in the flavor sector, a prolonged exploitation of the LHCb experiment for the entire HL-LHC phase is envisaged, with improvements being necessary in this case. In a complementary way, this flavor sector is being studied by the Belle-II experiment at the e^+e^- SuperKEKB collider, the B-meson factory in Japan, whose data collection will continue until 2031, and in which IN2P3 physicists are also directly involved.

For 2035 and beyond, the update of the European Strategy in Particle Physics in 2020 has identified Higgs boson physics as a top priority. The only scalar particle in the SM, the Higgs boson, still holds mysteries by its role in the evolution of the Universe (inflation), which a new machine would allow to address thanks to ten times more precise measurements. The Future Circular Collider (FCC) represents the long-term vision to reach this scientific goal. In a two-stage sequential approach, a 100 km circular tunnel at CERN would allow to operate first an e^+e^- collider, the FCC-ee, as a Higgs factory, which would be followed around 2060 by a 100 TeV hadron collider, the FCC-hh. French scientists are strongly contributing to the feasibility studies of such an ambitious project which would enable Europe to remain the world leader in particle physics, in accelerator science, and in superconducting magnet technologies. Other proposals to succeed the LHC are also under consideration. These are linear colliders to be built at CERN in Europe (CLIC) or in Japan (ILC), or a circular collider in China (CEPC).

HADRON PHYSICS

The strong interaction is responsible for the interactions of color-charged quarks and gluons, how they combine into hadrons, and in particular into protons and neutrons, and thus accounts for 99% of the mass of visible matter of the Universe. Knowing how quarks and gluons combine to build-up nucleons and finally nuclei, is certainly a key for understanding the properties of the Universe.

Strong interactions are well described in the perturbative regime of quantum chromodynamics, i.e., at very small distances. A major unresolved question of physics is the understanding of the strong force at low energies which confines quarks and gluons within color-singlet hadrons and how hadron properties emerge from combinations of quarks and gluons. Discoveries of new types of hadrons, especially of exotics states like double-charm baryon, tetraquarks or pentaquarks, predicted by theory and the subsequent measurements of their properties (mass, spin, parity), are essential tests of QCD interactions in the non-perturbative regime. Numerical simulations, in particular in the framework of lattice QCD, made great progress in recent years, and are very important to confront theory with these experimental results.

The studies of the structure and properties of hadrons, and in particular of nucleons, in deep-inelastic scattering allow to obtain form factors, parton distribution functions or more universal parametrizations like generalized parton distributions. Current experiments at Jefferson Lab in the US are exploiting the upgraded capacities of this facility to study the quark distribution and their dynamics in order to reconstruct a 3D picture of nucleons.

Finally, ultra-relativistic heavy-ion collisions allow to recreate and to study the quark-gluon plasma (QGP), predicted by lattice QCD to represent the state of the Universe several microseconds after the Big-Bang. At the LHC, the QGP is formed at high temperature and low net-baryon density, which corresponds to early Universe conditions where lattice QCD calculations are reliable. One of the most important discoveries, already reached with RHIC data and confirmed at the LHC at higher initial temperature, is the fluid-like behavior observed not only in collisions between heavy nuclei corresponding to comparatively large initial sizes, but arising also dynamically in systems like proton-lead or even proton-proton collisions, questioning the existence of universal mechanisms at the origin of collective patterns. Finite net-baryon densities are accessible via heavy-ion collisions at lower energies in order to reproduce high density matter similar to astrophysical compact-objects, like neutron stars. Scanning the energy range down to few GeV per nucleon, a program in preparation at FAIR in Germany and NICA in Russia, should allow to identify the QCD phase transition and the critical point in this phase diagram and represent a breakthrough in our understanding of an expanding quark-gluon system towards nuclear matter at lower energies.

The LHC makes it possible to produce ultra-relativistic ion collisions and this facility will remain for the next decade the spearhead for the study of quark and gluon plasma. The ALICE experiment is dedicated to these studies, the ATLAS and CMS experiments also exploit this data, as well as more recently the LHCb experiment in a dual modality: collider or fixed target. The ongoing upgrade of the ALICE detector will allow its operation from 2022 to 2032. Both ATLAS and CMS, and possibly LHCb after an additional upgrade, could collect data for a longer period of time. In addition, a proposal for a new detector following ALICE is in preparation, however the possibility of heavy ion collisions at the LHC beyond 2032 is yet to be settled.

Complementary to the physics of heavy ions at the LHC, the EIC (Electron Ion Collider) project was recently deemed a priority by the DoE in the US, with construction set to begin in 2023 at Brookhaven for a start around 2030. The machine will collide polarized protons or ions with polarized electrons, at center-of-mass energies between 20 and 140 GeV and at high intensity, allowing precise measurements in order to understand the origin of mass and spin of the nucleons, to clarify the role of gluons in nucleons and nuclei, or even to discover a new state of matter saturated with gluons: the color glass condensate. The scientific community in France is considering the project with interest, as an ambitious continuation of the important work carried out on the structure of nucleons at HERA at DESY and COMPASS at CERN, and which will continue until around 2025 at Jefferson Lab in the US.

NUCLEAR PHYSICS AND ASTROPHYSICS

Recent results in nuclear physics have motivated ambitious efforts around the world for the production and study of exotic nuclei. In addition to RIBF (Radioactive Beam Factory at RIKEN) in operation since 2007 in Japan, large-scale facilities are emerging in the United States (FRIB at MSU), China (HIRFL in Lanzhou, HIAF in Huizhou), South Korea (RISP at RAON) and Russia (SHEF at JINR), accompanied by state-of-the-art instrumentation, demonstrating enthusiasm for new discoveries in the field of nuclear physics. The recent context of the discovery of gravitational waves and the global development of multi-messenger astronomy, has underlined the role of nuclear physics in the understanding of the Universe, some of the great cataclysmic events detected being the seat of nucleosynthesis that allows the creation of the elements constituting our world.

In this rapidly changing landscape, the French scientific community has a roadmap focused mainly on its national facility GANIL/SPIRAL2 and on FAIR in Germany, both recognized as ESFRI landmarks, while keeping an interest in other infrastructures such as at RIKEN in Japan, JINR in Russia or MSU in the United States. GANIL and FAIR use two different and complementary methods to produce radioactive beams: FAIR delivers high-energy beams, far from stability, but with optical properties of limited quality. GANIL produces lower energy exotic nuclei, but which can then be re-accelerated into beams of excellent optical quality and high intensity for precision measurements.

FAIR, after its planned start-up in 2027, will have an unparalleled potential for discoveries as the facility will deliver the most energetic beams compared to other existing facilities. GANIL, which just started a new linear accelerator, will see the first phase of its main upgrade project, SPIRAL2, deployed in the next decade. With this new equipment, major discoveries are expected in the field of very heavy and super-heavy elements, neutron-deficient intermediate mass elements (with

Aerial view of GANIL in 2018 with the new SPIRAL2 installation in the foreground © SEPTIEME CIEL/Photothèque IN2P3

Grand Accélérateur National d'Ions Lourds (GANIL)

GANIL is a world leading heavy-ion research laboratory for research in nuclear physics, atomic physics, astrophysics and condensed matter physics located in Caen, which offers a wide range of ion beams. GANIL hosts about 600 users, 2/3 of whom come from foreign research organizations. SPIRAL2 is a new facility consisting of a linear ion accelerator which delivered its first beams in 2020 and of 3 new experimental areas currently being set up: NFS, DESIR, and S3. The organizations leading this pluridisciplinary research laboratory are CNRS-IN2P3 and CEA-DRF.

S3 and NEWGAIN), ground state properties of exotic nuclei and Standard Model tests (with DESIR). GANIL also develops a rich scientific program in applied fields, whether at NFS or using the cyclotrons: nuclear data measurements or the study of irradiated stress materials for the reactors of the future or fusion technology, studies on the production of innovative radioisotopes for medical applications, or in the field of radiobiology. In addition, GANIL/SPIRAL2 beams will allow precision measurements impossible with FAIR's energy beams. An operation to rejuvenate the cyclotrons is also planned, allowing for an experimental program with stable beams or exotic beams with the SPIRAL1 installation, always at the best international level thanks to the intensity of the accelerated beams and the quality of the instruments on site (LISE, VAMOS, ACTAR, INDRA / FAZIA) or hosted for extended periods such as AGATA and PARIS.

AGATA (Advance Gamma Tracking Array) is a European collaboration which builds and operates a new multidetector for photon detection with high purity Germanium using the new concept of gamma tracking. This is a technological breakthrough based on modern signal treatment and data analysis techniques, which allows an improved resolution power of one to two orders of magnitude higher than conventional detection techniques. AGATA will therefore be able to reveal the structure of the nucleus under extreme experimental conditions, whether with relativistic beams at FAIR or with exotic beams of lower energy at GANIL. The detector will be used in these two European infrastructures, illustrating their complementary nature. The phase 2 of the AGATA detector construction is one of the five priorities of NuPECC's Long Range Plan, following the construction of FAIR and SPIRAL2, highlighting its strong discovery potential.

For the longer term, an international committee composed of renowned scientific experts was set up at the initiative of the CNRS and the CEA to reflect on GANIL's perspectives in the context of its local, national and international environment. This committee points out the unique positioning of GANIL and its facilities at the international level. In particular, the unparalleled intensities of SPIRAL2 heavy beams, thanks to the future NEWGAIN injector, will allow for unique experiments using the equipment built as part of S3 and DESIR, that promise a new impetus for the long-term scientific program of the facility. A later phase would then consider the acceleration of a considerably enlarged variety of exotic beams as well as an electromagnetic probe for the study of their structure.

ASTROPARTICLE PHYSICS

Astroparticle physics is thriving at the intersection of particle physics, astrophysics and cosmology, with the opening of the gravitational wave window to the Universe being its most spectacular success over the past decade. Many other significant achievements have occurred and are paving the way for the next decade.

Gravitational Waves

The discovery of gravitational waves (GW) in 2016 (Physics Nobel Prize in 2017) by the LIGO-VIRGO collaboration is probably the most dramatic change the field has undergone in the past decade, as it has opened a new window of observation of the Universe and brought new constraints on quantum theory models of gravitation. In addition, LIGO-VIRGO's observation of the GWs produced by the collision of two neutron stars addresses the question of the equation of state of nuclear matter under extreme conditions of pressure and isospin. The concomitant observation of electromagnetic emissions has implications for astrophysics (the nucleosynthesis of elements heavier than iron and the equation of state of dense matter) and cosmology (independent measurement of the Hubble parameter). This event opens up new perspectives for probing the physics at play in extreme astrophysical phenomena using high-energy multi-messenger astroparticle observations.

CNRS, INFN and, since the beginning of 2021, Nikhef, are building and operating within the EGO consortium (European Gravitational Observatory), the VIRGO interferometer located in Pisa, Italy. With the ongoing improvements (AdvancedVirgo+), the Virgo and LIGO gravitational antennas are so-called second-generation GW detectors. By 2030, additional upgrades to these infrastructures could bring them to the limit of what is feasible with current sizing and technologies. A significant jump in performance, with an order of magnitude gain in sensitivity for GW detection which seems close at hand, requires the implementation of a 3rd generation (3G) interferometer. A strong scientific return by serendipity alone is expected, and the "guaranteed" science with a post-Virgo third 3G detector for which French researchers have expressed a strong interest (about 200 permanent researchers), concerns (i) tests of gravitation and the nature of black holes, (ii) the nature of dark energy, and alternative theories of gravitation and (iii) the physics of supernovae and compact stars (neutron stars), which links the observation of GWs and that, for example, of astrophysical neutrinos.

In Europe, an innovative concept, the ESFRI project Einstein Telescope (ET), was developed and led to a conceptual design study. For the realization of ET by 2035, a preparatory phase including R&D studies carried out in partnership with EGO is being pursued. The hosting country will ideally provide as "host premium" an environmentally optimal infrastructure.

In space, the LISA (Laser Interferometer Space Antenna) observatory, ESA's L3 mission selected in 2017 and the first space-based GW observatory, will be able to provide from 2037 complementary measurements in the field of low frequencies compared to those at higher frequencies measured by ground-based interferometers. This will allow to probe a whole new range of phenomena, such as the observation of stochastic GW background signals, but also search for signs of new physics (e.g., quantum gravity) through tests of general relativity in a different regime than the ground-based interferometers.

Cosmic Radiation

While the use of cosmic radiation to study particle physics has all but halted through the advent of particle accelerators, more than a century after its discovery, their origin, and the mechanisms that generate extra-terrestrial cosmic rays, gamma rays and neutrinos, are still little understood. Precise observation of cosmic radiation, which cannot be reproduced in the laboratory, together with theoretical and phenomenological efforts to model these high-energy phenomena has improved our understanding and helped the interpretation of their signals.

Cosmic Rays

Very energetic charged particles originating from the Cosmos have been a puzzle for more than a century now. They are detected either directly with space-based detectors (AMS experiment on the ISS) or through their interaction with the atmosphere. The Pierre Auger Observatory (PAO), covering 3,000 km^2 in Argentina is designed for the study of charged cosmic rays at the highest energies (around and above 10^{18} eV).The IN2P3 teams have had key roles since the design and construction of the observatory (commissioned in 2008), and have important skills and responsibilities in its operation, in the production of scientific results as well as in the detector improvement project (AugerPrime) now in operation. While the French participation to the mentioned experiments has decreased over the past decade, with IN2P3 scientists concentrating their efforts on understanding the highest energy events, there is a vibrant community of French theoretical and phenomenological physicists much dedicated to the research of this field. At this time, no major cosmic ray projects, on the ground or in space, are currently scheduled for the next decade even though interesting ideas are being explored.

High energy gamma rays

Since the discovery just three decades ago of the first very high-energy gamma-ray cosmic source, the Atmospheric Cherenkov Telescope (ACT) technique has tremendously progressed, resulting now in about 250 entries in the reference catalog TeVCat. The international collaborations, as well as the interest of unaffiliated researchers, have also significantly grown. Over the past decade, the HESS telescopes in Namibia, observing the Universe in the 20 GeV - 50 TeV band, have all been upgraded. Recent results show that the vicinity of the supermassive black hole at the center of our Galaxy is a powerful particle accelerator generating cosmic rays with energies of the order of

Aerial view of the Virgo site © Virgo Collaboration/Photothèque IN2P3

European Gravitational Observatory (EGO-Virgo)

EGO is the European laboratory dedicated to the detection of gravitational waves. Founded in 2000 by CNRS and INFN and joined by NWO/Nikhef in 2021, it hosts and operates Virgo, the laser interferometer with 3 km arms located near Pisa in Italy. Virgo is able to measure variations in length of the order of a billionth of a billionth of a meter caused by GW space-time distortion. The laser beams are contained in vacuum tubes and are reflected by mirrors (cylinders of fused silica of 35 cm in diameter with a flatness better than one nanometer) suspended from chains of cascading pendulums, the seismic super-attenuators. EGO employs 60 people and hosts 800 visiting scientists from the Virgo collaboration (136 institutions from 15 countries).

10^{15} electronvolts (along with supernovae), and that the so-called gamma-ray bursts are also visible in the very high-energy band. HESS is foreseen to take data until the upcoming ESFRI landmark CTA observatory, operating the next generation of ACTs, goes online in the middle of this decade.

French laboratories' pioneering expertise in building and operating ACT cameras, has naturally led to France providing them for the medium-size class of CTA telescopes. The Key Science Projects are CTA's core program on which French scientists are major players. Composed of two sites, in the southern and northern hemispheres, this new observatory reaching an angular resolution of 2 arc minutes and covering an energy range from 30 GeV to 300 TeV, extending the coverage of its predecessors. CTA should answer several questions in physics and astrophysics, such as the origin of cosmic rays, the nature of particle acceleration processes in the Universe, in particular around black holes, and their role in the structuring of the interstellar medium, the exploration of physics beyond the Standard Model and the study of cosmic dark matter. These Key Science Projects are CTA's core program with a strong participation of French scientists. Meanwhile the space-based Fermi mission has been extended beyond its initial duration, and its fourth catalog of gamma-ray sources in the 50 MeV - 1 TeV band has now close to 6,000 entries. No follow-up mission is currently foreseen in this energy range, but strong interest has been expressed in a new observatory for the energy range immediately below Fermi's.

Very high energy neutrinos

The discovery of a cosmic neutrino flux of astrophysical origin in the 10 TeV - 10 PeV energy range by the IceCube experiment, a Cherenkov detector instrumenting 1 km^3 of ice located at the South Pole, is another marker of the past decade. This forebodes well for the distributed ESFRI project KM3NeT currently under construction in Catania, Italy (KM3NeT-ARCA), and Toulon, France (KM3NeT-ORCA), instrumenting 1 km^3 of seawater. Located in the northern hemisphere, the ARCA detector, complementary to IceCube located in the opposite hemisphere, is dedicated to the observation of astrophysical neutrinos in the energy range from 100 GeV to 1 EeV, while ORCA will use a large sample of atmospheric neutrinos to determine how the neutrino masses are ordered. KM3NeT builds on the success and the expertise developed for the recently decommissioned ANTARES experiment. Together with the Russia-led Baikal-GVD project and the US led IceCube detector, KM3NeT is part of the Global Neutrino Network.

COSMIC INFLATION AND DARK ENERGY

The discovery of the accelerated expansion of the Universe through the observation of the brightness of distant supernovae (Physics Nobel Prize 2011), and the dramatic improvement brought by the Planck space mission to the measurements of the cosmic microwave background (CMB), have led to assume the existence of (i) an unknown form of matter ("dark matter"), accounting for 85% of all the matter in the Universe (ii) a new, near-uniform field ("dark energy") representing 68% of the current energy density of our Universe (iii) a short epoch of exponential expansion of the Universe 10^{-33} s after the Big Bang known as "cosmic inflation". The standard model of particle physics cannot describe this new type of matter, this new form of energy, nor the inflationary epoch at the birth of the Universe believed to have occurred with an energy scale 27 orders of magnitude higher than that of dark energy. Their mere existence is therefore a challenge for our understanding of the fundamental constituents of the Universe and the underlying laws of physics. The properties of dark energy will be further explored in the near future through increasingly precise cosmic surveys, in particular through the expansion history and the growth of large structures. The properties of cosmic inflation, and the ultra-high energy physics that drove it, will be further studied through upcoming measurements of the CMB polarization.

These undertakings have significant instrumental and computational needs, requiring strong organized teams to address them. French teams have participated in major international programs since their inception, building the surveys which allowed the current ~5% precision measurement of the parameters that characterize dark energy with various cosmological probes, and tightening the primordial tensor-to-scalar ratio to $r \leq 0.03$. Essential to these measurements, unique technological capabilities and expertise have been developed in French laboratories.

Leading hardware contributions coming from French laboratories, including flight hardware, have been made to the two major projects addressing dark energy, which aim at improving the precision of the cosmological parameters to 1%. The first light of ESA's Euclid space mission, and the decade-long Legacy Survey of Space and Time (LSST) project at the Vera Rubin Observatory in Chile, are both expected in 2023-24. Whith CNES and IRFU, IN2P3 and INSU led lab have developped Euclid's Near Infrared Spectro-Photometer, while the only non-US contribution of key elements of the LSST 3.2 Gigapixel camera, such as for the readout electronics and the filter changer, comes from IN2P3 laboratories. In addition, the CC-IN2P3 plays a central role in both projects, in data processing and storage, which opens opportunities for exploiting the synergies between them.

Building upon the success of their participation in ESA's Planck mission and with a strong motivation to further explore the ultra-high energy physics at play behind cosmic inflation, French teams joined Japan's LiteBird space mission, which aims at detecting the CMB polarization signal imprinted by cosmic inflation around 2030. Here too, French laboratories, in partnership with CNES, intend to make important flight hardware contributions even though the mission is not to this date formally adopted. There are also plans for a French participation in a US-led ground-based Stage 4 CMB experiment.

Finally, there is a sense that the effectiveness of cosmological physics research in France can be improved if the links between the CMB and dark energy related research programs can be strengthened and made more explicit.

NEUTRINO PHYSICS AND DARK MATTER

After more than six decades of experimental and theoretical studies (Physics Nobel Prizes 1988, 1995, 2002, 2015), neutrinos remain enigmatic particles. Their non-vanishing mass not only challenges the completeness of the Standard Model but also has a measurable effect, due to the relic Big Bang neutrinos, on the evolution of the largest structures of the Universe. Unlike the other fermions, their mass might not be generated through interactions with the Higgs boson. Proving the existence of neutrinoless double beta decays would unambiguously determine whether the neutrino is a Majorana or a Dirac fermion, and hint at the mass generation mechanism at play. The three known flavors of neutrinos are characterized by their yet unknown masses, and by the oscillation parameters of the neutrino mixing matrix which characterizes their probability of changing into another flavor. The three mixing angles of the matrix, as well as the three neutrinos squared mass differences, have been measured over the past decade with accuracies of the order of a few percent, when the aim for the next decade is to get a fraction of a percent precision. The last parameter of the matrix, the CP violation phase, is currently unknown but is constrained to be very likely non-zero.

The exploration of neutrinos' fundamental properties requires dedicated infrastructures and experiments, which either produce them using accelerators (T2K, Hyper-Kamiokande, DUNE) or nuclear reactors (Double Chooz, JUNO), or through their observation from nuclear decays (SuperNEMO, CUPID) or as atmospheric and cosmic radiation (KM3NeT).

There are striking similarities with the search for the nature of dark matter. Most models propose a hypothetical weakly interacting particle, either a massive WIMP in the GeV range or above, or a low mass sub-eV WISP. The existence of some of the hypothesized dark matter particles have adjacent theoretical motivations for unresolved questions spanning from particle physics through nuclear physics. For example, a new pseudo-scalar particle called axion might explain the puzzling conservation of CP-symmetry in quantum chromodynamics, and could also be the looked-for WISP if it were produced in the Big Bang with a large relic density. Proposed extensions of the SM could also yield WIMP candidates, such as the lightest predicted supersymmetric particle which could be a neutralino at the GeV scale and produced after the Big Bang, or

Launching operation of the detection lines of the KM3NeT experiment off the Toulon shore in the mediterranean sea.
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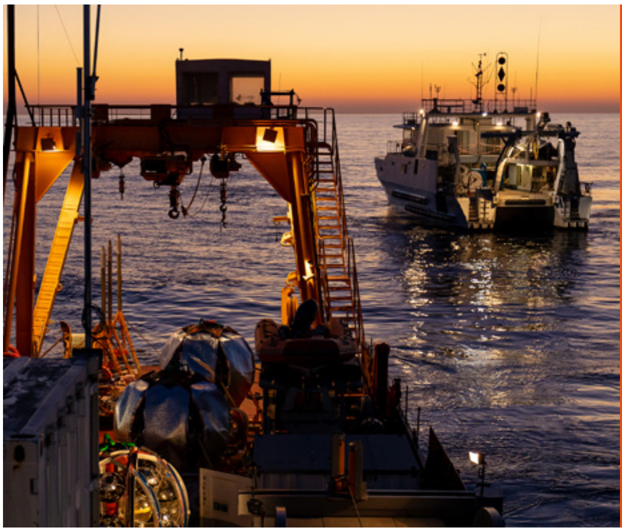


Laboratoire Sous-Marin Provence Méditerranée (LSPM)

The LSPM is a seabed infrastructure in the Mediterranean Sea, which consists of a growing distributed modular network connecting a wide variety of detectors in an area of 35,000 m^2 at a depth of 2,500 m. Onshore data centers 40 km away near Toulon acquire scientific and environmental data in real-time. LSPM's primary objective is to host the 115 KM3NeT experiment detection lines, an international endeavor to establish the neutrino mass hierarchy.

neutrinos with right chirality instead of the SM left chirality neutrinos called sterile neutrinos. The range of probed masses and possible (very weak) interaction types of cosmic dark matter with ground-based detectors is extremely wide, but some scenarios are being aggressively pursued globally. Chief among them currently is the search for the signature of a massive ≥GeV but weakly interacting particle (WIMP) (i) of cosmic origin, observed directly scattering on ordinary matter in large detectors located deeply underground, or observed indirectly in self-annihilating to SM particles in cosmic dark matter clusters (ii) produced directly at colliders such as the LHC. Theorized particles as light as 10^{-9} eV, such as axions, have however gained attraction over the past decade, requiring very different detection techniques. The identification of the nature of dark matter, and getting a better grasp of the physics associated with the neutrino, are major science drivers for the coming decade.

French efforts in the field of neutrino and dark matter physics take place both at the national and the international level, through a vibrant portfolio of small, medium and large-scale experiments. There is a significant and growing effort put in the characterization and the validity of the three-neutrino oscillation paradigm, through French participation and leading contributions in the Double Chooz experiment and in the currently running Japanese long baseline program. Using the Laboratoire Souterrain de Modane, the SuperNEMO experiment demonstrator searching for NDBD, and the Edelweiss low-mass WIMP detector, along with a portfolio of smaller experiments, are currently operated. Using liquid noble gas as target for interactions with cosmic dark matter, the XENON experiment at LNGS in Italy had increased the size of its fiducial target mass from 5 kg to 1,300 kg, and has currently one of the most sensitive measurements for WIMP dark matter, with another factor of four expected from data-taking in progress.

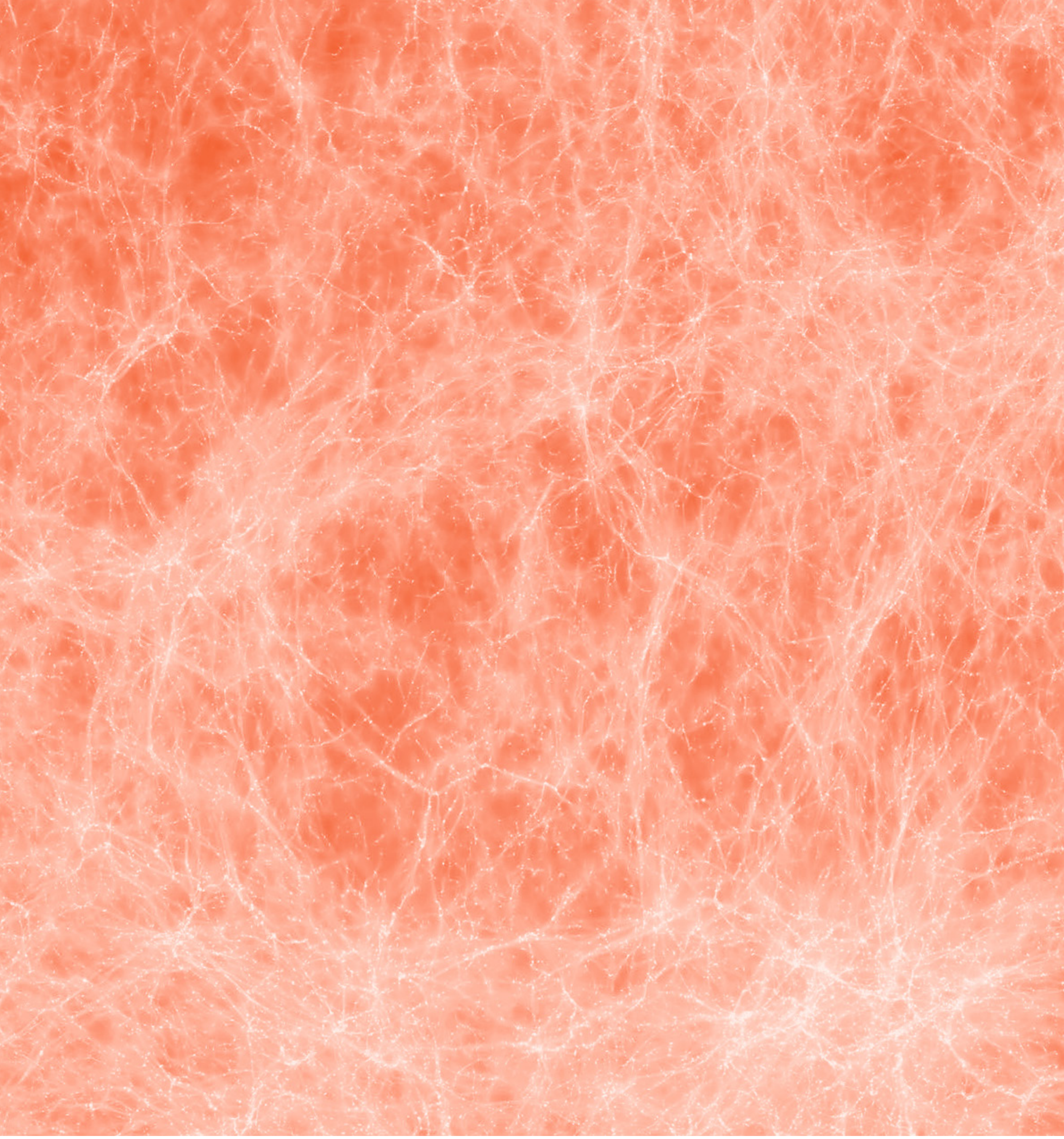
In addition, the recently created GDR (Groupement de Recherche) "Deep Underground Physics" enables exchanges among French scientists for the benefit of the emergence of a long-term program for the next-generation DM and NDBD experiments.

After the T2K experiment in Japan, very complementary measurements of neutrino properties will be made at JUNO (China) and the future DUNE (United States) and Hyper-Kamiokande (Japan) experiments, with the two formers being included in the French research infrastructure roadmap. While participating and contributing with hardware in all three, France is investing primarily in the DUNE experiment carried by the US DoE. Among the top priorities however are the complete and timely deployment of the KM3NeT-ORCA, which should answer the fundamental question of the mass ordering of the three neutrinos, and of the second generation XENONnT which will guide the technology of next decade's ultimate third-generation experiments identified on the APPEC roadmap such as DARWIN. The neutrino and dark matter problems are fundamental issues that propagate from subatomic to cosmological scales, and which are unambiguously related to new physics.

Laboratoire Souterrain de Modane (LSM)

Located at a depth of 1.7 km in the French Alps, directly accessible through the Fréjus tunnel, LSM is Europe's deepest underground facility. It has one of the lowest cosmic background radiation level on earth, a requirement for performing experimental rare-event physics research. The facility hosts dark matter detectors, experiments aiming to observe ultra-rare neutrinoless double beta decays, along with a variety of more interdisciplinary themed instruments. It has been included in the 2021 update of the National Strategy for Research Infrastructures.

The entrance of the LSM © IN2P3 LSM/Photothèque IN2P3



DEVELOPING A 10-YEAR RESEARCH PLAN

Within the scientific domains where IN2P3 coordinates research, Science Drivers have been defined for the next decade as actionable lines of inquiry derived from those identified in the reports from GT01 to GT06.

These twelve Science Drivers provide a unifying view of the theoretical and experimental branches of Nuclear, Particle and Astroparticle physics; they are as independent as possible from the research approach used to address the most compelling scientific questions of the fields. There is obviously some level of entanglement between the Science Drivers; for instance, the search for the properties of weakly interacting massive dark matter particles, mainly carried out in massive underground detectors, may also be carried out by looking for the transformation of the Higgs boson into undetected particles, or by looking into new types of gravitational waves carrying the imprint of new particles or dark matter around black holes. Constraining the equation of state of dense matter through either the observation of gravitational waves coming from neutron-star mergers, or the study of high-energy heavy-ion collisions at accelerators, is another example tying Science Drivers.

The twelve Science Drivers

- Enhance knowledge of the Higgs sector (Higgs)
- Study matter-antimatter asymmetry and flavor transitions (Flavor)
- Pursue searches for unknown particles and interactions (New Phenomena)
- Understand the structure and the origin of the properties of hadrons (Hadrons)
- Pursue the exploration of the nuclear matter phase diagram (Nuclear Matter)
- Explore the limits of stability of nuclear systems (Nuclear Structure)
- Understand how nuclear processes shape the Universe (Nuclear Processes)
- Use gravitational waves to explore the Universe and its fundamental laws (Gravitational Waves)
- Study the physics of high energy messengers and probe extreme astrophysical phenomena (High Energy Gamma and Cosmic Rays)
- Understand the physics behind inflation and dark energy (Inflation and Dark Energy)
- Explore further the physics associated with the properties of neutrinos (Neutrinos)
- Identify the nature of dark matter (Dark Matter)

QUARK AND LEPTON PHYSICS

Enhance knowledge of the Higgs sector

Precision measurements of the properties of the Higgs boson are the very first priorities for particle physics. They make it possible to study in depth the most mysterious sector of the SM, opening the door to an understanding of the mechanism which generates the mass of elementary particles. Because it has a spin 0, the Higgs boson is unique and very different from all other SM particles. And as most of the unsatisfactory aspects of the SM seem to be coming from the structure of the Higgs sector, these precision measurements are also a portal to probing physics beyond the Standard Model (BSM). Furthermore, many questions remain open. The origin and the principles which determine the value of the Higgs couplings to quarks and leptons are completely unknown, as is the possible involvement of the Higgs sector in the mechanism giving mass to neutrinos. Questions related to BSM physics are also of crucial importance, e.g., (i) the Higgs field could couple to dark matter (ii) instead of being a fundamental particle, the Higgs boson could be composite (iii) additional Higgs particles could exist as predicted for example by supersymmetric models. Higgs boson studies are therefore important probes to understand these questions and to potentially discover new physics.

The measurement of the Higgs boson couplings to all fundamental fields at the (sub-)percent precision is mandatory for a more precise understanding of electroweak symmetry breaking. The Higgs self-coupling plays an important role as, for instance, it dictates the dynamics of the electroweak phase transition. Its direct measurement is therefore of fundamental importance as it is the only way to experimentally reconstruct the Higgs potential in a model-independent way. Finally, it is crucial to measure vector boson scattering processes, as longitudinally polarized vector bosons are a direct consequence of the Higgs mechanism and their coupling to the Higgs boson ensures the unitarity of the SM.

Study matter-antimatter asymmetry and flavor transitions

Understanding the organizing principle of fermion masses and mixings encoded in their Yukawa couplings is an open question directly connected to the Higgs sector. The apparent absence of strong CP violation in the quark and neutrino sectors leaves the phase of the Cabibbo-Kobayashi-Maskawa matrix as the unique source of CP violation in the SM. Extra sources of CP violation are therefore required to explain the matter-antimatter asymmetry of our Universe. Precision measurements in the flavor sector are thus formidable tools to probe BSM physics. General experiments are in progress to study b- and c-hadrons, and tau leptons, aiming at improving measurements by at least one order of magnitude in precision during the next decade. A portfolio of smaller experiments, each dedicated to a particular channel, are also in preparation to complete this panorama, especially in the kaon and muon sectors. Solving the flavor puzzle of the SM is of crucial importance and requires to encompass both the quark sector, the charged lepton sector and the neutrino sector. It also requires essential theory inputs in the coming years, in particular on precision calculations, such as those carried out in Lattice QCD.

Pursue searches for unknown particles and interactions

Measurements of numerous observables have confirmed the validity of the SM with astonishing precision. However, there is clear experimental evidence that physics beyond the SM is needed, in particular to account for neutrino oscillations, the baryon asymmetry of the Universe and the presence of dark matter. Likewise, new physics is also necessary to explain certain theoretical issues and observed patterns in the SM parameters, such as the enigma of the scalar potential and the hierarchy problem, the gauge-coupling unification, strong CP-violation, or the flavor hierarchies in fermion masses and mixings. BSM constructions are also necessary to solve further theoretical puzzles such as the naturalness of the theory, and the quest for grand unification of all the forces. Theoretical developments are essential to answer these questions and seek to establish links with cosmology and astrophysics.

The search for the "known unknown" is and has always been at the very heart of Nuclear, Particle and Astroparticle physics, and it requires a very broad approach, both concerning experimental and theoretical aspects. Pursuing the exploration of the energy frontier is one of the main drivers of the field. Direct searches for new particles are culminating since the beginning of the LHC era. The physics behind the very high-energy Universe remains elusive, as does the nature of cosmic dark matter and dark energy. The quantum contribution of new physics on precision observables, which offers an indirect way to test the presence of BSM physics, is also being pursued by many experiments, in particular at B-hadrons factories. Measurements at the highest precision allows to test BSM scenarios featuring ultra-low couplings between SM and new physics. Moreover, they allow testing the presence of new physics over a wide range of energy scales, from very low energies at which feeblycoupling new physics is not always excluded, up to energies close to the PeV scale. Experiments aiming at improving the measurements of the muon anomalous-magnetic moment and of electric dipole moments are strategic in this aspect. Finally, testing the unknown, such as the measurement of the free-fall acceleration of antimatter under gravity, should be pursued since it can lead to striking discoveries.

HADRON PHYSICS

Understand the structure and the origin of the properties of hadrons

A major unresolved question of physics is the understanding of the strong force at low energies, which confines quarks and gluons within color-singlet hadrons, and of the emergence of hadron properties from combinations of quarks and gluons. The discovery of new types of hadrons, especially of exotic states such as tetraquarks and pentaquarks, predicted by QCD, and the subsequent measurements of their properties (mass, spin, parity), are important tests of QCD interactions in the non-perturbative regime. The studies of the structure and properties of hadrons, in particular of nucleons, with electron scattering and deep-inelastic scattering experiments allow us to carry out tomography of nucleons by extracting form factors, parton distribution functions, and generalized parton distributions. Current experiments are paving the way for future precision measurements which will start in the next decade. These studies may allow to handle and answer very fundamental questions, such as the origin of the mass and of the spin of nucleons, or the existence of gluon-density saturation at high energies, known as color glass condensate.

Pursue the exploration of nuclear matter phase diagram

Ultra-relativistic heavy-ion collisions enable the study of quark-gluon plasma at net-baryon density which is believed to represent the state of the Universe between 10^{-9} and 10^{-6} s after the Big-Bang, and which may exist at large baryonic density in the core of neutron stars. Current experiments operating at the highest energies led to enormous progress, establishing QGP as a nearly-perfect liquid, with vanishing mean-free path, high color-charge density, and a high opacity blocking even the most energetic colored particles. Fluid-like behavior is observed not only in collisions between heavy nuclei, but also in proton-lead or even proton-proton collisions, questioning the existence of universal mechanisms at the origin of collective patterns. Further studies of QGP aim at characterizing more precisely QGP properties and at exploring the QCD phase diagram. This requires data not only from heavy-ion collisions at the highest available energies, but also at lower energies in order to identify the transition line and the critical point of the QCD phase transition. This exploration has to be carried out in close connection with theoreticians, who provide state-of-the-art modeling and calculations based on lattice QCD, hydrodynamics and transport models.

NUCLEAR PHYSICS AND ASTROPHYSICS

Explore the limits of stability of nuclear systems

Studying the structure of atomic nuclei and describing their dynamics are of primordial importance to investigate the strong interaction which binds together the constituents of these quantum many-body systems, and to address one fundamental challenge in nuclear physics, such as deriving nuclear forces from first principles. This research domain is facing new questions, especially for nuclei with neutron-to-proton asymmetries at the limits of nuclear binding. The traditional shell structure of atomic nuclei is reassessed and new "magic numbers" have for example emerged on the neutron-rich side of the nuclear chart. The study of super-heavy elements and of nuclei with extreme angular momenta may also lead to the observation of novel properties and unexpected behaviors. New experimental techniques and projects are currently in development and will make it possible to reach unexplored regions of the nuclear chart, to achieve unprecedented precisions, and to test the predictive power of theoretical models. The development of sophisticated theoretical methods (ab-initio, modern energy-density functionals, complex many-body approaches…), and innovative computing techniques (quantum computing, artificial intelligence...), represent a valuable support and provide essential driving forces for the experimental program.

Understand how nuclear processes shape the Universe

Nuclear astrophysics addresses key questions such as the origin of chemical elements in the Universe, the evolution of stars and the properties of nuclear matter in neutron stars and their composition. The study of rare and short-lived isotopes by nuclear physics experiments is necessary to understand the reaction chains occurring in explosive astrophysical events and thus trace back the synthesis of heavy elements in the Universe. This is particularly notable in binary neutron-star mergers, which have been identified as sites for nuclear synthesis through the r-process. The study of gravitational waves produced by neutron-star mergers has a strong impact on the microscopic construction of the nuclear matter equation of state. Thanks to new radioactive beams and to high intensities available in existing or planned dedicated facilities around the world, major progress is anticipated in the next decade. Through observations of compact astrophysical objects, important new results are expected on the understanding of dense nuclear matter, providing for example insight into the composition of neutron stars, from their core to the outer crust.

ASTROPARTICLE PHYSICS

Use gravitational waves to explore the Universe and its fundamental laws

The past decade has seen a dramatic change in the field of gravitational wave physics, benefiting from the long-term investments made by a few leading countries finally being reaped, after their first detections in the laboratory. If the wealth of science coming from each observation since 2015 is a guide, then our understanding of high-energy astrophysical phenomena as well as fundamental physics can be expected to significantly improve during the upcoming observations, together with pursuing the theoretical and phenomenological effort to model the observed cosmic phenomena and interpret their signals. The observation of more astrophysical mergers and precision measurements will further probe the structure of matter under extreme density and pressure conditions, as well as provide new insights into strong interactions and quantum gravity. Pushing the existing detectors to their physical and technological limits will pave the way for the next generation of gravitational wave detectors expected to become operational at the end of the next decade.

Study the physics of high energy messengers and probe extreme astrophysical phenomena

The most powerful high-energy phenomena of the Universe radiate a wide variety of cosmic signals - also known as multi-messengers - through not well understood mechanisms which push the laws of fundamental physics to their extreme. As all these phenomena are near impossible to be reproduced in a laboratory, their understanding heavily relies on the confrontation of multi-messenger observations with theoretical models. The underlying microphysics, such as the equation of state of supranuclear densities, the acceleration mechanism of particles in relativistic outflows coming from compact objects, or WIMP thermal annihilation into SM particles, play an important role in all models. In some instances, deviations from these predictions can be used as probes of the cosmic fields they travel through. Currently operating and upcoming infrastructures have a huge potential to make unexpected discoveries and significant progress in key science objectives.

COSMIC INFLATION AND DARK ENERGY

Understand the physics behind inflation and dark energy

The concordance model of cosmology satisfies all current observational constraints, but at the price of introducing inflation and dark energy. These two ingredients, which are beyond the SM, are introduced by our current knowledge of the primordial and the late-time Universe expansion history. Reinforced by the discovery of the Higgs boson, many possible mechanisms to explain the origin of these two exponential acceleration epochs are based on the existence of (additional) scalar fields, although other hypothetical processes remain to be explored. Mapping out with a higher precision the expansion history during the past ten billion years, along with the forthcoming CMB probes, will bring these investigations significant step further in the next decade.

NEUTRINO PHYSICS AND DARK MATTER

Explore further the physics associated with the properties of neutrinos

There have been several discoveries in neutrino physics in the recent past, in particular that of the oscillation phenomenon which implies that neutrinos have non-zero mass. A rich and comprehensive research program is underway to measure the properties of these neutrinos which, due to their weak interaction with matter, remain the least well-known particles of the SM. Recent progress indicates that experiments which are currently in operation or in construction will be able during the next decade to provide initial answers to fundamental questions such as the mass hierarchy of the three families of neutrinos, whether the neutrino is its own antiparticle or not, whether CP violation in the neutrino sector could explain the imbalance of matter and antimatter abundances in the Universe,or whether unknown types of neutrinos exist. These large experiments are using various detection techniques and neutrino sources from accelerators, reactors, or cosmic origin.

Identify the nature of dark matter

What exactly dark matter is made of remains an open question and is the most pressing one for the coming decade, as are missing an explanation for the existence of this dominant and fundamental building block of the Universe. Among the many experimental paths searching for dark matter, some address questions with theoretical motivations other than elucidating the dark matter's nature, and are therefore more active and more strongly supported. Also, astrophysical observations or collider experiments, not specifically dedicated to this research, provide additional important clues. The exploration of the full WIMP parameter space is ongoing, with the objective to reach the neutrino floor with the next generation of multi-ton noble liquid scintillator experiments with a high level of technological readiness. Doping the noble liquid with some isotopes allow searching simultaneously for neutrinoless double-beta decay with the same experiments, addressing another Science Driver. Simultaneously a portfolio of small- to medium-scale experiments, exploring smaller mass ranges, are expected to come online this decade, providing the broad experimental approaches required by our current state of knowledge.

IMPLEMENTING THE PRIORITIES FOR THE NEXT DECADE

The projects and actions considered below require large scale resource investments and are expected to have a strong impact. Important aspects are their relevance on the Science Drivers, their alignment with Program Wide Priorities, as well as considerations on the timeliness, the feasibility, already existing commitments, and the strength of the scientific effort involved. It is also essential that new ideas and developments, possibly leading to new opportunities, are supported at a level which the research programs can provide. The result of this prioritization follows the funding scheme scenario and assumptions described in page 7.

PROGRAM WIDE PRIORITIES

Enable optimal research programs which address the Science Drivers

The landscape which emerges from the planning exercise calls to enable world-leading research to be undertaken in the fields of nuclear, particle, and astroparticle physics, along the compelling lines of inquiry defined by the Science Drivers. French scientists have the ambition to carry out world-class research with a large scientific impact and visible contributions. This requires optimal research environments, collaborations and infrastructures, where projects are implemented using available critical expertise and resources from French laboratories.

Complete French commitments to large national and international projects and secure the expected scientific return

The completion of existing commitments to research programs from previous prioritizations, in particular those issued in the associated European roadmaps, require stability over the period of their implementation, from their inception throughout the production of scientific results, unless a change in direction occurs for unexpected reasons. The type of research programs carried out in these scientific fields are inherently long-term efforts, generating significant amounts of increasingly large and complex research data to be leveraged in order to expand our knowledge and maximize the scientific return of the French investments in this field.

Pave the way to sustainable programs which will enable to support small scale projects which could result in a leading role when opportunities arise

Advances in Nuclear, Particle and Astroparticle physics require a balance between large- and mid-scale international projects and small-scale projects, together with strong support from theoretical inputs. Furthermore, the development of instruments with ultimate performances requires dedicated programs of Research & Technological Development to push available or emerging technologies beyond their current limits. Given the long timescale of R&D cycles which often span over more than 10 years, addressing the Science Drivers at the end of the next decade requires to set up in this roadmap an innovative and renewed R&D program, drawing on existing expertise, technological platforms and industrial partnerships. This will allow French laboratories to take the next technological leap and maintain leadership at the international level.

Enable the definition of French contributions supporting emerging or evolving projects

The physics programs are implemented via large scale projects, whose fundings mainly come through the French research infrastructures funding scheme, and via mid- and small-scale projects whose funding coming from research organisation budgets and more versatile external resources. Keeping, in this roadmap, the potential for discovery and innovation at the highest level requires mechanisms to exploit new opportunities, either for new projects or upgrades of existing ones. Decisions to reassess priorities at the critical stages via project reviews should provide flexibility to support new ideas and opportunities. Entrusting resources and the related responsibilities to early-career physicists, will both encourage creative approaches and provide stimulating working conditions.

Maintain a world-class theoretical and computational physics research program, and support developments aligned with the Science Drivers

Theoretical and computational physics involves a variety of activities and investments that foster scientific progress, promote collaboration, and enable discoveries. These disciplines work together to push the boundaries of knowledge and provide the best technology available to experimentally search for new phenomena. Strong IN2P3 increase of support in the past years has allowed to maintain a theoretical implication which is on par with the experimental investments and plans. Support in theoretical and computational activities in Nuclear, Particle and Astroparticle physics should be further enhanced in order to enable new discoveries and progress in these fields.

PROJECT PRIORITIES

Pursue the exploration of the energy frontier at high energy collider

- Access to Higgs boson sector properties has opened a new era in the understanding of elementary particles and of their interactions. The Higgs boson scalar nature is of primordial importance for a further and wider understanding of the Universe contents, of its stability and evolution, and its study will continue strengthen the links between particle physics and cosmology. The French participation in the LHC program is a top priority in this roadmap. The exploitation of the ATLAS and CMS experiments, which address five of the Science Drivers (Higgs, Flavor, New Phenomena, Dark Matter, Nuclear Matter) is providing huge science return and important discovery potential for the next decade in which French scientists are deeply involved.

  Pursue a full and optimal exploitation of the ATLAS and CMS general-purpose experiments at LHC

- The upgrades of the ATLAS and CMS experiments for the high-luminosity phase of the LHC are a model of international and interagency cooperation which will keep LHC and CERN as the world-leading facility and laboratory for particle physics until 2040. The French contribution to the ATLAS and CMS phase 2 upgrades for the HL-LHC has been secured with an IR* funding and French laboratories are committed to provide key instruments and detector elements within the next five years for an installation on-site in 2026-2028.

  Complete the ATLAS and CMS phase 2 upgrades on schedule and prepare their exploitation at the HL-LHC.

- Motivated by the strong scientific case provided by LHC results, the 2021 update of the European Strategy for Particle Physics has identified an electron-positron Higgs factory as the highest-priority next collider. A feasibility study for a future circular machine at CERN has been launched and R&D programs are being pursued to develop technologies for particle detection and acceleration. Those developments should be done in partnership with industry in order to fully exploit a wide range of potential societal applications.

  Contribute to the European effort to investigate the feasibility of the FCC at CERN, and engage in the R&D programs to develop technologies for particle detection and acceleration.

Pursue flavor physics at the intensity frontier

- Important investments have been made on the phase-1 upgrade of the LHCb experiment at the LHC. Data taking is resuming in 2022, with increased capacities of the detector which will give rise to a broad scientific return addressing four of the Science Drivers (Flavor, New Phenomena, Nuclear Matter, Hadrons). In parallel, smaller groups of French scientists are also involved in other international experiments exploring, in a complementary way, either the intensity frontier (Belle-II, COMET), or new precision measurements (nEDM, Gbar).

  Fully exploit the on-going LHCb physics program. Maintain an appropriate participation in other experiments addressing the Science Drivers.

- The Flavor physics program at the LHC beyond Run 4 (2032) is not yet established and a proposal to operate an upgraded LHCb detector at the HL-LHC is currently in preparation. In parallel the Belle-II experiment is expected to run until 2031.

  Prepare a sustainable experimental flavor physics program beyond 2030.

Pursue studies of strongly interacting matter at high energy and of nucleon structure

- The French teams must capitalize on the substantial investments made on the LHC detectors, in particular for the phase-1 upgrades of the ALICE detector, which enable an ambitious and diversified physics program on the studies of QGP with heavy-ion collisions at the highest energies (addressing the Nuclear Matter SD). The global interpretation of hadronic data and the associated calculation and simulation techniques are strong assets of the French laboratories which must be consolidated within national scientific networks associating theoreticians and experimentalists.

  Achieve a successful physics program on the study of QCD matter at the highest energies during Run 3 and 4 of the LHC.

- Based on the expertise acquired through the exploitation of electron-ion collisions at Jefferson Lab (addressing the Hadrons SD), an ambitious physics program on hadron structure, the EIC project, is being prepared in the US, with opportunities for French contributions. Participation in this program is currently competing with the proposition to pursue in Europe the heavy-ion program at the HL-LHC for which the first results of the LHC at Run3 will be critical.

Pave the way for a strategic decision to be taken around 2025 concerning potential involvement in hadronic and hadron physics programs beyond 2030.

Tap the potential of nuclear structure and nuclear astrophysics research

- France is well positioned to host a world-leading nuclear physics program, with GANIL as its centerpiece facility. The commissioning of the SPIRAL2 linac and the first experiments at NFS marked the start at GANIL of a renewed and rich program in nuclear physics which will span the next two decades. Completing the approved SPIRAL2 phase 1 projects should be the highest priority, for which focusing and consolidating the national resources is required, as well as fostering a broader international participation in GANIL's coordination and funding.

  Complete the construction of the experimental installations S3, DESIR and NEWGAIN at GANIL as planned.

- In order to fully exploit AGATA during the operational phases planned at the European nuclear facilities LNL, FAIR, and GANIL, construction of AGATA should proceed as planned.

  Secure the French participation to the phase 2 construction of the AGATA detector.

- A vibrant nuclear physics program relies on interpreting the data, and on developing new calculation techniques and models. Nuclear Physics provides essential inputs to other fields, in particular to astrophysics for the study of compact objects and to neutrinos and dark matter physics for the calculation of nuclear matrix elements.

  Enable the emergence of new techniques and innovative ideas in nuclear computing physics, especially those arising with quantum computing and parallel computing.

- The future of GANIL proceeds in two steps. First, the completion of the SPIRAL2 Phase 1, including installation of the new A/q=7 injector which will be operational in 2029 and the renovation of the GANIL cyclotrons. This will ensure a world-class physics program at GANIL in the 2030's. The future of the GANIL installation beyond 2040, the so-called SPIRAL2-Phase2, is being revisited. Possibilities include accelerating an enlarged variety of exotic beams as well as building an electromagnetic probe for the study of their structure. These discussions should proceed and lead in a timely manner to a full upgrade plan that can be submitted to funding approval.

  Decisions and design studies should proceed diligently toward submitting a proposal for GANIL upgrade beyond SPIRAL2 phase 1.

Maintain French international leadership in Gravitational Wave physics

- The importance of the opening of a new window onto the Universe and into the properties of gravity, through extremely challenging experiments after decades of European efforts, cannot be understated. Since the discovery of GW, the international scientific collaboration has tripled in size while the French participation has nearly doubled. The completion of the Advanced Virgo+ phase at EGO, which reach a broad inter-institutes range of scientific and technical interests, is required to reach sensitivity levels keeping the infrastructure at the highest levels of competitiveness for the future of the field and to address three of the main Science Drivers (Nuclear Matter, Gravitational Waves, High Energy Gamma and Cosmic Rays). In addition, the participation in EGO continues to be a successful example of French reliability in international partnerships.

  Maintain continuous and adequate support to keep a competitive and successful GW antenna at EGO.

- Virgo's sensitivity can be further improved over time, perhaps evolving into a 2.5G instrument after the end of the O5 run in 2028, but will rapidly run into structural limits. Motivated by the strong scientific importance of a 3G detector and the intent expressed by some countries to host at least one in Europe, France should engage in developing Einstein Telescope's (ET) technologies where France can contribute critical expertise.

  Participate in the 3G GW interferometer development guided by the leveraging of French Virgo expertise and facilities.

- Through the strategic partnership of CNRS with the French space agency, along with the impressive results of the LISA-pathfinder mission, France is among the leading countries in the space-based LISA mission. Given LISA's complementarity with the ground-based GW antennas, France is also in a strong position to develop the multiwavelength-enabled synergies

  Develop the French contribution to LISA.

Fully exploit the High Energy Messengers

- French laboratories have pioneered many of the techniques currently used by operating or upcoming projects. In just two decades, the imaging atmospheric Cherenkov telescope technique has greatly evolved, progressively opening up an unsuspectedly rich high-energy gamma-ray Universe. French laboratories have made significant investments and contributed with major science results to the HESS experiment, which will be discontinued in the upcoming decade when CTA becomes operational.

  Complete the French contributions to the CTA-North site as planned.

- The organization has also evolved, from small teams operating a single instrument, to now a full-blown observatory with significant observation time allocated to meritorious proposals coming from the whole world.

  Deliver and promote the science return on the CTA telescope and computing investment through strong engagement in Key Science Projects aligned with the Science Drivers.

- The suite of operating or upcoming astroparticle physics experiments (ultra-high energy cosmic rays and neutrinos with Pierre Auger "Prime" Observatory (PAO), astrophysical neutrinos with KM3NeT, gravitational waves with Virgo-LIGO, and possibly still high-energy gamma-rays with Fermi), is observing in many different ways high-energy cosmic phenomena. This largely multi-disciplinary science, which transcends research fields, warrants multiagency support to fully exploit it.

  Support the high-energy multi-messengers approach to understand the High Energy Universe.

Investigate further Inflation and Dark Energy

- We are now entering a new era of precision cosmology. With significant French contributions to the construction, operation and upcoming physics exploitation, the decade-long Legacy Survey of Space and Time (LSST) and the Euclid space mission survey will become operational in the first half of the decade. The expectations for the science extracted from the huge amount of information which will be delivered by both projects, and from their combination, are very high.

  Reap the science rewards of the ongoing and upcoming large optical surveys, in particular LSST and those carried out as part of the Euclid mission. Maximize science return on cameras and computing investment by effecting research with impact on the Science Drivers.

- An essential part of the French cosmological physics research program requires millimetric observations of the CMB and high-redshift objects. The next generation dedicated ground- and space-based experiments are still in their early stages of development and have not yet reached full international commitments, pushing their operation beyond this decade. The JAXA-led LiteBird satellite will significantly enhance the sensitivity to B-mode polarizations in the CMB induced by inflationary GWs, and has received a broad interest from French scientists and CNES to provide essential hardware components.

  Develop the French contribution to LiteBird.

- The ground-based US-led CMB-S4 project addresses complementary scientific objectives to LiteBird, with also here a huge scientific potential for joint analyses. Even if the project has reached a high level of technological readiness, French laboratories should engage in appropriate contributions with some critical expertise and components. An increased level of investment could be considered if CMB-S4 proceeds and LiteBird does not.

  Develop a project plan based on the required expertise and identified resources for a French contribution to the CMB-S4 project.

All these surveys will not only significantly improve our knowledge of cosmological parameters, but also improve on the most precise constraints we get indirectly for the sum of the neutrino masses $\Sigma m\nu$ through the effect of relics on cosmic structures, and hence addressing the neutrino Science Driver.

Build the future of Neutrinos oscillation physics

- The KM3NeT/ORCA experiment is the only research infrastructure in astroparticle physics located in France, and it has strong assets to provide world-class neutrino physics results. Expanding international participation in the coordination and funding of ORCA is a very high priority in order to complete the building of the experiment. In parallel, the JUNO experiment in China will soon (2024) be able to start taking data.

  Complete the KM3NeT/ORCA and JUNO experiments and prepare the determination of the neutrino mass ordering.

- The French teams involved in the Japanese neutrino long-baseline program (T2K) must now consolidate the investments of recent years, in particular on the upgrade of the near detector ND280, in order to aim in the coming years at the world first measurement of CP violation in the neutrino sector. The recent involvement in SK also provides unique opportunities in cosmic neutrinos analyses.

  Fully exploit neutrino data from T2K and SK.

- French teams are actively preparing the next generation neutrino long-baseline program, in particular the DUNE project in the US. The French investment in the DUNE far-site detector, as well as in the PIP-II accelerator which will produce the neutrino beam, corresponds to a strategic and essential investment in line with the expertise of French scientists and industries. On the other side of the Pacific Ocean, the next stage of the Japanese neutrino program is the construction of Hyper-Kamiokande, which constitutes, for the French part, the continuation of the current involvement in T2K and SK, and for which limited levels of hardware contributions are foreseen.

  Participate in the next generation neutrino oscillation experiments, DUNE and Hyper-Kamiokande, including the completion of major instrumental commitments to the DUNE far-site detector and to the PIP-II accelerator at Fermilab.

Define a future of neutrinoless double-beta decay and dark matter searches

- The Laboratoire Souterrain de Modane currently provides an optimal environment used by small- to medium-scale, mostly French-led, international experiments using silicon or germanium technologies. They explore sub-GeV dark matter candidates, and develop low-background technologies which might lead to new opportunities relevant for third generation instruments. XENONnT is currently one of the world's most sensitive WIMP dark matter detector, with historical French contributions to liquid Xenon technology which has been expanding into detector and computing contributions. The existing expertise could pave the way for a participation in the proposed next generation liquid Xenon based DARWIN project, using similar technology aiming at achieving the ultimate DM detector. Alternative projects aiming at similar performance such as DarkSide are also discussed internationally. A contribution to the search for "hidden sector" physics with direct dark matter detectors appears less resource demanding at this stage and would not directly compete with ton-scale DM detectors.

  Fully exploit DM physics and the NDBD potential of XENONnT.

- Establishing the nature of the neutrino is a major challenge in fundamental physics, with now several proposed projects aiming at half-life sensitivities to NDBD >10^{27} years for various nuclei. Opportunities to host a next generation of world-class NDBD (or DM) detector in France would require a yet unplanned extension of the LSM. The existing or planned French involvements in this type of experiment do not require at this stage major construction investments.

  Develop a strategy for opportunities of a French participation in a next generation DM and NDBD experiment.

Table 1: Timeline of major projects in nuclear, particle and Astroparticle physics.

SCIENTIFIC DOMAIN	PROJECT	2021	2022	2023	2024
QUARKS AND LEPTON PHYSICS	ATLAS	Upgrade	Operations		
	CMS	Upgrade	Operations		
	LHCb	Upgrade	Operations		
	Belle-II	Operations	Upgrade	Operations	
	FCC Feasibility Study	Feasibility study			
HADRON PHYSICS	ALICE	Upgrade	Operations		
	CMS HI	Upgrade	Operations		
	LHCb HI	Upgrade	Operations		
	EIC project	Conception			Construction
NUCLEAR PHYSICS & ASTROPHYSICS	AGATA	Operations @ GANIL	Operations @ LEGNARO		
	SPIRAL2/S3	Construction			Operations
	SPIRAL2/DESIR	Construction			
	FAIR/NUSTAR	Construction			
ASTROPARTICLE PHYSICS	HESS	Operations			
	PAO	Operations			
	Adv Virgo+	Construction		Operations - O4	Construction
	CTA	Construction			
	LISA	Construction			
	ET project	Design study			
COSMIC INFLATION & DARK ENERGY	LSST	Construction			Operations
	Euclid	Construction			
	LiteBird project	Construction			
	CMB-S4 project	Design study			
NEUTRINO PHYSICS & DARK MATTER	XenonNT	Construction	Operations		
	T2K-II/SK	Upgrade		Operations	
	JUNO	Construction		Operations	
	KM3NeT	Construction			
	HK	Construction			
	DUNE	Construction			


2025
2026
2027
2028
2029
2030
Upgrade
Operations
Upgrade
Operations
Shutdown
Operations
Upgrade
Operations
Shutdown
Operations
Shutdown
Operations
Shutdown
Operations
Operations
Operations @ FAIR, ISOLDE, GANIL…
Operations
Operations
Operations - O5
Operations
Operations
Construction
Operations
Operations
Operations

Table 2: Science Drivers addressed by each major project in Nuclear, Particle and Astroparticle physics.

SCIENTIFIC DOMAIN	PROJECT	SD1 HIGGS	SD2 FLAVOR	SD3 NEW PHENOMENA	SD4 HADRONS	SD5 NUCLEAR MATTER	SD6 NUCLEAR STRUCTURE	SD7 NUCLEAR PROCESSES	SD8 GRAVITATIONAL WAVES	SD9 HIGH ENERGY GAMMA & COSMIC RAYS	SD10 INFLATION & DARK ENERGY	SD11 Neutrinos	SD12 DARK MATTER
QUARKS AND LEPTON PHYSICS	ATLAS	●		●		●							●
	CMS	●		●									●
	LHCb		●	●	●								
	Belle-II		●	●	●								
	FCC Feasibility Study	●	●	●	●	●							●
HADRON PHYSICS	ALICE				●	●							
	CMS HI				●	●							
	LHCb HI				●	●							
	EIC project				●	●							
NUCLEAR PHYSIC & ASTROPHYSICS	AGATA						●	●					
	SPIRAL2/S3						●	●					
	SPIRAL2/DESIR			●			●	●					
	FAIR/NUSTAR					●	●	●					
ASTROPARTICLE PHYSICS	HESS									●			●
	PAO									●		●	
	Adv Virgo+							●	●	●	●		●
	CTA									●			●
	LISA								●	●	●		●
	ET project							●	●	●	●		●
COSMIC INFLATION & DARK ENERGY	LSST									●	●	●	●
	Euclid										●		●
	LiteBird										●	●	●
	CMB-S4 project										●	●	●
NEUTRINO PHYSICS & DARK MATTER	XenonNT											●	●
	T2K-II/SK									●		●	
	JUNO									●		●	
	KM3NeT									●		●	●
	HK									●		●	
	DUNE									●		●	

SUMMARY OF PROJECT PRIORITIES

Pursue the exploration of the energy frontier at high energy collider

- Pursue a full and optimal exploitation of the ATLAS and CMS general-purpose experiments at LHC.
- Complete the ATLAS and CMS phase 2 upgrades on schedule and prepare their exploitation at the HL-LHC.
- Contribute to the European effort to investigate the feasibility of the FCC at CERN, and engage in the R&D programs to develop technologies for particle detection and acceleration.

Pursue flavor physics at the intensity frontier

- Fully exploit the on-going LHCb physics program. Maintain an appropriate participation in other experiments addressing the Science Drivers.
- Prepare a sustainable experimental flavor physics program beyond 2030.

Pursue studies of strongly interacting matter at high energy and of nucleon structure

- Achieve a successful physics program on the study of QCD matter at the highest energies during Run 3 and 4 of the LHC.
- Pave the way for a strategic decision to be taken around 2025 concerning potential involvement in hadronic and hadron physics programs beyond 2030.

Tap the potential of nuclear structure and nuclear astrophysics research

- Complete the construction of the experimental installations S3, DESIR and NEWGAIN at GANIL as planned.
- Secure the French participation to the phase 2 construction of the AGATA detector.
- Enable the emergence of new techniques and innovative ideas in nuclear computing physics, especially those arising with quantum computing and parallel computing.
- Decisions and design studies should proceed diligently toward submitting a proposal for GANIL upgrade beyond SPIRAL2 phase 1.

Maintain French international leadership in Gravitational Wave physics

- Maintain continuous and adequate support to keep a competitive and successful GW antenna at EGO.
- Participate in the 3G GW interferometer development guided by the leveraging of French Virgo expertise and facilities.
- Develop the French contribution to LISA.

Fully exploit the High Energy Messengers

- Complete the French contributions to the CTA-North site as planned.
- Deliver and promote the science return on the CTA telescope and computing investment through strong engagement in Key Science Projects aligned with the Science Drivers.
- Support the high-energy multi-messengers approach to understand the High Energy Universe.

Investigate further Inflation and Dark Energy

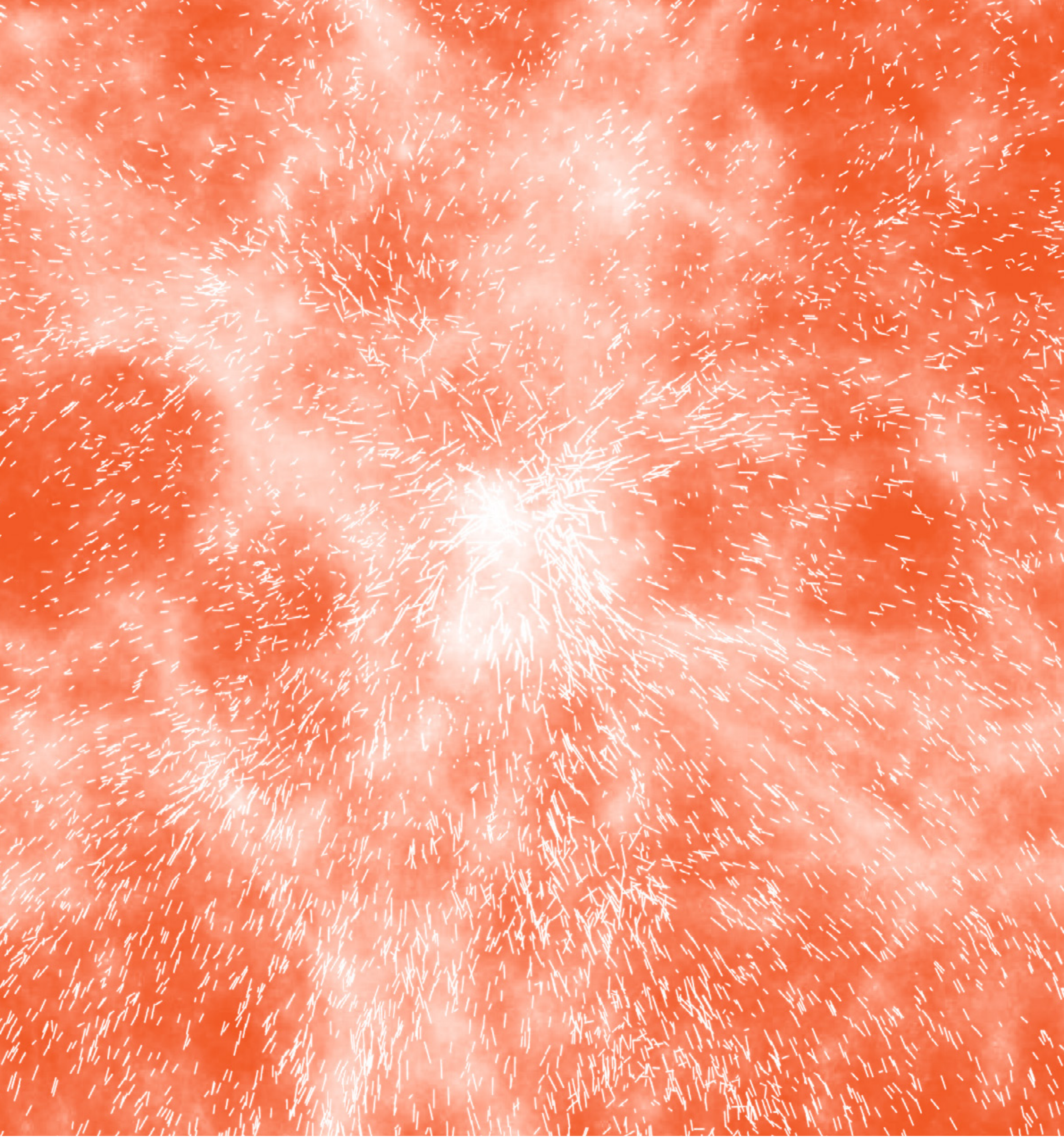
- Reap the science rewards of the ongoing and upcoming large optical surveys, in particular LSST and those carried out as part of the Euclid mission. Maximize science return on cameras and computing investment by effecting research with impact on the Science Drivers.
- Develop the French contribution to LiteBird.
- Develop a project plan based on the required expertise and identified resources for a French contribution to the CMB-S4 project.

Build the future of Neutrinos oscillation physics

- Complete the KM3NeT/ORCA and JUNO experiments and prepare the determination of the neutrino mass ordering.
- Fully exploit neutrino data from T2K and SK.
- Participate in the next generation neutrino oscillation experiments, DUNE and Hyper-Kamiokande, including the completion of major instrumental commitments to the DUNE far-site detector and to the PIP-II accelerator at Fermilab.

Define a future of neutrinoless double-beta decay and dark matter searches

- Fully exploit DM physics and the NDBD potential of XENONnT.
- Develop a strategy for opportunities of a French participation in a next generation DM and NDBD discovery experiments.



BREAKING THE TECHNOLOGICAL FRONTIER

Particle accelerators, detectors and associated technologies, including computing and software techniques, are essential for fundamental and applied Nuclear, Particle and Astroparticle physics. Research in these scientific domains pushed our know-how towards unexplored technological frontiers. These extraordinary progresses have enabled several major discoveries, two recent famous examples being the discoveries of the Higgs boson and Gravitational Waves in 2012 and 2015 respectively. Directly linked to these outstanding results, computing centers have meanwhile experienced a data flood that has challenged our ability to process and analyze them.

The motivation for the future generation technological research must be primarily the Science Drivers expressed in this scientific roadmap. Pursuing a strong research and development effort in accelerators, detectors and computing technologies should be focused in order to:

- Enhance detectors performance towards better sensitivities and resolutions;
- Enhance particle accelerators performance towards higher beam energies, intensities and luminosities;
- Make use and develop breakthrough solutions in order to tackle the upcoming data flows;
- Improve technologies towards increased efficiency, reliability, and sustainability.

Due to the high technological skills required to conduct research in these fields, the IN2P3 led laboratories as well as the CEA's IRFU, have chosen for decades to develop strong and competent technical expertise, especially in mechanics, electronics and micro-electronics, computing and software. This situation is relatively unique in Europe and is a strength of the French organization: the capacity of French teams to start new projects with qualified engineers holding permanent position in academic institutes is highly recognized by international partners.

The need for advanced technologies and highly specialized equipment, for example in electronics, micro-electronics, optics or advanced materials, and the requirement of a large-scale production capacities to construct those scientific instruments makes the role of industry essential in the R&D process and cycle. Conducting these R&D programs in close collaboration between the academic world and the industry strengthens expertise and know-how of both partners, and allows to identify at an early stage, and therefore to accelerate, possible knowledge transfer toward applications for society and to other scientific fields.

In the coming decade, the development of several new technologies will open new ways to produce scientific results (artificial intelligence techniques, quantum technologies and computing, and nano-technologies…). Moreover, addressing the challenges of the ecological transition by focusing in particular on energy consumption reduction will also require new and dedicated efforts to propose innovative solutions for the next generation of experiments and infrastructures, while fully responding to societal questions on the environmental impact of fundamental science.

PARTICLE DETECTORS AND ASSOCIATED INSTRUMENTATION

Particle detectors are playing a crucial role in fundamental and applied Nuclear, Particle and Astroparticle physics and are being increasingly used in areas such as medicine, energy, environment, industry or security. The entire research in Nuclear, Particle and Astroparticle physics relies on the use of very complex detector systems based on several advanced technologies. In this context, R&D programs are focusing on the design, development and construction of detectors able to address the Science Drivers. Top priorities are the development of world-class experiments at CERN, GANIL and EGO. Continuous efforts are made to make these detector technologies available, when appropriate, to other scientific users and for specific societal needs.

Given the scientific and technical advances made in the last 10 years and the limited amount of resources available worldwide, scientists working in particle detectors and associated instrumentation conducts prospective exercises in order to identify the necessary

Laboratoire des Matériaux Avancés (LMA)

LMA, located in Lyon, is a world leader in the production and characterization of low-loss coatings for large optics (up to 1 m in diameter). Thanks to its unique know-how in coating and characterization, LMA has processed the most critical mirrors of the three ground-based GW detectors currently in service (Ligo, Virgo and Kagra). Smaller optics for the development of systems in the field of quantum technologies where optical losses must be kept at the ppm level (quantum opto-mechanical instruments, next generation frequency-dependent light squeezers) are also developed. Finally, at LMA are also produced large filters with optimal optical transmission for spectrographs and cameras that equip large ground- and space-based telescope.

R&D programs. For example, the recent update of the European strategy for particle physics released in 2020 gave rise to a wide and meticulous analysis, to which the French laboratories largely contributed. It resulted in the publication, at the end of 2021, of an ECFA (European Committee for Future Accelerators) Detector Research and Development Roadmap. In order to maximize the impact of the French teams, our roadmap has been carried out based on scientific priorities identified in European and international strategies and where impact of French teams is expected to be maximal. In 2022, a new GDR ("Groupement de Recherche") gathering the French detector community has been setup in order to further organize networking activities and to implement a French strategy on detector R&D.

French laboratories have a very long-standing and solid background in the field, which spans from the detector characteristics to the final measurement interpretation. They designed and constructed a multitude of successful detector projects during the last decades. The development of a new detector technology follows quite a long cycle over at least one decade. It usually starts with generic "blue-sky" R&D followed by a prototyping phase, where R&D is more focused towards the future detector project requirements, and then by a technological demonstrator phase (once the experiment is approved) before the final production/industrialization phase and subsequent installation and commissioning.

Detectors can use very diverse technologies that require the development of dedicated R&D programs capable of leading to cutting-edge technological breakthroughs in these fields.

Microelectronics

The know-how of engineers from French laboratories to develop and design high-tech instruments is highly recognized at international level. Microelectronics R&D is an example where this expertise is particularly sought since experiments in these fields of research rely on efficient data acquisition and processing systems to digest huge data flows with extreme precisions. The increasing complexity of microelectronics developments requires organizing the 80 engineers working in this R&D domain in order to maintain the French laboratories among the world leaders. This workforce is mainly located in three structures. OMEGA (CNRS-IN2P3 and École Polytechnique) designs specific ASICs with analog (low-noise amplifiers, shaping filters, comparators, etc.) and digital (digitalization of data) functionalities. The Competence Center for CMOS Sensors with Integrated Pixels (C4PI) is a IN2P3 platform hosted by the IPHC laboratory in Strasbourg. It is dedicated to the development of CMOS monolithic active pixel sensors from the definition of specifications and design through to validation and construction. At CEA-IRFU, the DEDIP has strong experience in analog and mixed design of low-noise integrated circuits for particle detection, including expertise in multi-channel front-end ASICs, fast analog memories, CMOS sensors, ultra-cryogenic microelectronics and picosecond time measurement.

Push detector development towards:

- enhanced sensitivity and lower background, in particular to detect very rare and/or low signal-to-noise events, like typically for neutrino and gravitational wave detection or for dark matter search;
- better energy, time and space resolutions, in particular to improve the identification of the particles produced by a collision or a decay event;
- higher efficiency, lower greenhouse emissions, and increased reliability and lifetime, in particular when used in extreme conditions like in space or in accelerator-based research infrastructures with a harsh radiation environment;
- high-rate and high-speed read-out with efficient data acquisition, in particular for particle and nuclear physics experiments.

PARTICLE ACCELERATORS AND ASSOCIATED INSTRUMENTATION

A major part of the research in nuclear and particle physics relies on the use of particle accelerators, which have made possible several major discoveries, a recent famous example being the Higgs boson discovery with the LHC. Today, accelerators are also being increasingly used in areas such as health, energy, environment, industry and security, and a growing number of research fields plans to use them even more, in particular for irradiation, analysis or imaging purposes as for the next-generation light and neutron sources.

In the next decade, particle accelerators will remain of paramount importance for the research programs presented in this document. At CERN, accelerator developments are primarily dedicated to particle physics, with the LHC and its planned upgrade the HL-LHC. At GANIL, accelerator developments are mainly dedicated to nuclear physics with the advent of the SPIRAL2 project. Other important machines are: SuperKEKB in Japan for particle physics; GSI/FAIR in Germany, FRIB and CEBAF in the US, or RIBF at Riken in Japan among others for nuclear and/or hadron physics; J-PARC in Japan and soon PIP-II at Fermilab for long baseline neutrino physics. In France, several smaller scale accelerator-based research platforms are also used for multidisciplinary research and applications, like AIFIRA in Bordeaux, ALTO, ANDROMEDE and SCALP in Orsay, ARRONAX in Nantes, CYRCé in Strasbourg or GENESIS in Grenoble.

For about 20 years, accelerator teams in France have developed a unique expertise on high-intensity linear accelerators (linacs), and in particular on those using Superconducting RadioFrequency (SRF) cavities. Thanks to a vigorous R&D program supported by the creation of dedicated high-level technological research platforms (Supratech in Orsay, Synergium in Saclay), IN2P3 labs and IRFU have become together one of the major international players in the field of high-power SRF linacs. Research teams have in particular contributed decisively to the design and construction of several very high-visibility international projects over the past 10 years. The 3 main ones are:

- the SPIRAL2 linac at GANIL (2005 - 2019);
- the XFEL linac in Hamburg (2007 - 2017);
- the ESS linac in Lund (2010 - 2021).

Other contributions have also been made to the construction of LINAC4 at CERN (2008-2014), to the construction of the FAIR proton linac (still on-going since 2009), and also, since 2005, to the design and prototyping phase of the MYRRHA ADS accelerator, in which IN2P3 teams have played a leading role at the European level, as the main designers of the machine. In this context, French labs have been developing for about 15 years several R&D activities and innovative concepts to try to improve the reliability of high-power accelerators and subsequently their availability.

French expertise in superconducting magnet technology made an essential contribution to the development and construction of the LHC 7T magnets. The European Strategy for Particle Physics is leading an extensive R&D program aimed at developing high-field superconducting magnets by overcoming the current limits of magnets based on NbTi or NbSn conductors. The European roadmap shared between CERN and European laboratories will make it possible to explore during the next years promising technologies by involving European industries. This research on magnets also has strategic applications in the fields of energy and life sciences.

The PIP-II project aims at upgrading the Fermilab accelerator complex in order to produce a neutrino beam for the new long-baseline neutrino experiment (LBNF/DUNE), thanks to a 1.2 MW proton primary beam in the energy range of 60 to 120 GeV. The contribution to the construction of PIP-II, which has been validated by the French ministry in 2020, is a top priority in the 5 next years. This contribution is indeed fully coherent with the world-leading expertise of IJCLab and IRFU teams on SRF cavities and will allow further enhancing their skills and international visibility in the field of SRF technology R&D.

The SPIRAL2 linac at GANIL will produce, in its energy range, the most powerful beams worldwide over a large variety of ions (from protons to Uranium). In order to provide GANIL with a unique potential to increase its international competitiveness in nuclear physics and associated application, reaching the nominal beam specifications of the linac and completing the construction of the new heavy-ion injector are top priorities. The development of intense multi-charged heavy-ion ECR sources is also a R&D area to be strongly pursued.

Energy Recovery Linacs (ERL) are a promising concept allowing for high-power multi-GeV electron beams with a very compact footprint, together with excellent beam quality and unprecedented operation efficiencies.

Accelerator platforms

In France, R&D, design and construction of superconducting accelerating cavities for high-energy particle accelerators are carried out at the SUPRATECH and Synergium research platforms, respectively at IJCLab and IRFU, on the Paris-Saclay site. These platforms play a major role in the construction of accelerator elements for facilities dedicated to high-energy physics and nuclear physics (GANIL, FAIR, LHC, PIP-II) but also for facilities dedicated to photon/neutron sources (XFEL, ESS) and other applications (MYRRHA…). They are among the major accelerator platforms in the world, especially in the field of high-power superconducting RF linacs.

In this context, ERLs are starting to be considered for several applications, including particle physics colliders or nuclear physics accelerators. French laboratories are playing a leading role in the international development of this concept which will require an adequate R&D effort during the next ten years. Laser-driven acceleration is presently making fast progress with the advent of PW class laser drivers. 10 GeV energy range for electrons and 100 MeV for protons are within reach of emerging experimental facilities like the APOLLON laser facility in Saclay and exploratory programs should be actively pursued. Building a prototype for multistage acceleration of electrons at the GeV level aiming at demonstrating the reliability of this technology is of high priority. It will allow fostering French collaboration at the national level and serve as a dedicated test facility in the frame of the European EuPRAXIA initiative, which entered in 2021 the ESFRI roadmap.

For the next decade, the top priorities will be the development of the accelerator infrastructure at GANIL, CERN, and other world-class accelerator facilities, such as Fermilab, addressing the Science Drivers. This planification should ensure an appropriate contribution to the design, construction and upgrade of high-energy and high-intensity colliders, in strong cooperation with CERN and with other institutes. French teams, who have acquired strong expertise in the field, should in particular reinforce their participation in the ongoing international conceptual studies and associated R&D programs for next-generation colliders, with a priority given to the FCC feasibility studies. Research teams should also, when appropriate, make accelerator technologies available to other scientific users and to specific societal needs

Push accelerator development towards:

- higher beam energies, to study and develop the next generation high-energy colliders and beyond;
- enhanced beam intensities and luminosities, to be able to track rare events more efficiently, at Isotope Separation On-Line (ISOL) factories for nuclear physics, at high-intensity frontier colliders for particle physics or at long baseline facilities for neutrino physics;
- higher beam quality, efficiency and reliability, to increase the general performance of accelerator-based research infrastructures. nuclear physics experiments.

COMPUTING AND DATA SCIENCE

Today's scientific research relies on computing and data science in the wider sense, and nuclear, particle and astroparticle physicists are among the largest producers, users, and analyzers of scientific data. This research field has a proven track record of creating innovative and disruptive solutions, such as the creation of the Worldwide LHC Computing Grid (W-LCG), of which IN2P3 with its e-infrastructures and expertise is currently a vital part. The main challenge here is not only the order of magnitude increase of data volume to be expected with HL-LHC, but also the growing number of significant data volumes to be produced by the next generation of experiments in astroparticle and nuclear physics.

The field has to further push the limits in the computing and data handling domains, finding new solutions to efficiently use infrastructures, to develop state-of-the-art software, and to follow and participate in the usage of emerging technologies. In addition, the international dimension of today's experiments imposes strong constraints on the IT ecosystem, in hardware and software and the setting of collaboration agreements.

In particle physics for example, one key aspect in this context is the development of the next generation computing model following the computing grid, with CC-IN2P3 at the cornerstone of the French high energy physics e-infrastructure. In addition, the efficient usage of accelerators like GPUs and FPGAs, a continuous effort to lead in the domain of AI in Nuclear, Particle and Astroparticle physics, and assuring high quality standards for the software and workflows are high priorities of the involved laboratories. This also relies heavily on the ability to attract and train experts in the field

Continuous improvement of the national computing infrastructure CC-IN2P3, a national strategic asset, is therefore essential to be able to process, simulate and analyze data produced by experiments in the context of large international projects. The current national Tier1/Tier2 organization with CC-IN2P3 at the heart of the grid completed by regional centers has proven robust in the rapidly evolving landscape of France research organization. Nevertheless, to make the most efficient use of resources, regional centers could, for example, be data or CPU oriented, federated with a unique user portal bearing in mind local specificities and the evolution of experiment computing models in the international landscape.

Furthermore, efficient access to resources providing new types of hardware (Ex.: HPC with GPU or FPGA) will be important to allow massive usage of AI and specific simulations. The close links between the CC-IN2P3 and the laboratories has proven essential in facilitating exchanges on user support or on innovative solutions.

The importance of software in processing and simulating Nuclear, Particle and Astroparticle physics data continues to grow. Researchers, for example, have developed expertise and make extensive use of Real Time Analysis, enhancing the scientific throughput of experiments, in particular when facing limited storage resources. This has required using advanced algorithms (in particular in machine learning) on GPU/FPGA when processing larger and larger data volumes. In the recent years, collaborations with machine-learning computer scientists have developed through the release of open data sets, funding of co-supervised PhD theses, and collaborative projects. In addition, joint physicists and computer scientist teams have engaged in evolving and emerging technologies (GPU/FPGA evolutions, quantum computing...) and developed innovative testbeds. They also have adopted common tools for software development such as collaborative tools for project management.

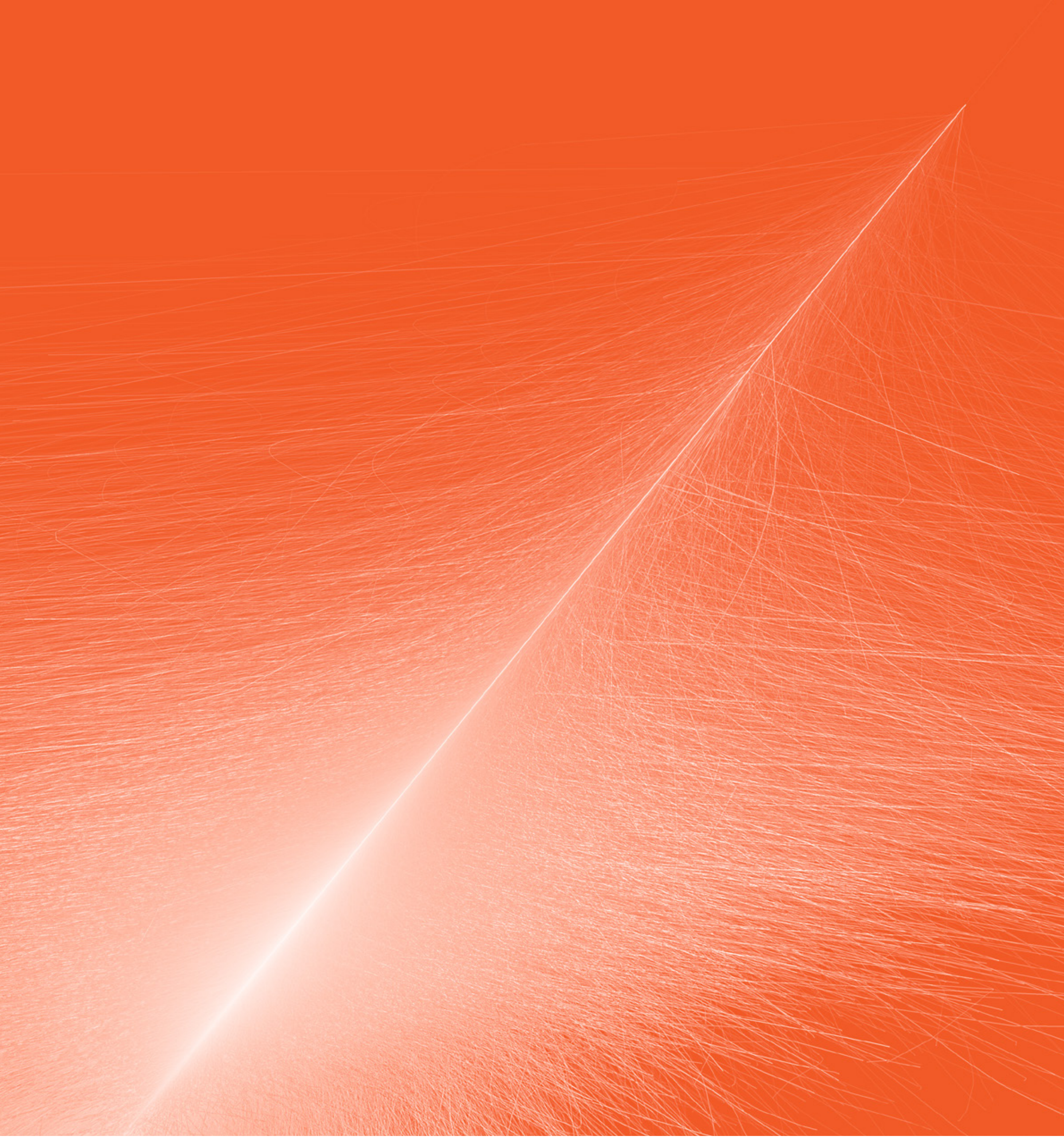
In addition, the strong engagement of IN2P3 teams in European projects or international initiatives has been key to the French impact on the future computing landscape and its implementation in France, including on R&Ds and experiment computing models or in the choice of common tools across experiments and sites.

IN2P3 computing center: CC-IN2P3

CC-IN2P3 is a CNRS laboratory founded in 1986 and located in Lyon. It has a world-class data center housing the IT services necessary for the analysis and interpretation of fundamental processes in particle, astroparticle and nuclear physics, which require the transport, storage and processing of the huge amount of data (up to hundreds of Peta-Bytes) generated by major international experiments in this area. Co-designed by CC-IN2P3 computer scientists and international collaborations, those IT services are tailored to meet increasingly stringent scientific specifications. CC-IN2P3 is one of the 15 major first-level centers of the global computing grid, the "Worldwide LHC Computing Grid" project; and around 70% of CC-IN2P3 resources are used for LHC data processing and simulations. This essential know-how in massive data processing benefits to other fields such as for LSST, CC-IN2P3 being one of the three major data processing centers of this project. CC-IN2P3 is also the main element of the French ground segment of the European space mission EUCLID. Other international organizations or scientific collaborations that use the CC-IN2P3 services are GANIL, EGO, HESS, PAO, JUNO and KM3NeT. More than 2,500 researchers around the world use the center IT resources, which are available 24/7 throughout the year, currently developed, maintained and operated by 60 permanent and 20 non-permanent staff.

Push computing and data handling development towards:

- more powerful and efficient IT solutions to worldwide Nuclear, Particle and Astroparticle scientific collaborations;
- consolidating, at the national level, the organization of the computing resources and services providers;
- strengthening further the links between the CC-IN2P3 and the laboratories involved in processing, simulating and analyzing data;
- intensifying collaborations of researchers and engineers with Machine learning Computer Scientists;
- broadening the use of Real Time Analyses to enhance the scientific throughput of experiments;
- engaging further in evolving and emerging technologies, including quantum computing.



BROADER IMPACTS

Research activities and technological developments carried out in Nuclear, Particle and Astroparticle physics scientific programs, contribute to the emergence of new fundamental research activities through interactions with other basic science curiosity-driven research fields. These include multi-disciplinary projects involved in major societal challenges for advancing sustainability and address obstacles, as well as for society as a whole in promoting to citizens the advances and discoveries achieved with scientific methodology.

Long-term relations exist between research in the domains of Nuclear, Particle and Astroparticle physics, and fundamental research in other basic sciences, which has provided tremendous benefits to the partners within their own specific programs. These relations have often been initiated through sharing of the practical knowledge laboratories have in some specific domains, and are often allocated dedicated resources coming from public funding, such as project funding through specific calls (e.g., from the interdisciplinary program of CNRS) dedicated to further fertilizing cross-collaborations between fields. The joint research with the field of astronomy is particularly remarkable, since there is now a strong collaboration between laboratories and institutes in building and exploiting large and complex international instruments (e.g., the Euclid satellite, the ground-based Cherenkov Telescope Array) as well as the US lead Vera C. Rubin Legacy Survey of Space and Time. Other examples are the 3 kilometer-long laser beams in the European Virgo gravitational wave experiment, and the materials required to make them interfere, which have required the funding of some fundamental developments jointly with physics laboratories, and the 41.5 km-long telecom cable that is deployed at a depth of 2,500 m to connect the LSPM facility to the shore which provides monitoring of marine and solid earth phenomena (geophysicist could e.g. monitor regional micro-earthquake). So does the use of particle physics instrumentation dedicated to the measurement of muons, which are being put to a new use for probing the inside of pyramids and volcanoes providing new information which could not be accessed before. More of such joint developments exist, and more are expected to arise in the coming decade, strengthening curiosity-driven research connections across the entire spectrum of basic science.

Developments in nuclear and particle physics have direct applications within society especially in the sectors of health, energy, space and the environment. The transfer to societal and industrial applications is of primary importance and concerns both the technologies developed initially for fundamental physics experiments (e.g., particle detectors and accelerators), platforms providing high-tech equipment (e.g., irradiation and computing platforms) or the know-how present in the laboratories (e.g., high-level simulation tools). These research applications are conducted in partnership with research organizations and French industries that are also involved in these domains such as Inserm, Institut Curie, IRSN and ESA for health science, and CEA, EDF, Framatome, Orano, Andra for the nuclear energy sector. The presence of laboratories on university sites ensures the development of links with local academic and industrial partners, and the strong organization in international networks of particle and nuclear physics, in particular via infrastructures such as CERN, EGO, GANIL, GSI/FAIR or FNAL, brings visibility and international structuring to these developments.

NUCLEAR ENERGY AND ENVIRONMENT

Within IN2P3 laboratories, about 100 nuclear physicists, chemists and radiochemists with permanent positions at CNRS or universities are committed into research efforts related to nuclear energy production, from the modeling of innovative nuclear reactors to the study of nuclear materials, nuclear waste and the impact of radionuclides on the environment. The Euratom program in Horizon Europe provides strong support to this domain, both in terms of research and training. At the national level, the multi-partner NEEDS program led by CNRS with CEA, Andra, BRGM, EDF, Framatome, IRSN and Orano is aiming at building research projects that address fundamental scientific questions of interest to nuclear energy. The irradiation facilities needed for this research are organized within the EMIR&A network which is identified as a distributed research infrastructure on the French research infrastructure roadmap. Finally, the Becquerel network brings together IN2P3 resources and expertise for the measurement of radioactivity in the environment.

In the years to come, the developments related to nuclear energy will remain crucial subjects on which the expertise of nuclear physicists remains essential, notably for the study of alternatives to deep geological waste disposal, the decommissioning and safety of facilities, or the studies of more fundamental aspects such as the modeling of nuclear reactions, or radionuclide chemistry. In order to pursue this research, it will be necessary to continue the structuring at the national level of this research work on the model of current partnerships, with industries (e.g., the CNRS-Framatome agreement) and with all academic actors in these fields.

HEALTH AND LIFE SCIENCE

In the field of health and life-science, 80 researchers with permanent positions are working at IN2P3 laboratories on the development of new medical-imaging techniques and new approaches in radiotherapy. This research is conducted in partnership with academic partners (mainly INSB, INSIS, INS2I and INP at CNRS, CEA, Inserm, IRSN, Institut Curie) working also in this field and in close relation with university hospital centers. French nuclear and particle physicists bring techniques coming from fundamental physics projects, especially particle detectors and their associated electronics (e.g., the innovative camera XEMIS based on liquid-xenon), but also essential expertise on data-handling and on the development of open-source software like Geant4-DNA and OpenGATE to simulate particle interaction with biological tissues and medical physics applications.

The research activities follow four main axes: imaging, radiobiology, radiotherapy and radionuclides. Regarding imaging, the main achievements include preclinical molecular imaging and portal clinical imaging, new techniques for X-ray, gamma-ray and particle imaging: photon counting, time-of-flight Positron Emission Tomography and Single Photon Emission Tomography, Compton imaging, proton radiography, and novel approaches for quantitative reconstruction. Radiobiology activities are dedicated to the development of tools and methods for biological data acquisition within a network of national irradiation facilities, and to the development of biophysical models to understand and predict the effects of irradiation. In relation to clinical applications, radiotherapy-related activities aim at optimizing therapeutic efficiency, by means of beam monitoring, dose control and prediction. In particular, nuclear and biological data of interest are acquired, and online control of the treatment with PET and prompt-gamma are developed for hadrontherapy. Last, new research activities have emerged with the launch of ARRONAX, CYRCé and with other French irradiation platforms in particular for the production of new radiotracers, and the study of their use for imaging and therapy. At the national level, project funding in this field is provided by Institut National du Cancer and by CNRS interdisciplinary program, and universities where this research is pursued. Through their participation in European projects like the ENLIGHT network for ion therapy, French nuclear scientists contribute to the structuring of the discipline in order to bring together clinicians, physicists, biologists and engineers. Using particle and nuclear physics techniques to develop innovative and efficient cancer treatment techniques has strong societal impact. These developments on innovative instruments and simulation software will be continued in collaboration with international collaborators and in close relation with treatment centers in France (CAL-Nice, CPOrsay, Archade-Caen) and in Europe (CNAO-Pavia, Heidelberg/GSI).

COMMUNICATION AND OUTREACH

Scientific results in Nuclear, Particle and Astroparticle physics offer many subjects for communication and dissemination to society. The French scientists involved in these results contribute to numerous outreach actions whose impact on the general public is often very strong, as we have seen for the discovery of the Higgs boson and that of gravitational waves. This communication work is organized and managed by a vibrant network of communication staff at CEA and IN2P3, in close collaboration with other scientific institutions and networks, especially with CERN (EPPCN[5], IPPOG[6]), and through the Interactions network[7].

Scientists are also involved in educational actions and scientific communication aimed at the general public, teachers and students: laboratory visits, master class discovery days, teacher training, loans of educational detectors for cosmic ray detection in schools, educational materials, exhibitions, websites, MOOCs, etc. These initiatives are based on partnerships, for example with CERN and the ministerial "Science à l'École" program which brings high-school professors to CERN, and benefit from the support of many members of the institute's staff.

OPEN SCIENCE

Particle and astroparticle physics collaborations are major players in the international movement for open science. The pioneering work of the HEP theory community in the 1990s has led to the creation of arXiv where authors offer an open access version of their work and IN2P3 contributes to the SCOAP3 initiative for open-access publications led by CERN. The management of publications is entirely supported by IN2P3 Scientific and Technical Information professionals. Curators ensure the quality and completeness of the metadata of each publication in the INSPIRE[8] database, of which IN2P3 is a partner, and in the French open-archive HAL[9]. The goal of 100% of the publications in open access should be reached in the next few years.

Following the successful work done for GW and LHC data, an open data policy is being adopted to release systematically particle, astroparticle and nuclear physics data publicly in international repositories with high-quality metadata and open software allowing to reach the FAIR standards. The tools and skills developed for large, distributed and complex datasets are key elements for the construction of open science in all scientific fields as in the European effort to build the European Open Science Cloud (EOSC).

5. https://espace.cern.ch/EPPCN-site/ 6. https:// www .ippog.org/ 7. https://interactions.org/ 8. http://inspirehep.net 9. http://hal.in2p3.fr

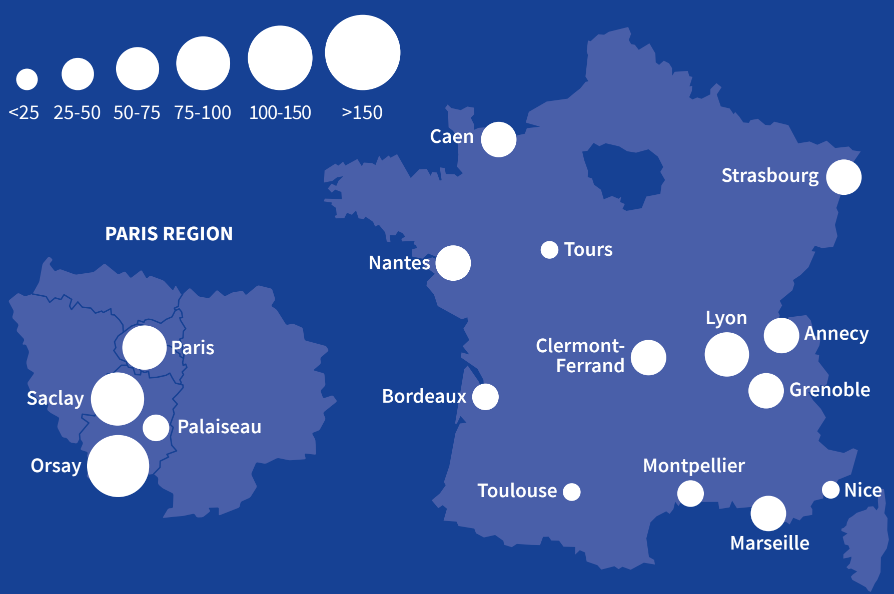
APPENDIXES

Appendix A: Nuclear, Particle and Astroparticle physics in France

In France, research in Nuclear, Particle and Astroparticle physics is performed in laboratories, most of them jointly managed by CNRS and Universities and at CEA. About a thousand permanent researchers in these fields are in laboratories operated by IN2P3, a hundred in laboratories operated by INP, around fifty in laboratories operated by INSU and 130 at IRFU in CEA.

Created in 1971, the Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) operates 25 laboratories and national research platforms and infrastructures, most of the time in partnership with French universities. These laboratories are primarily located in major French university campuses: 15 are campus research structures, 10 are national platforms or research infrastructures which provide special experimental conditions (underground laboratory, proximity to a nuclear reactor), house major infrastructures (GANIL jointly run with CEA, LSM, LSPM), contribute to the technological development of large experiments (OMEGA, LMA), or aimed at the general public (Musée Curie). This ensemble of laboratories is completed and connected by CC-IN2P3, both a digital infrastructure and a research center on computing and big data, at the heart of the institute's data strategy. Two recently created International Research laboratories (IRL) located for one in the United States at the University of Berkeley and for the other one at the University of Tokyo, and a third one being set up with the Helmholtz centers in Germany, add to a dense network of international scientific partnerships with many international research organizations and universities. In 2021, the IN2P3 laboratories comprises 3,200 staff: around 1,000 permanent researchers, including 600 from CNRS and 400 from universities, 1,500 permanent engineers, technicians and administrators including 600 research engineers mostly from CNRS, and around 750 doctoral students and post-docs. About a hundred fifty permanent researchers and university professors and around 75 doctoral students and post-doctoral fellows performing research in Nuclear, Particle and Astroparticle physics theory are located in laboratories operated by INP and INSU. Researchers from CEA are mostly in the IRFU laboratory operated by the Fundamental Research Department (DRF) of CEA, as well as in GANIL in Caen. Located in Saclay, IRFU comprises about 850 employees (among which 400 staff working on accelerators technologies and superconducting magnets) including 130 permanent researchers engaged in Nuclear, Particle and Astroparticle physics.

Fig. 1: Permanent researchers involved in Nuclear, Particle and Astroparticle physics



Appendix B: Composition of the supervising committee and of the working-group steering committees.

Supervising Committee

IN2P3 Director: Reynald Pain ‖ IN2P3 Deputy Director: Patrice Verdier ‖ Aix Marseille Université: José Busto ‖ École polytechnique/Institut Polytechnique de Paris: Benoit Deveaud ‖ Sorbonne Université: Marco Cirelli ‖ Université de Bordeaux: Philippe Moretto ‖ Université Caen Normandie: Francesca Gulminelli ‖ ENSI Caen: Marco Daturi ‖ Université Claude Bernard Lyon 1/ Université de Lyon: Aldo Deandrea ‖ Université Clermont-Auvergne: Philippe Rosnet ‖ Université Grenoble Alpes: Laurent Derome ‖ Université de Montpellier: Jacques Mercier ‖ Nantes Université: Gines Martinez ‖ IMT Atlantique: Pol-Bernard Gossiaux ‖ Université Paris-Diderot/Université de Paris: Matteo Cacciari ‖ Université Paris-Sud/Université Paris-Saclay: Tiina Suomijarvi ‖ Université Savoie-Mont Blanc: Roman Kossakowski ‖ Université de Strasbourg: Christelle Roy

Coordinators of the Working Groups

- GT01 – Particle physics, L. Vacavant (IN2P3) ‖ Dirk Zerwas (IJCLab, also IRN Terascale Director), Francesco Polci (LPNHE, GDR Intensity Frontiers Director), Christopher Smith* (LPSC), Marie-Hélène Genest (LPSC), Christophe Ochando (LLR)
- GT02 – Nuclear physics and astrophysics, Fanny Farget (IN2P3) ‖ Jérôme Margueron (IP2I, GDR Resanet Director), Giuseppe Verde* (L2IT), Stéphane Grévy (CENBG), Iulian Stéphan (IJCLab)
- GT03 – Hadronic physics, L. Vacavant (IN2P3) ‖ Frédéric Fleuret (LLR, GDR QCD Director), Béatrice Ramstein* (IJCLab), Klaus Werner (SUBATECH), Carlos Munoz (IJCLab)
- GT04 – Physics of astroparticles, B. Giebels (IN2P3) ‖ Chiara Caprini (Ondes Gravitationnelles APC, GDR Ondes Gravitationnelles Director), Frédérique Marion* (LAPP), Régis Terrier (APC), Francesca Calore (LAPTH)
- GT05 – Inflation physics and dark energy, B. Giebels (IN2P3) ‖ Sophie Henrot* (IJCLab) Emmanuel Gangler (LPC), Mathieu Tristram (IJCLab), Andrea Catalano (LPSC), Ken Ganga (APC)
- GT06 – Neutrino physics and dark matter, B. Giebels (IN2P3) ‖ Dominique Duchesneau (LAPP, GDR neutrino Director), Anselmo Meregaglia (CENBG, GDR neutrino Director), Corinne Augier (IP2I, GDR Underground physics Director), Frédéric Yermia* (SUBATECH), Laurent Vacavant (IN2P3), Fanny Farget (IN2P3)
- GT07 – Accelerators and associated instrumentation, J.-L. Biarrotte (IN2P3) ‖ Rodolphe Cledassou (IN2P3), Brigitte Cros* (LPGP, GDR Appel Director), Angeles Faus-Golfe (IJCLab), Luc Perrot (IJCLab)
- GT08 – Detectors and associated instrumentation, J.-L. Biarrotte (IN2P3) ‖ Rodolphe Cledassou (IN2P3), Giulia Hull (IJCLab), Didier Laporte* (LPNHE), Julien Pancin (GANIL), Véronique Puill (IJCLab), Laurent Serin (IJCLab), Mariangela Settimo (SUBATECH)
- GT09 – Computing, algorithms and data, V. Beckmann (IN2P3) and S. Crépé-Renaudin (IN2P3) ‖ Catherine Biscarat (L2IT), Rodolphe Cledassou (IN2P3), Pierre-Etienne Macchi (CCIN2P3), Nadine Neyroud* (LAPP), David Rousseau (IJCLab)
- GT10 – Radiation physics for health, S. Incerti (IN2P3) ‖ Fanny Farget (IN2P3), Sylvain David (IJCLab, IN2P3), Marc Rousseau* (IPHC), Denis Dauvergne (LPSC, GDR MI2B Director), Lydia Maigne (LPC), Hervé Seznec (LP2IB), Christian Morel (CPPM)
- GT11 – Nuclear energy and the environment, S. Incerti (IN2P3) ‖ Fanny Farget (IN2P3), Sylvain David (IJCLab, IN2P3), Annick Billebaud (LPSC, GDR SCINEE Director), Rémi Maurice* (SUBATECH), Gilles Montavon (SUBATECH), Maëlle Kerveno (IPHC), Nathalie Moncoffre (IP2I)
- GT12 – Geosciences, solar system and interstellar medium, S. Incerti (IN2P3) ‖ Berrie Giebels (IN2P3), Olivier Drapier* (LLR), Marin Chabot (IPNO), Jean Duprat (CSNSM), Véronique Van Elewyck (APC)
- GT13 – Human and financial resources, R. Pain (IN2P3) and P. Verdier (IN2P3) ‖ Rodolphe Clédassou (IN2P3), Olivier Drapier* (LLR), Anne Ealet (IP2I), Eric Kajfasz (CPPM), Arnaud Lucotte (LPSC), Laurence Mathy-Montalescot (IN2P3), Steve Pannetier (IN2P3), Christelle Roy (IPHC)
- Workshop – Quantum Technologies for the 2 infinities, Laurent Vacavant (IN2P3) ‖ Rémi Barbier (IP2I), Giulia Hull (IJCLab), Stéphane Jezequel (LAPP), Guillaume Pignol (LPSC), Mahfoud Yamouni * (LPSC)
- Workshop – Theoretical Physics of the 2 infinities, Berrie Giebels (IN2P3) ‖ Marcella Grasso (IJCLab), Christopher Smith* (LPSC), Ana Teixeira (LPC)

*N.B.: * indicate the members of the IN2P3 Scientific Council.*

Appendix C: Acronyms

ACT: Atmospheric Cherenkov Telescope

AGATA: Advance Gamma Tracking Array

ARCA: Astroparticle Research with Cosmics in the Abyss

ALICE: A Large Ion Collider Experiment

AMS: Alpha Magnetic Spectrometer

ATLAS: A Toroidal LHC ApparatuS

APPEC: Astroparticle Physics European Consortium

ANR: Agence Nationale de la Recherche

BSM: Beyond the Standard Model

C4PI: Centre de Compétences de Capteurs CMOS à Pixels Intégrés.

CC-IN2P3: IN2P3 Computing Center

CEA: Commissariat à l’énergie atomique et aux énergies alternatives

CERN: Organisation Européenne pour la Recherche Nucléaire

CKM: Cabibbo-Kobayashi-Maskawa matrix

CMB: Cosmic Microwave Background

CMS: Compact Muon Solenoid

CNES: Centre National d’Études Spatiales

CNRS: Centre national de la recherche scientifique

CP: Charge conjugation Parity symmetry

CTA: Cherenkov Telescope Array

DARWIN: DARk matter WImp search with liquid xenoN

DESIR: Désintégration, Excitation et Stockage d’Ions Radioactifs

DESY: Deutsches Elektronen-Synchrotron

DM: Dark Matter

DOE: Department of Energy

DRF: Direction de la Recherche Fondamentale at CEA

DUNE: Deep Underground Neutrino Experiment

ECFA: European Committee for Future Accelerators

EGO: European Gravitational Observatory

EIC: Electron Ion Collider

ERC: European Research Council

ERL Energy Recovery Linac

ESA: Agence spatiale européenne

ESFRI: European Strategy Forum on Research Infrastructures

ESPP: European Strategy of Particle Physics

ESS: European Spallation Source

ET: Einstein Telescope

FAIR: Facility for Antiproton and Ion Research

FERMI: Fermi Gamma-ray Space Telescope

FCC: Future Circular Collider

FITS: Federated IT Services for CNRS research infrastructures

FPGA: Field-programmable gate array

GANIL: Grand accélérateur national d’ions lourds

GDR: Groupement de Recherche

GTs: Working Groups

GW: Gravitational Waves

HESS: The High Energy Stereoscopic System

HL-LHC: High-Luminosity Large Hadron Collider

HYPER-K (or HK): Hyper-Kamiokande

IN2P3: Institut National de Physique Nucléaire et de Physique des Particules

INFN: Istituto Nazionale Fisica Nucleare

INSU: Institut national des sciences de l’univers

IR*: Infrastructure de Recherche *, MESR funding scheme

IRFU: Institut de recherche sur les lois fondamentales de l’Univers

ISS: International Space Station

JINR: Joint Institute for Nuclear Research

JUNO: Jiangmen Underground Neutrino Observatory

KAGRA: Kamioka Gravitational Wave Detector

KM3NeT: Cubic Kilometre Neutrino Telescope

ΛCDM: Lambda - Cold Dark Matter, standard modell of Big Bang cosmology

LHC: Large Hadron Collider

LHCb: Large Hadron Collider beauty

LIGO: Laser Interferometer Gravitational-Wave Observatory

LISA: Laser Interferometer Space Antenna

LITEBIRD: The Lite satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection

LMA: Laboratoire des Matériaux Avancés

LNGS: Laboratori Nazionali del Gran Sasso

LNL: Laboratori Nazionali di Legnaro

LSM: Laboratoire Souterrain de Modane

LSPM: Laboratoire Sous-Marin Provence Méditerranée

LSST: Legacy Survey of Space and Time

MESR: Ministère de l'Enseignement supérieur et de la Recherche

MYRRHA: Multi-purpose hYbrid Research Reactor for High-tech Applications

NDBD: Neutrinoless Double Beta Decay

NEWGAIN: New GANIL Injector

NIKHEF: Nationaal instituut voor subatomaire fysica

NuPECC: Nuclear Physics European Collaboration CommitteeOMEGA Organisation de MicroÉlectronique Générale Avancée

ORCA: Oscillation Research with Cosmics in the Abyss

PACIFICS: Particle Accelerators Initiative for Future Innovative and Challenging Systems

PAO: Pierre Auger Observatory

PIA: Plan d'Investissement d'Avenir

PIP-II: Proton Improvement Plan II

QCD: Quantum ChromoDynamics

QGP: Quark-Gluon Plasma

RI: Research Infrastructure

S3: Super Separator Spectrometer

SD: Science Driver

SM: Standard Model

SPIRAL2: Système de Production d'Ions Radioactifs en Ligne de 2e génération

SRF: Superconducting RadioFrequency

SuperNEMO: Neutrino Ettore Majorana Observatory

T2K: Tokai to Kamioka

VIRGO: GW interferometer at EGO

WIMP: Weakly Interacting Massive Particles

WISP: Weakly Interacting Sub-eV Particle

WLCG: Worldwide LHC Computing Grid

XENON: Xenon Dark Matter experiment at LNGS

XFEL: European X-Ray Free-Electron Laser Facility

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