Research evaluation

EVALUATION REPORT OF THE UNIT

IRFU - Institut de recherche sur les lois fondamentales de l'univers

UNDER THE SUPERVISION OF THE FOLLOWING ESTABLISHMENTS AND ORGANISMS:

Commissariat à l'énergie atomique et aux énergies alternatives - CEA

EVALUATION CAMPAIGN 2024-2025

GROUP E

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High Council for evaluation of research and highter education

In the name of the expert committee :

Fernando Ferroni, chairman of the committee

For the Hcéres :

Coralie Chevallier, president

In accordance with articles R. 114-15 and R. 114-10 of the Research Code, the evaluation reports drawn up by the expert committees are signed by the chairmen of these committees and countersigned by the president of Hcéres.

To make the document easier to read, the names used in this report to designate functions, professions or responsibilities (expert, researcher, teacher-researcher, professor, lecturer, engineer, technician, director, doctoral student, etc.) are used in a generic sense and have a neutral value.

This report is the result of the unit's evaluation by the expert committee, the composition of which is specified below. The appreciations it contains are the expression of the independent and collegial deliberation of this committee. The numbers in this report are the certified exact data extracted from the deposited files by the supervising body on behalf of the unit.

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Ms. Sophie D'Ambrosio, CEA-DRF
Ms. Anne-Elisabeth Etienvre, CEA-DRF

CHARACTERISATION OF THE UNIT

- Name : Institut de recherche sur les lois fondamentales de l'univers
- Acronym: IRFU
- Label and number: Not applicable to IRFU
- Composition of the executive team: Mr Franck Sabatié (director), Mr Philippe Rebourgeard (deputy director)

SCIENTIFIC PANELS OF THE UNIT

ST Sciences et technologies
ST2 Physique
ST3 Earth and Universe Science

THEMES OF THE UNIT

The IRFU, institute for research on the fundamental laws of the universe, brings together three scientific disciplines, astrophysics, nuclear physics and particle physics, as well as all the associated technological expertise.

The IRFU is one of the eleven institutes of the Direction of Fundamental Research (DRF) of CEA. It represents almost 20% of the headcount of the DRF and approximately 5% of all CEA's headcount. IRFU is positioned to answer the main questions we face in understanding the four fundamental interactions, at different scales, from the very smallest (building blocks of matter, nuclear matter) to the largest (energy content and structure of the Universe). This research requires the processing of large volumes of data, as well as expertise in the use of complex simulation tools. IRFU also takes part in developing and operating GANIL (national large heavy ion accelerator), a very large research infrastructure, through a CEA-CNRS GIE. The Institute's technological position is aimed at developing the instruments needed for this research (accelerators, magnets, detectors, electronics, and engineering systems). These developments, carried out in close conjunction with industry, go well beyond the scientific community of the physics of the two infinities, with the institute being called on for its technologies by other scientific communities, at the heart of CEA. It aims to exploit its developments for various societal applications.

IRFU is structured into seven departments, each comprising its own set of laboratories or teams:
- The astrophysics department (DAP), the CEA component of the AIM joint research unit, under the supervision of CEA, CNRS and Université Paris Cité.
- The particle physics Department (DPHP).
- The nuclear physics department (DPHN).
- The GANIL (Grand Accélérateur National d'Ions Lourds) in the frame of the CEA-CNRS GIE.
- The electronics, detectors, and computing department (DEDIP).
- The accelerators, cryogenics, and magnetism department (DACM).
- The systems engineering department (DIS).

In the scope of its activities, IRFU departments operate many platforms covering all its research fields.

The scientific subjects studied at IRFU break down into eleven research themes. This thematic subdivision allows covering the fundamental components of matter, the study of the structures of nuclear matter, the sciences of the Universe, accelerators, superconducting magnets and the scientific computing required for both physics and engineering.

The eleven scientific themes are listed below:
- Theme 1: Consistency tests of the Standard model.
- Theme 2: Structural tests of the Standard model.
- Theme 3: Dynamics of quarks and gluons.
- Theme 4: Nuclear structure and dynamics.
- Theme 5: Stars and planetary systems.
- Theme 6: Evolution of structures, galaxies and stars.
- Theme 7: Energy content of the Universe.
- Theme 8: Exploration of transient Universe.
- Theme 9: High energy and high intensity accelerators.
- Theme 10: High field superconducting magnets.
- Theme 11: Scientific computing, data analysis and simulation.

The institute also hosts the laboratory of research into the sciences of matter (LARSIM), which activity is devoted to the philosophy of science, ethics, and social aspects of emerging technologies. The present evaluation does not cover LARSIM. The committee understands that the laboratory is presently attached to IRFU for administrative reasons only. It however suggests to include its activities in any future evaluation.

HISTORIC AND GEOGRAPHICAL LOCATION OF THE UNIT

IRFU emerged from the restructuring in 2008 of the Département d'astrophysique, de physique des particules, de physique nucléaire et d'instrumentation associée (DAPNIA), a former fundamental physics research structure of the CEA.

IRFU is built around three main hubs. The primary hub is located on the main CEA site of Paris-Saclay. It brings together about 580 staff and includes the DPHP, DEDIP, DIS and DACM departments. L'Orme des Merisiers site about 2 km away from the main site comprises nearly 255 DAP and DPHN staff. Finally, 115 CEA employees work at GANIL in Caen on the Jules Horowitz campus.

RESEARCH ENVIRONMENT OF THE UNIT

As an institute within the CEA-DRF, IRFU is part of the CEA organizational structure, where the roles assigned to different levels (directions, institutes, functional directions, centres) are precisely defined. Thus, the links of IRFU with its internal or external institutional partners are based on the level of the DRF for high-level strategic relations:

- with the supervisory ministries and their services, notably the Direction générale de la recherche et de l'innovation (DGRI) of the Ministère chargé de l'enseignement supérieur et de la recherche ;
- with other operational directions of the CEA (DRT, DES, DAM);
- with other functional directions of the CEA (DFP, DRI, DRHRS);
- with major institutional partners such as the CNRS.

This does not preclude direct links in practice with these partners concerning more operational or programmatic aspects. IRFU has particularly strong internal links with DES and DAM and external links with CNRS Nucléaire & Particules (formerly IN2P3), CNRS Terre & Univers (formerly INSU), CNRS Physique (formerly INP), with CNES, CERN, INFN, Fusion for Energy, or the Office of Science of the DoE (Department of Energy) as well as with several major global laboratories (Fermilab, KEK, BNL, JPL, Legnaro, GSI, SNRC). Furthermore, IRFU is directly represented in most European thematic expert committees (APPEC, ECFA, NuPECC).

Research infrastructures are a crucial component of IRFU scientific and technological programming and strategy. IRFU contributes either as a technology provider or as a user to several national and international research infrastructures. These are defined at the national level by the DGRI in the general framework of the so-called IR* (Very Large Research Infrastructures), formerly called TGIR: CERN-LHC, FAIR, CTA, DUNE-PIPII, GANIL, ESS. Particularly, IRFU contributes to the establishment and revision of the roadmap for French IR* in the fields of nuclear and particle physics.

After actively participating in the construction phase, IRFU witnessed the official establishment of Université Paris-Saclay in 2020. The IRFU departments constitute their own research units within the university, falling mostly under the Graduate School of Physics (GSP) and shared between the Astro and P2I (Physique des deux infinis) axes. Since 2023, both axes have benefited from a portion of the non-consumable interest allocation previously financing the Labex P2IO, which ceased operations at the end of 2022. IRFU is also associated with the OSUPS (Observatoire des Sciences de l'Univers de Paris-Saclay).

UNIT WORKFORCE: in physical persons at 31/12/2023

Catégories de personnel	Effectifs
Professeurs et assimilés	0
Maitres de conférences et assimilés	0
Directeurs de recherche et assimilés	0
Chargés de recherche et assimilés	505
Personnels d'appui à la recherche	177
Sous-total personnels permanents en activité	**682**
Enseignants-chercheurs et chercheurs non permanents et assimilés	89
Personnels d'appui non permanents	82
Post-doctorants	47
Doctorants	128
Sous-total personnels non permanents en activité	**346**
Total personnels	**1028**

DISTRIBUTION OF THE UNIT'S PERMANENTS BY EMPLOYER: in physical persons at 31/12/2023. Non-tutorship employers are grouped under the heading "others".

Nom de l'employeur	EC	C	PAR
CEA	0	505	177
Total personnels	0	505	177

GLOBAL ASSESSMENT

During the evaluation period, the unit has further strengthened its reputation as a globally recognized institute in its field. Its scientific research teams have played a central role in international collaborations, contributing significantly to technological advancements, data analysis, and instrumentation. IRFU members hold key positions at both national and international levels, shaping global research roadmaps in their respective domains.

IRFU is distinguished by its significant technical developments, with expertise spanning accelerator technologies, superconducting magnets, detector instrumentation, electronics design, mechanical engineering, space components, and data acquisition systems. One prominent example is the IRFU accelerator team, which has developed a strong and internationally recognized expertise in two key technological pillars of modern accelerators: high-intensity, low-energy linear accelerators and superconducting RF cavities. The teams are capable of designing, building, installing, commissioning, and operating complete state-of-the-art systems, including specialized components such as RFQs and ancillary equipment. Their expertise is underpinned by a robust foundation in beam dynamics, diagnostics, and controls, enabling them to contribute to the design of future accelerators.

A major success story is the recent conversion of the IPHI test stand into a new state-of-the-art compact neutron accelerator source that integrates expertise from multiple IRFU teams. This new project represents a strategic step forward, leveraging past investments in IPHI while fostering synergies and collaborations within CEA and across IRFU departments.

Theme 1: High-Energy Particle Physics

IRFU plays a major role in the ATLAS and CMS experiments at LHC (CERN), maintaining strong connections between physics analysis and detector expertise. The team excels in maximizing scientific returns from LHC data while preparing for the High-Luminosity LHC (HL-LHC) phase. IRFU contributes significantly to phase 2 upgrades of ATLAS and CMS and leads in Detector R&D across key areas, including gaseous and solid-state detectors, photodetectors, calorimetry, and electronics.

However, there is a noticeable lack of collaboration with theoreticians at IPhT. Given the political and geopolitical uncertainties surrounding high-energy physics, it is crucial to strengthen synergies with CNRS Nucléaire & Particules (formerly IN2P3).

Theme 2: Neutrino Physics

The neutrino research team focuses on three main areas:

- Neutrino oscillation studies via long-baseline (T2K, Hyper-K, DUNE) and reactor experiments (Double Chooz, STEREO, NUCLEUS).
- Investigating neutrino nature (Dirac or Majorana) through CUORE and CUPID.
- Direct neutrino mass measurements via KATRIN.

IRFU has played a leading role in the T2K experiment and will continue its involvement in Hyper-K, expected to start data collection in 2027. The contribution of the theme to double-beta decay searches and the successful STEREO reactor project, which ruled out the sterile neutrino hypothesis, have provided high visibility to IRFU.

However, given the team relatively small size, strategic choices must be made to avoid excessive dispersion, which could impact visibility and effectiveness.

Theme 3: Quark and Gluon Dynamics

IRFU researchers lead projects within the CERN Heavy-Ion program, Jefferson Lab, and the future Electron-Ion Collider. Their expertise in gaseous tracking detectors and Generalized Parton Distributions (GPDs) analysis has positioned them at the forefront of international research.

The team has a long-standing involvement in ALICE, covering detector, R&D, management, and data analysis. However, the shift from ALICE to LHCb appears to lack a clear, strong justification. A well-defined strategic motivation is needed to ensure the transition enhances the theme scientific impact.

Theme 4: Nuclear Physics

The IRFU nuclear research encompasses nuclear structure and reactions, with experimental programs at CERN (n_TOF), GSI/FAIR, LNL, RIKEN, and GANIL. The 2017 integration of GANIL as a IRFU department has fostered synergies, but the delayed startup of SPIRAL2 and a decline in full-time equivalent (FTE) staff must be addressed strategically.

Theme 5: Stellar and Planetary Sciences

The IRFU researchers engage in cutting-edge astrophysics research, addressing fundamental questions about the Sun, stars, and exoplanets. The unit benefits from interdisciplinary collaborations and advanced computational resources. This integrated expertise positions IRFU as a leader in space weather, solar activity, and planetary studies.

Theme 6: Astrophysical Structure Formation

Spanning 12 orders of magnitude between cosmological scales to planetary systems ones, this research area integrates gravitational, fluid dynamics, and magnetic interactions across cosmic structures. The teams effectively balance observational, theoretical, and numerical simulation approaches, maintaining a strong international reputation.

Theme 7: Cosmology and Dark Universe

The IRFU teams are deeply involved in leading cosmological missions such as LSST, Euclid, DESI, and SKA, focusing on dark energy, gravity, dark matter, and early Universe physics.

However, gravitational wave astronomy is underrepresented, with only a minor mention of CMB polarization imprints. Given the anticipated growth of this field, IRFU should consider participation in projects like LISA, the Einstein Telescope, and Cosmic Explorer.

Theme 8: Transient Universe

IRFU excels in time-domain astrophysics, leveraging multi-messenger observations and real-time data processing. The teams are well positioned internationally, particularly through SVOM and CTA projects. However, geopolitical considerations regarding China's role in SVOM should be factored into future strategies.

Theme 9: High-Energy and High-Intensity Accelerators

The IRFU accelerator teams play a pivotal role in international projects, particularly in RFQs and superconducting RF cavities. They maintain efficiently advanced infrastructure, but staffing challenges due to retirements must be addressed with a comprehensive recruitment and knowledge transfer plan. The engagement in a new state-of-the-art compact neutron accelerator source that integrates expertise from multiple IRFU teams, and compact neutron sources in general, represents a strategic move to maximize expertise and past investments.

Theme 10: High-Field Superconducting Magnets

The IRFU superconducting magnet division is a world leader in magnet technology, with applications spanning MRI, fusion, and particle accelerators. Key partnerships include CERN and national projects like Iseult and Suprafusion. However, the loss of collaboration with the former branch of Alstom is a significant weakness. Establishing new industry partnerships with well-defined intellectual property agreements is recommended.

Theme 11: Computational and Data Science

IRFU maintains a strong interdisciplinary presence in high-performance computing, AI, and data science. Participation in the PEPR NumPEx project for Dyablo code development is a major asset. Strengthening ties with the AI cluster of Université Paris-Saclay is advisable.

However, IRFU should ensure that emerging technologies such as AI are integrated effectively, avoiding short-lived trends and prioritizing practical applications aligned with long-term research goals.

IRFU remains a global leader in multiple scientific domains, with world-class expertise and infrastructure. Strategic recruitment, enhanced collaborations, and clear prioritization of research directions will be key to sustaining excellence and navigating emerging challenges in the coming years.

DETAILED EVALUATION OF THE UNIT

A - CONSIDERATION OF THE RECOMMENDATIONS IN THE PREVIOUS REPORT

The recommendations from the previous review have been acknowledged and largely addressed by the IRFU management.

- The initial decline in the number of employees, primarily technicians, has stabilized, and their numbers have even slightly increased over the past two years, thanks to strong managerial efforts across all levels of the CEA. Additionally, the salary concerns have been taken into account by CEA.
- IRFU remains committed to supporting and integrating temporary staff, recognizing their critical role in managing the evolving workforce composition. Steps have been taken to ensure their appropriate representation within the IRFU council.
- Efforts have also been made to support foreign employees, particularly during their relocation process. These include offering language courses and organizing team-building events, although the COVID-19 crisis posed challenges to these initiatives.
- Collaboration among departments has improved to some extent, with notable progress in R&D activities. Over this evaluation period, funding and both permanent and temporary human resources allocated to R&D have significantly increased. Key areas of growth include instrumentation (+60%), digital magnet safety systems (+200%, equivalent to +4 FTE), and accelerators (+50%).
- R&D in high-field magnets is expected to grow substantially in the coming years, driven by increased funding and dedicated personnel. This progress is supported by collaborations such as the CERN High-Field Magnet initiative, PEPR Suprafusion, and others.

B - EVALUATION AREAS

EVALUATION AREA 1: PROFILE, RESOURCES AND ORGANISATION OF THE UNIT

Assessment on the scientific objectives of the unit

IRFU is dedicated to addressing key questions about the four fundamental interactions across a wide range of scales, from the smallest particles to the vast structures of the Universe. This ambitious pursuit shapes the IRFU technological focus, driving the development of essential tools for exploration, including advancements in accelerator science (with prominent global recognition), novel detectors, electronics, engineering, and data science.

The scientific output of the unit is exceptional, reflecting an impressive track record of achieving strategic goals aligned with the institute's mission. These accomplishments demonstrate the IRFU ability to meet its scientific objectives while maintaining its high-ranking international reputation.

Assessment on the unit's resources

The budget during the years covered by this assessment remained stable (excluding GANIL), as did the quantity and profile of human resources. Notably, 33% of the budget is strongly reliant on contracts and competitive calls.

However, this budget stability does not reassure the committee regarding the future scientific evolution of the unit programs. The report does not address the implications of inflation, which has significantly impacted the post-COVID-19 economic recovery. This omission raises concerns about the long-term financial sustainability of the programs.

As is often the case in the French research system, the relatively modest number of postdoctoral researchers remains a challenge. Their positions are entirely dependent on external funding and therefore tied to specific projects, limiting flexibility.

Moreover, a concerning 15% or more of permanent staff are expected to retire within the next 5–6 years. To address this, IRFU has developed an employment plan aimed at replacing these positions, prioritizing the specific needs of its departments.

Assessment on the functioning of the unit

The unit has established a robust management structure that effectively addresses top-level strategy, internal quality of life, information dissemination within the laboratory, and mechanisms for assessing research quality at all levels.

The organization operates on a project-based model, utilizing a matrix structure. This setup requires careful coordination between project scientific coordinators, project managers, department heads, HR, and finance offices. Given that many projects span multiple years, maintaining a strong framework of long-term relationships and interactions is crucial.

Project managers are tasked with regularly providing progress reports, along with constant updates on planning, resource allocation, risks, and other critical factors. Continuous monitoring of the management teams at all levels is essential to ensure an accurate overview of the institute's resource utilization, skill deployment, and long-term planning.

Additionally, the presence of technical platforms enhances the unit flexibility in resource allocation, enabling the effective management of both immediate and long-term project needs.

1/ The unit has set itself relevant scientific objectives.

Strengths and possibilities linked to the context

The IRFU activities are extensive, solid, and well diversified. Many of the experiments involving the IRFU staff are on a long-term trajectory, ensuring that teams will remain engaged for the next 10 to 20 years. Several critical initiatives for the institute's future are currently in the preparation phase, with LISA standing out as the most challenging among them.

The IRFU expertise in the design of accelerator and superconducting magnets positions the institute to play a key role in the development of next-generation accelerators. The IRFU contribution to the European Strategy for Particle Physics will be a pivotal step in shaping the future of the field. However, this report does not provide any clear indication of preferences or priorities among the potential options for future directions.

The coordination with CNRS to produce a unified document represents a commendable and promising step forward in ensuring alignment and collaboration.

Weaknesses and risks linked to the context

The international context presents significant uncertainties regarding the future of large collaborations, which are essential for advancing big science. The growing influence of geopolitical factors poses major challenges to the collaborative model of particle physics (see the difficult decision taken by CERN and the challenge of maintaining scientific relations with China).

The future of particle physics remains uncertain and will depend heavily on the decisions made about collider physics, a field that currently faces an ambiguous and evolving landscape.

2/ The unit has resources that are suited to its activity profile and research environment and mobilises them.

Strengths and possibilities linked to the context

IRFU has sufficient human resources to achieve its goals in terms of both ongoing scientific activities and those currently under discussion. However, the critical challenge lies in the budget. A significant portion of the funding is tied to IR* or external sources, primarily national (e.g., ANR) and European (e.g., Horizon Europe) funds.

Since these funding sources are subject to fluctuations, they introduce an element of uncertainty that must be carefully assessed and mitigated to reduce potential risks to the institute's long-term stability.

Weaknesses and risks linked to the context

The complex international context poses risks that could lead to a decrease or stagnation in funding for large infrastructure projects. Examples include the CERN-Russia situation and the challenges of maintaining scientific relations with China.

Another potential risk lies in difficulties related to workforce replacement, particularly in areas connected to computing. These challenges could impact the institute's ability to sustain its activities and adapt to evolving demands in critical sectors.

3/ The unit's practices comply with the rules and directives laid down by its supervisory bodies in terms of human resources management, safety, environment, ethical protocols and protection of data and scientific heritage.

Strengths and possibilities linked to the context

The unit practices comply with the rules and directives laid down by its supervisory bodies.

Weaknesses and risks linked to the context

The challenge posed by environmental protection is significant, as is the need for the maintenance and upgrade of buildings, particularly in relation to sustainability and environmental considerations.

Open science and long-term accessibility of data are other themes to be looked after with attention.

EVALUATION AREA 2: ATTRACTIVENESS

Assessment on the attractiveness of the unit

IRFU maintains a well-balanced portfolio of activities, encompassing both fundamental research and technological development. The teams have built a solid reputation in both areas, with particularly prominent positions in accelerators, superconducting magnets, space detectors and science.

The IRFU cutting-edge platforms, infrastructure, and design tools present excellent opportunities for aspiring young researchers and engineers with a passion for science, as well as for professionals seeking experience in preparation for an industrial career.

The inclusion of GANIL in the IRFU portfolio has further enhanced the capabilities of its platforms, expanding the institute's potential and reach.

IRFU also boasts a strong success rate in competitive funding calls, surpassing both national and CEA averages in European calls. With an impressive 27.5% success rate in Horizon 2020 and 18.9% in ERC grants, the institute has demonstrated exceptional performance. Additionally, the funding obtained through the PIA program marks a significant success of great importance.

1/ The unit has an attractive scientific reputation and is part of the European research area.

2/ The unit is attractive because for the quality of its staff support policy.

3/ The unit is attractive through its success in competitive calls for projects.

4/ The unit is attractive for the quality of its major equipment and technical skills.

Strengths and possibilities linked to the context for the four references above

In the context of French and broader European research, IRFU, as part of CEA, enjoys significant visibility. The support provided to staff is evident, contributing to its success. The IRFU exceptional performance in competitive calls, well above the national average, demonstrates not only the outstanding quality of its people but also the effectiveness of the support offered in identifying opportunities and assisting with the application process.

The IRFU real strength as a hub for attracting young talent lies in its state-of-the-art laboratories and platforms, supported by experienced senior staff who excel at mentoring newcomers. This creates an environment where individuals can learn while working on stimulating and innovative projects.

This offers the chance for IRFU to be competitive in its recruitment with respect to offers by the private sectors.

Weaknesses and risks linked to the context for the four references above

As long as the institute continues to develop its program consistently, pursues emerging opportunities, and maintains the exceptional quality of its platforms, no significant risks are anticipated.

EVALUATION AREA 3: SCIENTIFIC PRODUCTION

Assessment on the scientific production of the unit

The scientific output of IRFU is truly impressive, with over 5,000 publications in highly respected journals during the review period. While a significant portion of this is linked to LHC experiments, which stand as a category of their own, the contribution from the "accelerator-linked sector" is particularly noteworthy within this globally productive environment.

In addition, nearly 1,000 presentations at international conferences, most of which were invited talks, demonstrate the institute's distinction and success in scientific production. The more than 200 conferences and round tables, along with radio and TV broadcasts aimed at the general public, highlight the researchers' commitment to outreach and share their work with a wider audience.

However, it remains unclear what specific opportunities and actions are in place for publications or conference presentations primarily authored by Postdocs or, more generally, young researchers.

IRFU has fully embraced open access and open science practices and is committed to making 100% of its publications available in open access by 2030. Furthermore, the institute's output adheres to the highest standards of integrity and ethics.

1/ The scientific production of the unit meets quality criteria.

2/ The unit's scientific production is proportionate to its research potential and properly shared out between its personnel.

3/ The scientific production of the unit complies with the principles of research integrity, ethics and open science. It complies with the directives applicable in this field.

Strengths and possibilities linked to the context for the three references above

The scientific output is abundant and fully aligned with the research potential, with a well-balanced distribution across various fields of study. Both students and postdocs make significant contributions to the institute's activities. All publications appear in top-tier journals, and the production adheres strictly to the principles of integrity and ethics.

Weaknesses and risks linked to the context for the three references above

No specific risk is seen.

EVALUATION AREA 4: CONTRIBUTION OF RESEARCH ACTIVITIES TO SOCIETY

Assessment on the inclusion of the unit's research in society

The high level of complexity in the specifications and performance requirements of instruments developed in the fields of nuclear, particles, and astrophysics, coupled with the advancement of cutting-edge technologies, fosters strong relationships with several leading industries. These industries specialize in areas such as electronics, materials science, semiconductors, and magnetic systems. These collaborations often span long-term projects and are frequently structured around strategic partnerships that facilitate technological transfers and, in some cases, the development or deployment of patents.

Around 80% of the IRFU budget is allocated directly to industry, with approximately 84% of the cash flow directed toward French industry. However, as noted in the institute's risk analysis, the technology transfer from IRFU to industry remains somewhat limited, primarily due to the relative weakness of the French industrial sector.

IRFU is deeply committed to outreach and communication, supported by a very active communication team. In addition, many of its scientists are highly engaged in this area, with some achieving national or even international recognition for their pedagogical contributions. The institute's outreach initiatives are diverse and numerous, targeting various audiences through activities such as TV and radio broadcasts, videos and books, open days and exhibitions, conferences and debates, and social media platforms.

1/ The unit stands out for the quality and the amount of its interactions with the non-academic world.

2/ The unit develops products for the cultural, economic and social world.

3/ The unit shares its knowledge with the general public and takes part in debates in society.

Strengths and possibilities linked to the context for the three references above

IRFU is renowned worldwide and has earned a solid reputation in both fundamental research and R&D, with a strong presence in nuclear and particle physics, accelerators, superconducting magnets, and space science. This success is also attributed to the availability of cutting-edge platforms, infrastructure, and design tools.

Looking ahead, there are numerous possibilities for future development, particularly linked to the revitalization of the nuclear sector, emerging computing technologies such as quantum computing and AI, additive manufacturing, and more.

Weaknesses and risks linked to the context for the three references above.

Some themes are sensitive in public debate and require attention for knowledge transmission to the general public.

ANALYSIS OF THE UNIT'S TRAJECTORY

The committee fully endorses the analysis presented in the self-assessment document. The trajectory for the short and medium terms is clear, well-thought-out, and filled with promising potential outcomes.

However, there are three key issues that will need to be addressed in the long term. The first concerns the future direction of CERN, as its decisions will inevitably influence IRFU's activities. The second issue relates to the IRFU relationship with GANIL, specifically, how the institute will position itself in terms of scientific exploitation and the operation of the centre. The third issue revolves around the IRFU relationships to foster with Université Paris-Saclay, particularly in the area of teaching and educational collaboration.

RECOMMENDATIONS TO THE UNIT

Recommendations regarding the Evaluation Area 1: Profile, Resources and Organization of the Unit

Despite the high quality of scientific research produced, the committee recommends a reorganization of certain themes: large-scale structure, galaxies and star formation (currently Theme 6); energy content of the universe (Theme 7); and scientific computing, data analysis, and simulation (Theme 11). Scientific and observational aspects should be consolidated under a single theme, while all topics related to simulations and code development should be grouped under another. This rationalization is necessary to ensure better balance and readability among the various research areas within the IRFU institute.

We recommend appointing a dedicated liaison at IRFU, either from CEA or a partner university, an "enseignant-chercheur" as part of his statutory service, or someone seconded to IRFU. This person would act as a point of contact for university-student interactions, providing support on administrative and financial matters as well as teaching-related concerns. A similar role existed in the past, and we recommend reinstating it.

Beyond the existing CST (comité de suivi de thèse), students and postdocs would benefit from a mentorship program, assigning them a clearly identified reference person, different from their supervisor, to assist with workplace-related issues. This "personne de confiance" would facilitate dialogue, help anticipate potential conflicts, and advise students on administrative matters. Some laboratories have implemented "tracking committees" that operate independently of PhD advisors and oversee the tracking procedures set by Doctoral Schools. Such a system could serve as a foundation for a broader implementation at IRFU.

PhD students highly value supervision by IRFU members. However, in cases where a supervisor is absent from the lab for an extended period, we recommend appointing a local reference person who is physically present.

To address psychosocial risks, we recommend making training in student supervision mandatory for all potential supervisors, as well as offering general training in projects and human management.

While some departments have PhD student representatives, there does not appear to be a standardized procedure across IRFU. We recommend improving PhD student representation at the institute level, which would also enhance its attractiveness for future recruitment and career development at CEA.

Additionally, we recommend appointing a diversity representative at IRFU, as has been done in the DAP.

We understand that the promotion system is well structured and that the number of available positions is sufficient. However, we encourage a more proactive approach in how results are communicated at the departmental level. Group leaders should be given the opportunity to support colleagues who are not promoted by helping them to deal effectively with any concerns.

The project matrix organization remains one of the IRFU greatest strengths, enabling strong management and responsive resource allocation. However, for human resources, the transitional phase between projects is critical, as the conclusion of existing projects often overlaps with the increasing demands of new ones. We recommend exercising particular vigilance during these transitions to prevent excessive workloads that exceed available capacity.

Recommendations regarding the Evaluation Area 2: Attractiveness

Given the presence of international students and postdocs, we recommend establishing or reinstating an international desk at the IRFU level to provide dedicated support.

The integration of new non-permanent staff (first-year PhD students and postdocs) could also be improved, as well as communication among PhD students across different departments. To address this, we recommend:

- Creating a dedicated mailing list for students and postdocs to facilitate communication.

- Developing and widely distributing a guidance leaflet for students, outlining key contacts for various concerns, such as administrative issues, university affiliations, Navigo reimbursement, and support for foreign nationals (following the model used at DAP).

The disparity in wages and social benefits between PhD students funded by CEA and those financed by doctoral schools is a significant issue, creating an unfair disadvantage. This discrepancy negatively impacts the IRFU attractiveness. We recommend that CEA compensate for the wage gap for the limited number of students funded by doctoral schools. This adjustment would significantly enhance the CEA appeal to PhD candidates, both in comparison to other research institutions and private companies.

Recommendations regarding Evaluation Area 3: Scientific Production

The scientific output is outstanding in both quantity and quality. It is important to encourage and create the necessary conditions for young researchers to publish independently and/or serve as corresponding authors whenever possible. Some groups have already implemented good practices in this regard, which could be used as a basis for developing an institute-wide policy.

We also recommend a dedicated independent evaluation of LARSIM by experts in the fields of history and philosophy of science, as well as science ethics and knowledge dissemination.

Recommendations regarding Evaluation Area 4: Contribution of Research Activities to Society

IRFU is remarkably active in science communication, offering an impressive variety of outreach activities that provide broad visibility to the general public. In addition to the high quality of these initiatives, we also recognize that they align with researchers' values and their vision for society.

However, we observed that most of these initiatives are driven from the bottom up. While this organic approach is valuable, there is a lack of an overarching strategy and organized vision at the institute level. Outreach activities could, for example, be leveraged to support key institutional policies, such as increasing women's representation in science, attracting more young people to technical careers, or raising public awareness on specific societal issues.

In an era where the values of science are often criticized or overlooked, it is crucial to reach as wide an audience as possible, using effective communication tools to engage the general public. We recommend developing a clear strategic direction for the existing communication team. Renaming it for instance to "Science Dissemination and Technology Awareness" would better reflect its overall goals and values while aligning with the way outreach activities is currently conducted at IRFU. Given the IRFU successful project-oriented approach, which has positioned it as a pioneer in its field, we suggest applying this methodology to outreach efforts as well. A dedicated budget could be allocated to calls for specific outreach projects, with minimal administrative burden, while ensuring that newly funded initiatives align with defined strategic priorities. These could include attracting women to science and engineering careers, encouraging young people to pursue technical professions where talent is currently scarce, raising public awareness of technology (e.g., nuclear science, space exploration, AI), and combating pseudoscience and distrust in scientific expertise.

Furthermore, outreach activities should be formally recognized in PhD programs (e.g., through academic credits) and acknowledged as a valuable community service in researcher evaluations.

Given the IRFU outstanding human and scientific resources, many of whom are already deeply engaged in outreach, we are confident that introducing a top-down strategic framework and institutional support will further strengthen IRFU's leadership in public engagement. This approach could even position IRFU as a pioneer in the field of science dissemination.

TEAM-BY-TEAM OR THEME ASSESSMENT

Theme 1: Coherence tests of standard model of particle physics

Name of the supervisors: Mr Maarten Boonekamp, Mr Federico Ferri

TOPICS OF THE THEME

Since the pivotal discovery of the Higgs boson at CERN for which IRFU played a key role, the team has been firmly committed to seeking a deeper understanding of the fundamental symmetries and forces of particle physics by studying the physics of the Standard Model (SM) and testing its consistency with the best possible precision.

To advance this program, IRFU intends to make major contributions in the high precision characterization of the Higgs boson properties, and in pushing to the limit of experimental precision the measurements it performs in electroweak and top physics, and in searches for physics beyond SM. IRFU participates in both the ATLAS and the CMS experiments at the LHC at CERN, and fosters strong connections between physics analyses and detector expertise.

CONSIDERATION OF THE RECOMMENDATIONS OF THE PREVIOUS REPORT

The recommendations for the theme expressed in the previous evaluation report have been taken seriously and addressed in the following way:

- "The project to upgrade the ATLAS New Small Wheels is delayed due to the problems with the industrialization of the large-sized PCBs intended for signal readout. IRFU is the only institute to perform all the assembly operations for the detector modules on the same site (CICLAD clean room), which might create a benefit while under pressure to deliver timely for installation during LS2".

  The project was challenging and suffered some issues that eventually got addressed successfully. The ATLAS NSW detector upgrade was successfully implemented during the LHC long shutdown LS2.

- "The update of the laser monitoring system of the ECAL in CMS requires more developments to meet the challenges related to the radiation environment at the HL-LHC".

  The design of the new laser monitoring systems for the ECAL in CMS has made significant progress, including production and validation of the first prototypes, and the dedicated readout ASIC (CATIA) is entering the production phase.

- "As stated in the document, a large number of IRFU researchers will need to embrace more technical work in their portfolios in order to cope as a team with the challenges related to the upgrades of the ATLAS and CMS detectors".

  The involvement of scientists in the ATLAS upgrade projects has improved, primarily through the commitment of young permanent researchers in support of their senior colleagues. However, the possibilities to find additional available resources to join the theme being limited, this issue should remain a point of serious attention.

WORKFORCE OF THE THEME: in physical persons at 31/12/2023

Catégories de personnel	Effectifs
Professeurs et assimilés	Not applicable to the classification of IRFU personnel
Maitres de conférences et assimilés	Not applicable to the classification of IRFU personnel
Directeurs de recherche et assimilés	Not applicable to the classification of IRFU personnel
Chargés de recherche et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui à la recherche	Not applicable to the classification of IRFU personnel
Sous-total personnels permanents en activité	Not applicable to the classification of IRFU personnel

Enseignants-chercheurs et chercheurs non permanents et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui non permanents	Not applicable to the classification of IRFU personnel
Post-doctorants	Not applicable to the classification of IRFU personnel
Doctorants	12
Sous-total personnels non permanents en activité	
Total personnels	

EVALUATION

Overall assessment of the theme

The IRFU involvement in this theme is consequential. It corresponds to about 7% of its activities, coming just after High Energy and Intensity Accelerators (15%) and at the same level as "Exploration of the Transient Universe". The theme is comprised of 29 researchers and totalling 34.5 FTE when including both staff researchers and engineers. They are complemented with an adequate level of technical support currently providing sufficient workforce. In the period 2018-2023, 30 PhD students had ongoing theses and 15 graduated. IRFU has been successfully involved in both the ATLAS and CMS experiments since their inception and has leading roles in them.

By aligning physics and technological challenges with IRFU existing expertise and infrastructure, the teams are well positioned to excel on an international scale and produce outstanding results.

The theme is focused on a sustained effort to validate the Standard Model and test its predictions at the best possible precision achievable. A highly coherent set of measurements and investigations is conducted within the ATLAS and CMS collaborations, with IRFU demonstrating clear leadership in these efforts.

The teams of this theme play a major role in the electromagnetic calorimeters (ATLAS and CMS) and the muon spectrometer (ATLAS) which are crucial detectors for physics with electrons, muons, and photons in the final state, with applications in the Higgs sector (Higgs boson decays into two photons or four leptons), in electroweak precision measurements and in the study of the top quark in its semi-leptonic decays.

IRFU utilizes its extensive expertise to maximize scientific returns from current LHC data analysis while preparing for the High-Luminosity LHC (HL-LHC) phase in 2029. This includes making major contributions to the Phase 2 upgrades of the ATLAS and CMS detectors. Significant achievements have already been made in Higgs physics, including precision measurements of its properties and initial observations of production. Building on this success, the team aims to further reduce uncertainties in the Higgs-boson mass through collaborative ATLAS and CMS efforts, with a particular focus on electron, photon, and muon calibrations.

Looking ahead, the IRFU goals include exploring the structure of Higgs-top couplings, investigating CP violation in the Higgs sector, studying the Higgs diphoton decay channel, and establishing evidence for rare Higgs-boson decays within ATLAS and CMS. In the long term, IRFU will pursue studies of double-Higgs production and Higgs self-coupling during the HL-LHC era.

In the electroweak and top-quark sectors, the IRFU objectives include improving the precision of the W-boson mass measurement by a factor of two and further investigating the four-top-quark production process to search for new physics.

As the future roadmap of particle physics takes shape, IRFU is committed to playing a pivotal role in shaping this evolution. This includes active participation in the update of the European Strategy for Particle Physics, which started in mid-2024 and will span two years.

In the Higgs sector, the teams of this theme play a direct and prominent role in major analyses and results, holding leadership positions and maintaining high visibility within both the ATLAS and CMS collaborations (ANR funding for CMS to be noted). IRFU is also deeply engaged in measuring other fundamental parameters of the Standard Model, including the Higgs boson mass (with ATLAS and CMS), the top quark mass (with ATLAS), and the W boson mass (with ATLAS, supported by ANR funding). Additionally, the teams are actively involved in precision measurements of the weak mixing angle, with significant contributions backed by both ANR and ERC funding.

The theme capitalizes on long-standing expertise on the current detectors: electromagnetic calorimeter (ECAL) and its calibration and monitoring system (CMS), Liquid Argon (LAr) calorimeter, muon spectrometer and its alignment system (ATLAS).

In detector activities, the teams achieved a significant milestone with the successful installation and commissioning of the New Small Wheels for ATLAS. This challenging project has already enhanced trigger performance and is laying the groundwork for the forward muon trigger system at the HL-LHC.

The theme brings expertise in and participates in the coordination of key-areas of the detector operations: data preparation, databases, luminosity determination, muon spectrometer alignment, LAr calorimeter calibration (ATLAS); computing for HL-LHC, ECAL monitoring, ECAL calibration, AI applied to the reconstruction of ECAL energy deposits (CMS).

The theme leadership is further demonstrated through key appointments, such as ATLAS Data Preparation Coordinator and ATLAS Muon Coordinator. Within CMS, the theme members have held prominent roles, including CMS Spokesperson (former Deputy) and CMS ECAL System Manager (former Deputy). Additionally, the IRFU teams include the Co-Spokesperson of RD51 and DRD1, as well as the D0 Physics Coordinator, underscoring their influential contributions to the field.

The theme actively contributes to the definition and development of Detector R&D groups in particle physics, intending to play a key role in advancing technologies across several critical areas. These include gaseous detectors (DRD1), solid-state detectors (DRD3), photodetectors (DRD4), calorimetry (DRD6), and electronics (DRD7). Their involvement underscores their will to commit to driving innovation and shaping the future of detector technologies to be used at future particle physics facilities.

The theme expertise in detector technology extends beyond particle physics, with significant contributions to medical applications. Leveraging the detector knowledge developed at IRFU, the teams have made impactful advancements in areas such as Positron Emission Tomography (PET), exemplified by projects like BoldPET and ClearMind-One. These initiatives highlight IRFU's ability to transfer cutting-edge detector innovations into practical, real-world solutions that benefit healthcare and medical research.

The theme exemplifies a forward-thinking approach to long-term research, seamlessly integrating every stage of the process, from R&D and design of innovative detectors, to their construction and operation, and ultimately to physics analyses. This comprehensive strategy ensures a coherent alignment between hardware development, operational expertise, and reconstruction capabilities, utilizing the team's extensive experience to achieve exceptional results.

Strengths and possibilities linked to the context

The nature of the organization of IRFU is well suited to managing large-scale hybrid projects integrating both physics and technology.

The trajectory of the theme is well defined and supports an ambitious physics program with a strong focus on precision measurements, which involves the theme's members in major analyses of the ATLAS and CMS collaborations.

This theme is well positioned to seize opportunities in future projects, thanks to its expertise in critical detector technologies for both current and next-generation detector systems. This capability is deeply rooted in the skills and experience of IRFU's engineers and technicians.

Additionally, the teams of this theme have demonstrated consistent success in securing external funding at both national (ANR) and European (ERC) levels, further underscoring their leadership and credibility in the field.

Regarding the future, the teams of this theme are actively engaged in key bodies and forums that are shaping the development of next-generation particle accelerators. They are involved in exploring all major options for future particle physics machines. Once decisions are made regarding which accelerator(s) and detector(s) will be built, IRFU is prepared to play a significant role in these projects, contingent upon the availability of the necessary workforce and resources.

Weaknesses and risks linked to the context

There seem to be only a very weak connection with the theoreticians of the IPhT (Institut de Physique Théorique), a joint research unit (UMR 3681) supervised by CEA/DRF and CNRS/Physique. The IPhT research focuses on major topics of modern theoretical physics including high-energy physics, cosmology and quantum gravitation.

One of the key challenges of the theme lies in managing the simultaneous demands of operating and optimizing the current detectors, conducting high-quality data analyses, and preparing for the production and the installation of their upgrades. This requires significant resources and expertise, particularly as the teams balance ongoing scientific output with the development and assembly of the upgrades of both ATLAS and CMS detectors for the HL-LHC. A concerning trend is the gradual decrease in the number of FTEs dedicated to this theme over time. This decline raises concerns about the ability to effectively address the parallel objectives of

LHC and HL-LHC activities, and R&D efforts in the preparations for future colliders. Ensuring sufficient manpower is critical to maintaining the performance of the current detector, delivering impactful scientific results, and successfully executing the transition to next-generation detector systems.

Analysis of the theme's trajectory

The theme trajectory is well thought-out and in-line with the skills and previous commitments, though achieving its ambitious goals may pose challenges due to the significant person power required.

The trajectory is shaped in the following context: completion of LHC Run 3 (one year remaining) and the subsequent three-year and a half Long Shutdown 3 (LS3); installation, commissioning, operation, and physics exploitation of the HL-LHC, including the extended Run 5 and the absence of Long Shutdown 5 (replaced by an Extended Year-End Technical Stop, EYETS); preparation for future colliders, in line with the evolving landscape of particle physics in connection with the European Strategy for Particle Physics Update.

As a short-term trajectory, the teams' immediate focus is on maintaining key responsibilities for the current detectors while continuing to advance along established physics research lines. A strong emphasis is placed on leveraging expertise in Artificial Intelligence (AI) to enhance both detector performance and physics analyses. Additionally, the transition to a new computing model, utilizing heterogeneous architectures (e.g., CPU + GPU) and High-Performance Computing (HPC), is underway, benefiting from IRFU's well-established expertise in these areas. Detector upgrade deliverables remain on track and are progressing well. For ATLAS, this includes wire bonding and testing of pixel modules for the ITk inner tracker, development of electronic boards for the LAr calorimeter, and upgrades to the alignment system for the muon chambers. For CMS, the key activities involve the design and production of ASICs and boards for the ECAL and HGCAL, development of the DAQ system for the MTD and of the clock distribution system for the MTD and HGCAL, and enhancements to the laser monitoring system for the ECAL. These efforts ensure that the team remains at the forefront of detector technology and physics analysis, while also preparing for the next phases of the LHC program.

As a medium-term trajectory, the IRFU team focus is centred on the High-Luminosity LHC (HL-LHC) era, during which both ATLAS and CMS will undergo significant transformations, effectively becoming new detectors. These upgraded detectors will require thorough commissioning, detailed understanding, and comprehensive characterization to ensure optimal performance. In parallel, physics analyses will leverage IRFU's core expertise in electrons, photons, and muons to push the precision of current Higgs sector studies to their limits. The increased data volume, approximately six times that of Run 2 and Run 3 combined, will enable the team to achieve unprecedented precision in measuring rare Higgs decays. This will provide deeper insights into the properties of the Higgs boson and further test the predictions of the Standard Model.

As a long-term trajectory, the IRFU teams' long-term vision is firmly focused on the development of future particle accelerators. The strategy for this endeavour is a dynamic and evolving process, with regular updates and active discussions at IRFU, at national, and at European levels. IRFU intends to play a prominent and influential role in shaping this future. At national level, IRFU co-chairs two working groups dedicated to this theme, ensuring a strong French contribution to the global effort. At the European level, IRFU is represented as one of the ten Major European National Labs in the Physics Preparatory Group of the European Strategy Group (ESG) and is actively involved in one of the key working groups with a team member serving as co-convener. Moreover, the CEA Director General is one of the French delegates at the CERN Council, further underscoring IRFU's strategic influence in high-level decision-making processes at the international level in particle physics. Through these roles, IRFU is well positioned to drive and lead innovation and collaboration in the development of next-generation particle accelerators for particle physics.

The IRFU teams are actively engaged in the study of future colliders from both physics and technological perspectives, playing a leading role in several key initiatives:

In physics studies, for FCC (Future Circular Collider), they hold leading roles in various study groups, contributing to the development of the physics case and detector concepts. For ILC (International Linear Collider), IRFU is involved in the technical coordination of the Time Projection Chamber (TPC) project. For LHeC (Large Hadron-electron Collider), IRFU participates in the coordination panel, shaping the scientific and technical direction of the project. For the Muon Colliders, IRFU contributes to study groups (MuCol), exploring the potential of muon-based colliders for high-energy physics.

In Technological contributions, for Accelerator R&D, they are involved in critical accelerator technologies, including the FCC-ee booster, FCC-hh beam dynamics and optics, and the high-energy complex and RF systems for MuCol. In innovative technologies, IRFU is advancing cutting-edge developments in RF cavities, utilizing additive manufacturing, Atomic Layer Deposition (ALD), and electropolishing techniques. Additionally, IRFU is contributing to the development of high-field magnets, essential for next-generation colliders.

Through all these efforts, the theme is well positioned at the forefront of both the scientific and technological advancements required to realize significant contributions to future colliders, ensuring an influential and leading role in shaping the future of high-energy particle physics.

RECOMMENDATIONS TO THE THEME

Building and expanding collaborations with colleagues from IPhT (Institut de Physique Théorique, Saclay) could significantly enhance the scientific output derived from the vast amounts of data accumulated at the LHC. Such partnerships would not only maximize the potential of existing research but also foster innovative approaches in preparing for HL-LHC and for future colliders. Strengthening collaboration with IPhT could foster a more synergistic relationship between theoretical and experimental research, enhancing the scientific impact of both institutes.

Given the potential political and geopolitical uncertainties surrounding the future of high-energy particle physics, it appears essential to establish stronger synergy with CNRS Nucléaire & Particules (formerly IN2P3). Collaborating closely on strategic planning for future developments would ensure a more cohesive and resilient approach to advancing the field.

The ongoing trend of workforce reduction over time must not be underestimated, especially in light of the diverse and parallel activities required in the coming years, coupled with limited opportunities to expand human resources. Particular attention must be paid to ensure that sufficient personnel are available to: deliver, commission, and operate detector upgrades; exploit through comprehensive analyses the LHC and HL-LHC data to the full extent of their potential for groundbreaking results; actively participate in generic developments within the framework of the ECFA DRD groups. Addressing this challenge is critical for maintaining the momentum and success of the initiatives of this IRFU theme.

On the detector front, gaseous detectors are a well-recognized speciality of IRFU. However, strengthening its expertise regarding solid-state detectors could further enhance its positioning, enabling it to play a major role in the development of detection systems for future particle physics accelerators.

The use of AI (Artificial Intelligence) is growing rapidly in all fields of science and beyond, frequently delivering superior results compared to more conventional methods. The development of AI techniques aiming at improving detector performance and physics analyses should be encouraged and supported. Strengthening collaborations within IRFU, as well as with external data scientists and mathematicians, will be essential to harnessing the full potential of these innovations for particle physics and assessing and maintaining leadership in the field.

Building on IRFU interest in joining LHCb Upgrade 2, motivated by the physics opportunities in heavy-ion collisions, it might be worthwhile for the IRFU teams, scientific council and management to consider evaluating an expansion of the IRFU participation in LHCb to include flavour physics as well, so as to further enhance IRFU contributions and visibility in the field.

Theme 2: Structural tests of standard model

Name of the supervisors: Ms Sara Bolognesi, Mr Alain Letourneau

TOPICS OF THE THEME

This theme mainly includes neutrino physics and tests of matter-antimatter asymmetry using neutrino oscillations and antimatter gravity (GBAR). For neutrino physics three branches are distinguished, the neutrino oscillation studies using long base line on accelerator experiments (T2K, HK, DUNE) and reactor experiments (Double Chooz, STEREO, NUCLEUS), the neutrino nature - Dirac or Majorana (CUORE, CUPID), and direct neutrino mass measurements (KATRIN). An application on muon tomography using detection techniques developed by this team is also part of this theme. Some of these projects are now over, as Double Chooz and STEREO.

CONSIDERATION OF THE RECOMMENDATIONS OF THE PREVIOUS REPORT

In the previous report, it was reported the following:

- "Only six conference abstracts are documented, out of which four are actually presented by IRFU scientists. The committee notes particularly that none of them is related to T2K. This looks surprising, given the consistency of the group and the high importance of the results. IRFU must reinforce their role to be fully recognised by T2K collaboration management."

  Upon request of the committee, some information has been provided on this issue indicating that on T2K the human resources increased from 3.6 FTE in 2018 to 7.7 FTE in 2023, by recruiting a physicist in 2019 and recuperating two physicists working on ATLAS. It has to be noted that six physicists working on T2K are also HyperK members. Also, during the evaluation period, several coordination responsibilities were attributed by the T2K Collaboration to IRFU members. However, only four presentations on T2K have been done during the same period, all of them technical and in low impacts workshops. It is surprising to see that no presentations on physics results have been done by the group during this prolific physics T2K period, while a member of this group was in charge of the overall physics coordination of T2K for the period of 2020-2024.
- The previous report pointed out the weak participation on neutrinoless double beta decay experiments with bolometers (only one person). This activity has been now reinforced with two recruitments and an internal mobility. Also, the two ERC-funded projects (BINGO Consolidation Grant, 2020-2026 and TINY Starting Grant, 2023-2028) both coordinated by IRFU, will greatly stimulate this activity.
- The absence of outreach activities was noted in the report. The situation has been improved since then with the production by one of the members of the team of a book for a wide public on supernova neutrinos, by the participation in teaching activities and by hosting short internships for very young high-school students. In popularization of science, 8 contributions are reported over 250, 3.2%, for the whole IRFU, the previous score was 3/202=1.5%. There is still room for improvement.
- The report had highlighted the small size of the GBAR group. This group now counts eight people with 6.5 FTE/year. Efforts are still ongoing to improve this situation. It has to be noted that this group has not mentioned any external financing (EU, ANR, Labex, etc.), as is the case for other activities of this theme. The publication of the first physics results in 2023 will probably help to obtain external resources.

WORKFORCE OF THE THEME: in physical persons at 31/12/2023

Catégories de personnel	Effectifs
Professeurs et assimilés	Not applicable to the classification of IRFU personnel
Maitres de conférences et assimilés	Not applicable to the classification of IRFU personnel
Directeurs de recherche et assimilés	Not applicable to the classification of IRFU personnel
Chargés de recherche et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui à la recherche	Not applicable to the classification of IRFU personnel
Sous-total personnels permanents en activité	Not applicable to the classification of IRFU personnel

Enseignants-chercheurs et chercheurs non permanents et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui non permanents	Not applicable to the classification of IRFU personnel
Post-doctorants	Not applicable to the classification of IRFU personnel
Doctorants	9
Sous-total personnels non permanents en activité	
Total personnels	

EVALUATION

Overall assessment of the theme

The theme actively participates to the T2K long-baseline experiment taking place at JPARC in Japan, with Super-Kamiokande as far detector and ND280 as near detector. T2K is a leading experiment in the search of CP violation in the leptonic sector, a discovery which would contribute to understanding the antimatter disappearance in the Universe. IRFU made a significant contribution in the construction and upgrades of the near detector through the development of the charge readout system of two new TPCs based on resistive Micromegas detectors. The upgrades will allow reducing the systematic errors, an important element of these experiments. As specified in the self-assessment document, the IRFU T2K group actively participates in developing new and more precise models of neutrino-nucleus interactions. It is now one of the driving actors in the analysis of the new data.

The theme participates to Hyper-K, the successor of T2K, using the T2K near detector. The Hyper-K far detector underground site is under excavation and it is expected that it will start data taking by the end of 2027. This new far detector, much larger than Super-K, associated with a more intense proton beam, will considerably improve the T2K physics performance and will probably lead to the discovery of the so awaited CP violation in the leptonic sector, depending on the achieved systematic errors and the value of the violating parameter δCP.

The theme also takes part in the preparation of a second long baseline experiment in the USA, DUNE. It has participated in the construction of the LAr prototypes at CERN, especially on the one called Double Phase Liquid Argon TPC. Finally, the Double Phase technique has been abandoned, keeping only a single-phase Vertical Drift technique. The theme has also proposed a near detector based on the design of the T2K one including 3 new TPCs based on resistive Micromegas. It is not mentioned if this proposal has been accepted by the Collaboration.

This theme also participates to neutrino double-beta decay searches with bolometers. This is an important activity in the searches for physics beyond the Standard Model. This activity is done in the framework of the CUORE/CUPID consortium. IRFU performs an R&D on scintillating bolometers based on Molybdenum (Mo) using a demonstrator installed in the underground laboratory of Modane. The team has the technical coordination of this project. After proving the feasibility of this technique, CUPID-Mo, not only set the best limit on 100Mo half-life, but also achieved the most precise model of background in a bolometric experiment.

The ERC Consolidation Grant BINGO (2020 - 2026) obtained by one of the $0\nu\beta\beta$ members will reinforce this activity. BINGO tries to exploit the design of molybdenum and tellurium bolometers coupled to more performant detectors of the scintillating light.

A second ERC Stating Grant (2023 - 2028), TINY - Two Isotopes for Neutrinoless double beta decaY search, proposes to study two zirconium and neodymium isotopes. This project includes a demonstrator based on 10 crystals. These activities give large visibility to IRFU in $0\nu\beta\beta$.

The theme also includes direct neutrino mass measurement activities through KATRIN experiment. Apparently, IRFU didn't participate in the construction of the detector, but only on the data taking period. This participation is very visible in the collaboration which entrusted the responsibility of the analysis coordination to an IRFU member. This allows him to be frequently invited to important conferences to present KATRIN results. Presently, KATRIN arrived now to the mass limit of $m\nu$<0.45 eV.

IRFU was a leading partner in Double Chooz. This experiment is now over, but the data analysis continues with the aim of improving the oscillation results. Anyway, it has to be said that Daya Bay has already published the θ13 value with an unprecedented precision lower than 2.5%, while Double Chooz is expected to remain higher than 10%.

IRFU also led the very successful STEREO reactor project, funded by the ANR, which ruled out the sterile neutrino hypothesis in a large phase space. This detector has been dismantled in 2020.

Since 2019, IRFU participates to the NUCLEUS project based on bolometers for the observation and measurement of coherent-elastic neutrino-nucleus scattering using the Chooz reactors. Coherent-elastic neutrino-nucleus scattering has already been observed at the spallation neutron source at Oak Ridge National Laboratory using a proton pulsed beam. This relatively new field will allow performing neutrino measurements with reduced size detectors. Thanks to the deep experience on neutrino reactor experiments, this team has strongly participated in the calculations of the nuclear reactor flux. The developed model is very often cited in conferences.

Other sources of matter-antimatter asymmetry, on top of the already observed one in the hadronic sector and the very promising one in the leptonic sector (but not yet observed), are investigated using gravity. IRFU is the initiator of GBAR experiments (Gravitational Behaviour of Antimatter at Rest) searching for such asymmetry by measuring the free fall acceleration of ultra-cold neutral anti-hydrogen atoms (produced at CERN) in the terrestrial gravitational field. This theme contributes to the production of the needed positrons. The first physics results have been published in 2023 with a total of 20±6 antihydrogen signals collected. Several upgrades to improve the performance are foreseen for the coming years. It has to be noted that the spokesperson of this experiment is a member of this group! GBAR is supported by the ANR project SPHINX - Study of Positronium-Hydrogen Interactions: Negative hydrogen production Cross-Sections (2022-2026), coordinated by IRFU.

Few other projects are mentioned in the self-assessment document without details, as MORA (Normandy region, ANR, 2020-2021), which appeared after discussion not really an IRFU project; and PandaX-III (Particle And Astrophysical Xenon Experiment III). Little information is also provided on the ultra-low radioactive background detector developed by IRFU for dark matter searches installed now at SNOLAB, and the performance and results obtained.

The theme activities show some multidisciplinary aspects, as nuclear reactor monitoring, imaging applications using Micromegas technology fully developed by IRFU, or muon radiography using detection technologies developed by IRFU.

Strengths and possibilities linked to the context

The theme has for many years a strong hardware background in detectors mainly in Micromegas. This has been very efficiently used for participating in projects as in-kind contributions, allowing thus the group to participate to associated physics programmes. Some of the hardware proposals, as HKROC or double-phase Argon TPC for DUNE, were not retained by the collaborations.

Another strong point is the coherent trajectory of projects taking profit of the experience in previous experiments to prepare the new ones. This is the case in the reactor experiments combined with calculations of neutrino fluxes and in the participation in T2K followed by the successor, HyperK; the same in double beta decay experiments.

The committee is very impressed by the success to external calls and appreciates the great efforts made on developing outreach activities.

The workforce of the theme is the following (FTE includes physicists, engineers and technicians):

- Double-Chooz/KATRIN/NUCLEUS (3 physicists)- Double-Chooz (0.2 FTE), KATRIN (0.3 FTE), NUCLEUS (4.2 FTE)
- T2K/HyperK/DUNE (6 physicists) - T2K (6.2 FTE), HyperK (1.5 FTE), DUNE (0 FTE)
- BINGO/TINY/CUPID (4 physicists) - BINGO (3.4 FTE), TINY (0.3 FTE), CUPID (2.1 FTE)
- GBar (7 physicists and 8 FTE) and Tomography with muons (1 physicist and 2.4 FTE)

Weaknesses and risks linked to the context

The size of the teams of this theme is relatively small compared to the involvement and engagements. Even if a coherent trajectory has been followed up to now, some choices have to be made in order to avoid too much dispersion which will unavoidably reduce the group visibility in each project taken separately.

While excellent data have been published by T2K on CP violation and many contributions in international conferences have been presented by the collaboration members, it seems that the theme doesn't take benefit of its involvement since only few interventions in workshops are reported, almost all of them on technical subjects.

The theme actively participates to HyperK with a strong wish to also participate to DUNE. The question is whether the theme has the potential to participate significantly and almost at the same time to two neutrino long baseline experiments.

As highlighted in the provided portfolio, the theme takes part to KATRIN but with very reduced human resources (0.3 FTE) and with poor possibility to increase this number in the future. This participation may be questioned if the situation doesn't change, with a high risk of vanishing.

Analysis of the theme's trajectory

The theme plays a significant role in neutrino physics, a very promising direction for physics beyond the Standard Model. It made the choice since a long time to actively participate in T2K long baseline experiment in Japan aiming in a first stage to discover the oscillation $\nu\mu \rightarrow \nu e$ and measure by the same way the last PMNS mixing angle θ13. This has partially been achieved, the reactor experiments having discovered this oscillation first.

T2K now puts all its efforts on the discovery of CP violation in the leptonic sector, which could help to understand the antimatter disappearance in the Universe. To increase the T2K capabilities, near detector upgrades have been proposed and realised, with IRFU having actively participated during the evaluated period.

Discovery of CP violation at 5σ will be limited by systematic errors and statistics. This is why IRFU naturally invests now in understanding the systematic errors, especially those coming from limited neutrino cross-section knowledge, and to the preparation of the HyperK experiment with the advantage of a significantly larger volume than SuperK for increasing statistics.

With apparently limited resources, the IRFU teams actively explore participation to the DUNE, the second long baseline experiment under preparation in the world in the USA. From a technical point of view, as done for ESS, IRFU participates significantly in PIP-II project in Fermilab aiming at providing the intense proton beam for the neutrino production for DUNE. However, the IRFU contribution to DUNE has to be clarified at this moment, taking into account the human resources available, and the fact that the natural continuation is undoubtedly HyperK.

Surfing on the deep knowledge of neutrino physics on reactors and the first observation of neutrino coherent scattering at SNS, IRFU now plays an important role in the NUCLEUS experiment. This very promising observation of neutrino coherent scattering will allow exploring phenomena more efficiently going beyond the Standard Model. This will also permit using reduced size neutrino detectors to monitor the activity of nuclear reactors.

The double beta decay search is a neutrino activity of IRFU in the framework of physics beyond the Standard Model. All previous efforts led to the CUPID experiment that was strongly supported by two ERC grants. This axe is a natural continuation of previous activities.

Concerning GBAR, the recommendation of the previous report, before the engagement into an upgrade of the GBAR program, was to verify the potential of GBAR in the landscape of competing experiments running in parallel. IRFU mentioned to the present committee that in March 2023, the CSTD recommended a continuation of the implication of IRFU in GBAR until LS3, and the allocation of the human resources matching the commitments of the institute. As agreed with this recommendation, IRFU maintained its implication as foreseen. However, this statement doesn't really answer the question about the state of the art in this research area and the potential of GBAR.

A clear timeline of all engagements in view of the available resources would help to better monitor all activities.

RECOMMENDATIONS TO THE THEME

It is strongly recommended to the theme to continue seeking external resources as done successfully up to now.

The committee reiterates a previous recommendation concerning T2K that is to increase the visibility on data analysis and thus the recognition inside this international collaboration. It is also recommended to make an effort in the participation to HyperK and, as for T2K, to increase the visibility of the IRFU.

Participation in DUNE must be carefully weighed against available resources so as not to compromise the contribution to HyperK, an experiment which will start taking data for CP violation a few years before DUNE. This recommendation doesn't concern the participation in the acceleration activity PIP-II which can continue independently.

The theme is encouraged to continue its involvement in multidisciplinary projects, such as nuclear reactor monitoring, imaging applications using Micromegas technology (fully developed by IRFU), or muon radiography using detection technologies developed by the theme's teams.

Considering the competence and strong implication of the IRFU, double beta decay activities are also encouraged to continue, expecting that funding for large detectors and appropriate isotopes will be found.

Theme 3: Dynamics of quarks and gluons

Name of the supervisor: Mr Francesco Bossu

TOPICS OF THE THEME

The theme research focuses on the experimental and theoretical study of strong interactions. This is achieved through two approaches: the study of how quarks and gluons interact and form hadrons by analysing their distributions in the hadrons themselves, and the study of the behaviour of large complex systems of quarks and gluons at large temperatures and density. In this way, the team approaches quarks and gluons both in their confined state inside hadrons and in their unconfined state as a quark-gluon plasma.

The research is conducted in world-class facilities, and the teams of the theme characterize their work with the development and operation of sophisticated instrumentation which is conceived specifically to address observables, usually called probes, sensitive to specific properties defining the behaviour of the systems under study.

The teams of the theme carry leading roles in the study of the QGP at the CERN heavy-Ion program and in the study of hadron structure at the Jefferson Lab and EIC experimental programs.

CONSIDERATION OF THE RECOMMENDATIONS OF THE PREVIOUS REPORT

The previous report underlined the necessity for the two teams in this theme, the one active in Hadron Physics and the one working on QGP, to each focus on a single experiment.

Given the size of the teams and the size of the collaborations they are active in, this was a very relevant recommendation. While the Hadron Physics team is indeed progressively focusing on the Electron Ion Collider experiment EPIC, the QGP one will be active for a long time both in ALICE and in LHCb. Indeed, this is a progressive move from one experiment to the other, accompanied by the decrease of responsibilities in ALICE for upcoming years, allowing a split of efforts..

The recommendation to seek more external funding has been followed with success, securing funding from both European programs and the ANR. In addition, the group preparing the Experiment at EIC has secured substantial funding for the development of detectors from DOE.

WORKFORCE OF THE THEME: in physical persons at 31/12/2023

Catégories de personnel	Effectifs
Professeurs et assimilés	Not applicable to the classification of IRFU personnel
Maitres de conférences et assimilés	Not applicable to the classification of IRFU personnel
Directeurs de recherche et assimilés	Not applicable to the classification of IRFU personnel
Chargés de recherche et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui à la recherche	Not applicable to the classification of IRFU personnel
Sous-total personnels permanents en activité	Not applicable to the classification of IRFU personnel
Enseignants-chercheurs et chercheurs non permanents et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui non permanents	Not applicable to the classification of IRFU personnel
Post-doctorants	Not applicable to the classification of IRFU personnel
Doctorants	12
Sous-total personnels non permanents en activité	
Total personnels	

EVALUATION

Overall assessment of the theme

Thanks to a very strong know-how in the realization and operation of gaseous tracking detectors and a well-established expertise in the extraction of relevant information on Generalized Parton Distributions (GPDs) and Transverse Momentum Dependent Distributions (TMDs) from experimental data, the theme's teams have been able to play an important role in the main experiments in the field (COMPASS at CERN and CLAS at JLAB), well beyond what one would expect from the limited size of those teams. At higher energy, the teams have contributed for 25 years with many responsibilities, installation, maintenance and operations at ALICE. More recently, they also made a substantial contribution to the ALICE upgrade through the operation of the Muon Forward Detector, and IRFU is now a full member of LHCb experiment (since the end of 2024), in which the teams will progressively move over the next seven years while their involvement in the ALICE experiment will decrease.

These efforts have given the IRFU a relevant visibility in the collaborations, and has brought a copious production of scientific papers in internationally recognized journals.

The theme has also made a limited contribution to the SPHENIX experiment, realizing a tracking layer and participating in the analysis of polarized proton collisions. This effort has been a side activity for the teams, with minimal human resources involved, but has contributed to consolidating the IRFU recognition at BNL as reliable constructor of high-quality detectors. This might be a useful element for the future work at the EIC.

The expertise of the theme in the study of GPDs, TMDs and QGP is very strong, and benefits from an excellent connection to theorists in the field, allowing them to make significant contributions to theoretical and phenomenological interpretation of the collected data.

It is very positive that the theme has closed the COMPASS activities and is now limiting the JLAB ones to data analysis, in order to make a coherent effort towards EIC; which is the world´s leading facility for the next generation of experiments in the field. The move of the teams from ALICE to LHCb for the HL-LHC era has been decided together with the direction of IRFU and after many meetings and workshops with particle physicists who have a strong interest in heavy flavour physics and may eventually participate as well. This shift will also facilitate the analysis of the quarkonium sectors on peripheral Pb-Pb and fixed target collisions.

The hadron physicists enjoy a very strong and productive cooperation with theoreticians who play a world class role in the field. This collaboration has also led to successful applications for funding. Particularly, the Compton Project promises to include also Lattice QCD calculations in the study of GPDs.

Last, the committee acknowledges the action of the team towards the general public by contributing to the creation of a game and videos.

Strengths and possibilities linked to the context

The theme has been demonstrated in all its activities, also in the recent construction for SPHENIX, to have the capability to realize demanding hardware on time and on budget and to operate it in the experiment successfully.

The experience gained in the CERN and JLAB programs allows for very effective participation in the EIC experiment.

The role of the teams of the theme to the study of the QGP at forward rapidities is well recognized, especially for the separation between prompt and non-prompt quarkonia. During the 25 years at ALICE, the IRFU teams have covered several facets of the project, from detector R&D and management responsibilities up to data analysis and assessment of theoretical models. In summary, the two strongest points to note are the technological capabilities in detector development and the very effective collaboration with theorists in the field.

Weaknesses and risks linked to the context

The teams of the theme remain fairly small and must resist the temptation to fragment the activity.

Some justification for new activities has not been adequately detailed in the self-evaluation document. It sometimes seems to be realized under the request from the host laboratory. While this is an important and even flattering recognition of the capabilities of the IRFU teams, the committee would have appreciated reading justifications mostly based on physics, scientific expertise or strategies. For instance, the shift of the team from ALICE to LHCb is ambitious, but a clear motivation for this shift is blurred by an accumulation of several arguments, some of them being not very strong. While the team expertise in technological realization is undoubtful, the scientific goal for such research should be considered first. This may, however, be important for defining the long-term perspective for EIC, after the CERN upgrades.

Analysis of the theme's trajectory

The EIC offers the most promising prospects for experiments dedicated to the understanding of the structure of hadrons. IRFU is very well positioned to make a very visible contribution both to the detector, through its expertise in gaseous tracking detectors, to the definition of the experiment strategies and the data analysis, and through its long and successful experience in a variety of complementary experimental programs. Given the size of the EPIC collaboration at EIC, though, it is essential that the teams of the theme work solidly on this program in order to reach the critical mass necessary for an impact proportionate to the ambition. IRFU has the potential to take a leading role at the EIC with worldwide relevance.

The theme has decided to move from ALICE to another CERN detector, LHCb, in order to investigate a key ingredient for the interpretation of the QGP evolution it suggested: the measurement of the di-lepton spectrum at intermediate mass between 1 and 5 GeV/c2, arguing that it is sensitive to the abundance of quarks and their momentum anisotropy. During the Upgrade 2 of the LHCb experiment, IRFU has the capacity to take the operation of the upgrade of the Upstream Tracker to a CMOS pixel technology.

RECOMMENDATIONS TO THE THEME

The hadron physics team should persevere in the direction it has traced for its own future, concluding and bringing to publication the data harvested in the various past data taking periods of the experiments it was involved in, but focusing its future activity on the experiment at EIC.

At higher energy, the study of the properties of QGP in the high temperature region of the QCD phase diagram is crucial for the understanding of the origin of our Universe, with impacts in cosmology, and the contribution of the team to this important physics question is crucial, particularly in collaboration with theoreticians from IPhT. It is very important that this physics question remains central to the team, and that the move to LHCb allows it to make a decisive contribution to the interpretation of the QGP evolution.

Theme 4: Nuclear structure and dynamics

Name of the supervisors: Ms Barbara Sulignano, Mr Gilles de France

TOPICS OF THE THEME

The nuclear theme consists of a team located at IRFU Saclay and another at GANIL Caen. The teams of this theme conduct experiments in several facilities around the world investigating nuclear structure and nuclear reactions.

The main goal of the research is the in-depth understanding of nuclear systems synthesized on Earth or representing systems and processes in different locations in the Universe. To address several open questions in nuclear physics and nuclear astrophysics that better characterize the nature of the nuclear interaction, the theme's teams have realized several types of studies, which are, for the most important ones: investigation of weakly bound and open quantum systems such as Borromean nuclei; the evolution of the nuclear structure across the nuclear chart, exotic shapes and shapes coexistence in nuclei; the measure of femtosecond lifetime of Na22 to determine the maximum detectability of novae; properties of superheavy nuclei, as well as collective motions in nuclei such as the pygmy dipole resonance in Ce140 multi-nucleon transfer; fission induced by transfer reaction and neutron-induced fission.

All these studies are complemented by theoretical developments, among which ab initio approaches made impressive progress in the last years, enabling the modelling of more and more heavy nuclei, the imaging of the shape of atomic nuclei through relativistic ion collisions, the Gamow shell model, and finally the properties of nuclei and hot dense matter necessary for the modelling of compact stars.

CONSIDERATION OF THE RECOMMENDATIONS OF THE PREVIOUS REPORT

Those recommendations are considered in the self-assessment document of the theme 4. Here below comments nuance some responses given by the theme's teams:

- Regarding the reduction of beam time in GANIL, running of GANIL and SPIRAL2 in parallel will contribute to increasing the beam time. However, the refurbishment of GANIL cyclotrons will induce important shutdown periods of the installation during the next period (2024-2029). As a consequence, beam delivery is expected to stay limited at GANIL until 2030.
- Concerning the importance of effectively replacing leaving people with newcomers, it was identified as a risk and the theme has therefore focused on gradually reversing this trend in his human resources plan by ensuring an overlap between departures and arrivals. However, this is not what is observed in the figure at page 125 of the self-assessment document presenting the FTE vs time: a continuous decrease with an effective loss of ~6 FTE between 2018 and 2023, which is not explained in the document.

WORKFORCE OF THE THEME: in physical persons at 31/12/2023

Catégories de personnel	Effectifs
Professeurs et assimilés	Not applicable to the classification of IRFU personnel
Maitres de conférences et assimilés	Not applicable to the classification of IRFU personnel
Directeurs de recherche et assimilés	Not applicable to the classification of IRFU personnel
Chargés de recherche et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui à la recherche	Not applicable to the classification of IRFU personnel
Sous-total personnels permanents en activité	Not applicable to the classification of IRFU personnel
Enseignants-chercheurs et chercheurs non permanents et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui non permanents	Not applicable to the classification of IRFU personnel

Post-doctorants	Not applicable to the classification of IRFU personnel
Doctorants	17
Sous-total personnels non permanents en activité	
Total personnels	

EVALUATION

Overall assessment of the theme

The teams of the theme working on nuclear structure and reaction dynamics rely on three solid pillars (theory, experiments, and technology) which enable them to play a leading role in many projects performed at international facilities such as n_ToF at CERN, GSI/FAIR in Germany, LNL in Italy, RIKEN in Japan and GANIL in France. They have important technical contributions and expertise in previously mentioned experiments.

For example, the researchers are specialists of liquid hydrogen targets: they have designed MINOS (previous term) used at RIKEN to study structure evolution in very neutron rich nuclei (Nature 2019), COCOTIER (funded by ANR) used at GSI to study short-range correlations in light exotic nuclei. They play a leading role in gamma spectroscopy using the AGATA array to study shape coexistence in heavy nuclei (EPJA 2020). The AGATA campaigns provide a significant number of peer-reviewed papers, 29 so far for the campaign at GANIL. In this experimental program a new method was developed to measure fs lifetimes (see Nature Communications 2022).

Success in getting funding reveals the dynamism of the theme. For example, the development of equipment like SEASON for S3 at GANIL were funded by the National Research Agency (ANR).

The future starting of S3 is an important opportunity for the theme to study superheavy nuclei. At GANIL, the higher availability of NFS is also an important opportunity to study collective motions in heavy nuclei and fission using the FALSTAFF spectrometer originally developed and led by IRFU.

Thanks to neural networks, impressive progress was made in ab initio calculations enabling them to simulate the nuclear structure of nuclei as heavy as 208Pb (PRL 2020). IRFU also joined an international group of theoreticians to explore the interface between low- and high-energy nuclear physics, and they produced the first proof of triaxiality for the nuclear ground state of 129Xe (see PRL 2022).

The above examples show the large domain covered by the IRFU teams in experimental and theoretical nuclear physics, with an impressive publication number (more than 600 papers during the assessment period).

The theme has a large contribution of research activities to society. Members are involved in teaching and one of them was co-responsible of the NPAC Master of Université Paris-Saclay. At GANIL, R&D activities are performed to develop innovative radioelements especially targeted for alpha therapy. The REPARE project, funded by ANR, focuses on the production of 211At. Efforts were also devoted at CERN in the n-TOF collaboration, with the development of specific instrumentation like fission chambers and n flux detectors (XY-Megas funded by ANR), to measure n capture cross sections (PRC 2020) which are now taken into account in the ENDF and JEFF evaluated nuclear data libraries. The theme teams are also involved in the development of compact accelerator-based neutron sources (CANS) to compensate for the shutdown of experimental reactors, for which they develop a new Monte Carlo neutron transport code using the GEANT4 toolkit (TOUCANS, NIM 2023).

The creation of a new department at IRFU in 2017 including GANIL has created new and beneficial synergies at IRFU between its members. The start of SPIRAL2 at GANIL is a major opportunity for the teams of the theme but they have to take into consideration the effective delays and uncertainties in the starting of some installations, as well as a continuous decrease of their human resources.

Strengths and possibilities linked to the context

The teams of the theme perform their experiments in world-class installations like GANIL (VAMOS, LISE, NFS …), CERN (n-TOF), GSI/FAIR, LNL and RIKEN, where they have leading roles in several projects and important technical contributions. Their skills are recognized internationally.

The revival of nuclear industry in France has a positive impact for fundamental and applied research, implying further opportunities at GANIL, beyond the starting of S3 and higher availability of NFS.

The teams are dynamic at various levels, which enables them to have high success in getting funds and prizes, and to reach an impressive publication rate.

They also contribute in activities with societal impact: teaching programs, communication and popularization of nuclear science and technology, nuclear medicine, and nuclear power technologies.

Weaknesses and risks linked to the context

The number of FTE devoted to theme 4 continuously decreased between 2018 and 2023. The teams don't give nor explain the consequences regarding their contributions in all the projects in which they continue to be involved.

In the coming years, GANIL cyclotrons will be refurbished implying long shutdown periods between 2025 and 2030 and, in addition, the venue of AGATA at GANIL is delayed to 2029. Moreover, the effective starting of S3 is also delayed and the future of FAIR has still uncertainties. All these risks could have a negative impact on the IRFU projects, which will have to continue a part of its activities on other facilities.

Analysis of the theme's trajectory

Over the last years, campaigns have been realized at international facilities, e.g., ISOLDE, n-TOF, SPES, TRIUMF and IGISOL, other than GANIL. They have also contributed to the development at GANIL of the following instruments: COCOTIER (LH2 target), MUSETT (Silicon wall for transfermium studies), ACTAR (Active target) and SEASON (Silicon box counter for electron and alpha particles).

In nuclear structure, direct reactions will be carried out to study nuclear shell structure and its evolution thanks to high-resolution spectroscopy using the future new detector GRIT (compact silicon array) associated with AGATA or EXOGAM at GANIL. The short-range correlation will be studied at FAIR (> 2028), and the shape of nuclei at HIE-ISOLDE, TRIUMF, S3 (with SEASON) or IGISOL. Especially octupole deformation could be used to measure atomic EDMs to emphasize CP violation. The study of superheavy elements will be performed at S3 using SIRIUS and SEASON. Finally, the search for new radio activities is the focus of an experimental campaign at ISOLDE (2 alpha emission) and future experiments in the DESIR hall (2p- and cluster radioactivity), where high-precision measurements in nuclear beta decay will also be carried out to search for new physics beyond the Standard Model.

In nuclear dynamics, the measurement of giant resonances to study collective motion will be performed at GANIL using the active target ACTAR, complemented by a program in OSAKA. The study of the fission process will be performed thanks to a complete program at GANIL (FALSTAFF/VAMOS, PISTA) and at ILL, CERN (n-TOF), JYFL/IGISOL. The study of n-rich nuclei structure will be performed at SPIRAL2 through multi-nucleon transfer using the future high-power injector NEWGAIN.

In theory, the goal is to develop ab initio approach to the whole Segrè chart, with the estimation of the theoretical uncertainties, which are relevant for many IRFU experiments that will be especially carried out at S3. This endeavour is achieved in the framework of a collaboration with theoreticians of CEA/DAM and CEA/DES. Teams are also involved in quantum computing in the context of a large national initiative (FRANCE 2030).

RECOMMENDATIONS TO THE THEME

The committee found difficulties in the exercise of presenting the activity of GANIL as a component of IRFU, since GANIL is a GIE structure receiving contributions from CEA and CNRS institutions. Since it seems very difficult, and probably counter nature, to differentiate the IRFU contribution from that of CNRS, the committee recommends for next term a separate assessment of GANIL, treated as a whole where the contributions and achievements of CEA and CNRS teams could be presented together.

The committee remarks that nuclear astrophysics is considered as one of the important contributions to the physics case of GANIL. The situation of IRFU, where nuclear physics and astrophysics departments are both present makes it a unique opportunity for synergy to be reinforced. The committee therefore suggests a strategical action towards the interface between nuclear physics and astrophysics, in either the direction of nuclear synthesis or dense nuclear equation of state or both.

During the visit, it appeared that the first priority for nuclear physics in the coming years was GANIL and its new installations. Discussions are currently underway to consider the possibility of contributing in physics projects to be carried out in the future DESIR hall. The committee strongly encourages this initiative, which would strengthen the DESIR community and enable it to benefit from the strong technical support provided by the IRFU.

The committee found that the perspective over the next years remains a bit vague. Several possibilities are considered without real priorities for the next term, and especially without considering the consequences of delays and uncertainties mentioned above in section "Weaknesses and risks linked to the context" nor the continuous decrease observed in the number of FTE with time. The committee recommends to better prioritize its key projects for the short-term future.

Theme 5: Stars and planetary systems

Name of the supervisor: Mr Stéphane MATHIS

TOPICS OF THE THEME

The theme addresses the following research areas: heliophysics; spaceweather for space and societal applications; asteroseismology; stellar evolution and dynamics; exoplanets; characterisation and modelling of extrasolar planets atmospheres; high-performance computing; numerical multi-physics simulations using magnetohydronamics.

CONSIDERATION OF THE RECOMMENDATIONS OF THE PREVIOUS REPORT

There was a concern about the manpower devoted to exploitation of the incoming data from JWST and the future ARIEL mission, particularly given the considerable instrumental investment in these missions.

Following this recommendation, the theme has hired a new permanent researcher who is a recognized expert in the modelling of exoplanets atmospheres. This position reinforces both the interpretation of data from JWST and the preparation of the ARIEL ESA M4 space mission for which IRFU is making major instrumental contributions.

WORKFORCE OF THE THEME: in physical persons at 31/12/2023

Catégories de personnel	Effectifs
Professeurs et assimilés	Not applicable to the classification of IRFU personnel
Maitres de conférences et assimilés	Not applicable to the classification of IRFU personnel
Directeurs de recherche et assimilés	Not applicable to the classification of IRFU personnel
Chargés de recherche et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui à la recherche	Not applicable to the classification of IRFU personnel
Sous-total personnels permanents en activité	Not applicable to the classification of IRFU personnel
Enseignants-chercheurs et chercheurs non permanents et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui non permanents	Not applicable to the classification of IRFU personnel
Post-doctorants	Not applicable to the classification of IRFU personnel
Doctorants	8
Sous-total personnels non permanents en activité	
Total personnels	

EVALUATION

Overall assessment of the theme

This research theme gathers several research teams within the Department of Astrophysics, covering the full range of scientific and technical expertise required to produce space and ground-based experiments at groundbreaking level. A special attention has been paid to organize all ongoing outstanding research into a coherent and ambitious research program on the Sun, the stars and their planets. The theme is at the cutting-edge of international science, on key questions of modern astrophysics, including some strategic aspects such as space weather and solar activity.

In addition to an excellent scientific activity, the theme has also very good internal organization and attractiveness, with special care of the management to maintain an efficient and developmental working environment.

Points of concern include some special attention to code adaptation with respect to upcoming radical changes in HPC architectures and artificial intelligence, and special attention from the IRFU management to overcommitted young tenured staff that will face both challenges of managing a large department while achieving state-of-the-art research under ERC grants.

Strengths and possibilities linked to the context

The exceptional configuration of IRFU provides the strategic advantage of combining expertise all along the science production chain, from instrumentation, observation, theory and modelling including multi-physics numerical simulations. This theme and others at IRFU benefit from transverse collaborations between IRFU departments, for instance, with the technological and instrumental platforms for the development of space missions and for the top-level HPC infrastructure in the activities using mixed HPC, AI and HPDA approaches.

This allows IRFU to stand in a world-leading position with high-citation publications alongside with many grants (ERC Whole Sun, 4D- Star, Exomagnets, and ANR Stormgenesis and WindTRUST, CNES and ESA programmes support). The attractiveness of the teams of the theme allows recruiting top-level Ph.D. students and postdocs from EU, North America and Asia. The strategy of IRFU of preparing/anticipating space missions while exploiting current ones allows its research teams to stay central actors in space-based science missions, both on ground segment and satellite instrumentation. A remarkable example is given by its involvement into the development of MIRIm, the imager for the JWST MIRI instrument, at the prime contractor and co-PI level. The teams benefit from guaranteed observation time (110 hours) and have taken responsibility for the Exoplanet Observing Program.

Widely anticipated world-class exoplanet missions such as PLATO and ARIEL are key science projects for the next decade. Strategic positioning is also underway through the preparation of future flagship project like Habitable World Observatory (HWO) and the Large Interferometer for Exoplanets (LIFE).

The access to high-performance computing at CEA TGCC, GENCI, PRACE, and PEPR NumPEx allows strengthening the team leadership in numerical modelling as well as participating in the fast development of AI for astrophysics.

The theme benefits also from a strong local, regional, national, and international network of collaborations.

The theme also offers its expertise to space weather applications, which are crucial for society through solar activity predictions using modern data assimilation techniques and machine learning.

Weaknesses and risks linked to the context

While the research teams of the theme are experiencing strong expansion, as is required by the accelerating international development of the associated hot research topics, their key permanent scientists face supplementary heavy burden of committee membership and departmental direction or services. Administrative tasks, although important, might divert key human resources and time to the detriment of science production and future strategic positioning.

The theme activity strongly depends on the success of space missions, like launch or operational failures. It must be reminded that new space activities like the deployment of mega constellations for private purposes pose an existential threat to many scientific programs, some of which are crucial for a safer life on Earth (e.g., Sun observation and near-Earth asteroid detection).

Another source of concern is the ongoing radical change in parallel supercomputing infrastructure, notably through the rush towards vector architectures (GPUs) for which some of the workhorse codes must be adapted.

The multiplicity of funding bodies is also identified as a threat, through the complexity and the increase of the time spent on drafting project proposals.

Analysis of the theme's trajectory

The teams of the theme have established a world-class leading expertise on the Sun, other very different stars, and their planets. This scientific theme is as central (e.g. for space weather and the risk mitigation related to solar activity) as it is complex. Developing such a centre of excellence including a large expertise on such a central issue is a major achievement. The scientific topics of stellar, solar and exoplanet physics globally enters an exciting era for which the IRFU has promising strengths and opportunities. Three strong axes of development have been identified: heliophysics for space weather applications; physics and evolution of other stars; and complete characterization and understanding of exoplanetary systems. One should also add multi-scale multi-physics high-performance computing.

On space weather, the Solar Orbiter mission will soon explore uncharted regions out of the ecliptic, while ESA Space Safety Program expands with the ambition to predict solar events and Earth's space conditions. To meet these challenges, the theme will have to strengthen its ab initio modelling of solar eruptive regions and its tools to assess solar environment models. Two different ANR projects will be devoted to this end. Data assimilation techniques combined with machine learning will help anticipate the strongest solar flares, predicting the solar corona emissions and assessing the cosmic ray flux hitting the Earth's atmosphere. Major efforts will be devoted to the state-of-the-art house code (Dyablo), paving the way to a chain of models bridging the interior of the Sun to the Earth environment thanks to a coupling with WindPredict. These efforts, aimed at understanding the heliosphere as a whole, will provide firm grounds to expand this research to other star-planet systems and develop exo-space weather.

On physics and evolution of other stars, the forthcoming PLATO mission will bring the discipline of asteroseismology (the study of oscillations of stars to unveil their inner physical processes) to a new era. These observations are expected to bring significant improvements to the understanding of the rotation and the magnetism in all types of stars from their surface to their core all along their evolution. A side result is also a better understanding of our own Sun (which is so central for all aspects of life on Earth) within this global framework. To interpret astero-seismic data, the teams will have to strengthen the models of stellar oscillations in rotating magnetic stars, notably through 3D numerical simulations of stellar interiors and winds using state-of-the art codes. IRFU will be key actor for the development of new generation stellar structure and evolution models.

On the science of exoplanets, the IRFU scientists will bring the realism of the modelling of star-planet interactions to the level required to interpret the forefront observations obtained with JWST and in the future with PLATO and ARIEL. This will be at the heart of a specific top-class ERC project. To understand the structure, evolution, and chemistry of exoplanets, they will continue the targeted studies of their atmosphere with JWST and prepare the ARIEL statistical survey (~ 1000 planets)

Another major asset to emphasise is the leading IRFU expertise in multi-scale multi-physics simulations with the development of the next-generation code Dyablo for exascale supercomputers. Such complex numerical simulations have produced amazing results standing beyond any expectations of old-school analytical predictions. Multi-scale multi-physics numerical simulations somehow constitute a new pillar of physics, aside with instrumentation, experiment and theory. These tools also require specific methods and architectures gathered into the term high-performance computing. This rather new branch of physics has brought to reality the hope that complex systems as the Sun can be understood to such an extent that dangerous events like geomagnetic storms can be efficiently anticipated.

All these activities are supported by the strong involvement of IRFU in major space missions (Solar Orbiter, JWST, PLATO and ARIEL) and include exciting perspectives such as the Habitable World Observatory (HWO).

The strong attractiveness of this theme with new recruitment of CEA Staff and CNAP and its success in securing funding (see for example the opportunity brought by the PEPR Origins and NumPEx), particularly for students and postdocs, puts IRFU in an excellent position to play a world-leading role in these active fields.

RECOMMENDATIONS TO THE THEME

Forthcoming HPC architectures for exascale computing are quite likely to pose new challenges for numerical simulations, since they rely on a larger variety of hardware types (GPUs, ARM processors) than the previous generation. Some of these hardware configurations imply coding particularities for which the existing codes must be adapted and optimized. This is a central issue for all topics largely based on numerically demanding modelling. We recommend reinforcing the teams' current efforts on code adaptation and optimisation, which could be assisted/accelerated through AI techniques like chatGPT.

While this theme is rapidly expanding, top key scientists of the teams will face both the challenges of heading the department while achieving cutting-edge research under ERC grant. Although the theme has already prepared itself to handle both challenges, a special attention from the IRFU management level should be paid to ensure these key young specialists will not face burnout while striving on all battlefields.

Although space-based science brings extra challenges and specific constraints at all levels, IRFU is a world leader and should not abandon this leadership, even in the case of mission failure or privatisation of the space sector to the detriment of fundamental science use. Performing top science in space automatically yields an extreme level of competence in such a wide variety of skills that any well-governed nation cannot afford to lose.

Theme 6: Evolution of structures, galaxies and stars

Name of the supervisor: Mr Frédéric Bournaud

TOPICS OF THE THEME

The research activity developed in this theme includes: large-scale structures and galaxy formation; interstellar medium and star formation; joint formation of stars and planets; Galaxy clusters; IR and X-ray astronomy; large-scale surveys of galaxies; and high-performance computing simulations.

CONSIDERATION OF THE RECOMMENDATIONS OF THE PREVIOUS REPORT

New permanent researchers have reinforced the teams of IR and X-ray astronomy, as well and theory and numerical simulations, some of them thanks to internal CNRS mobility. Reinforcing the X-ray area is now highly considered with the rescoping of ATHENA.

The theme has maintained its high capabilities to obtain time allocation on major observatories (VLT, ALMA, HST, JWST) and its role in VLT/BlueMuse and ELT/Metis will grant privileged access to these forthcoming instruments as well as being granting an impressive amount of HPC computing time, although not as high as in the previous evaluation period.

Despite the Covid-19 pandemic, the theme has been very proactive in attracting very recognized senior experts, who have been hosted as visitors for periods of at least three months and up to one year.

WORKFORCE OF THE THEME: in physical persons at 31/12/2023

Catégories de personnel	Effectifs
Professeurs et assimilés	Not applicable to the classification of IRFU personnel
Maitres de conférences et assimilés	Not applicable to the classification of IRFU personnel
Directeurs de recherche et assimilés	Not applicable to the classification of IRFU personnel
Chargés de recherche et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui à la recherche	Not applicable to the classification of IRFU personnel
Sous-total personnels permanents en activité	Not applicable to the classification of IRFU personnel
Enseignants-chercheurs et chercheurs non permanents et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui non permanents	Not applicable to the classification of IRFU personnel
Post-doctorants	Not applicable to the classification of IRFU personnel
Doctorants	20
Sous-total personnels non permanents en activité	
Total personnels	

EVALUATION

Overall assessment of the theme

This theme is based on research teams, covering a large range of scientific and technical expertise required to conduct an experimental programme at exceptional levels in evolution of structures, galaxies and stars. The teams stand at the cutting-edge of international science, on fundamental questions of modern astrophysics and cosmology, including some strategic aspects such as high-performance computing at its highest level.

IRFU should consider investigating further the mechanism of intermediate mass and supermassive black holes in a cosmological context and focus research efforts to ensure numerical artefacts and limitations do not bias conclusion on cosmological constraints.

The committee positions itself in favour of splitting this theme into science and numerical tools, rearranged considering the other theme that is overlapping. This is strongly suggested to ensure a better balance and readability at the level of the institute (see recommendations hereafter).

Strengths and possibilities linked to the context

The theme is very active and cohesive, with good interplay and collaborations within teams in the same department on related topics. The theme composition in terms of permanent researchers, postdocs, and students, leverages access to cutting-edge facilities. The theme also maintains efficient synergy between ground and space observatories and international supercomputers, in a virtuous circle of discovery.

The scientific production and research at state-of-the-art are at the top international level, remarkably similar in the fields of observations, theory, and numerical simulations.

Identified future opportunities include close collaboration with CEA-DAM on cosmological simulation programs, code development and adaptation, and the use of supercomputers; strong support of Extremely Large Telescope ground observatory (with ESO).

Weaknesses and risks linked to the context

Ageing and the increasing duration of big science projects, including their preparation phase constitutes a risk of potential loss of expertise in the medium and long terms.

Perspectives strongly rely on the acceptance and success of future space missions (e.g. ATHENA).

Losing expertise on X-ray observations of clusters and supernovae remnants is pointed as a threat on the short-term.

The committee points out a risk of focusing priority on numerical tools and high-performance computing numerical experiments to the detriment of science. While these amazing simulations are successfully applied to observations, there does not seem to have enough input from this simulation work to stimulate new instrumental developments.

One identified perspective of the theme is to push simulations towards supermassive black holes scales and investigate intermediate mass black holes formation. However, there is no indication on how the teams would push these investigations towards results that could be directly used by other teams involved into the emerging science of gravitational waves.

One of the workhorse codes of the team, RAMSES, is planned to be coupled or merged with the uprising Dyablo code. It constitutes an exciting perspective but presents a potential integration risk.

Analysis of the theme's trajectory

This theme is built around the central topic of astrophysical structure formation, spanning twelve orders of magnitude between cosmological and planetary systems. Although that wide, same phenomena are ruling all these scales: gravitation, fluid dynamics and magnetic interaction. Same modelling tools can therefore be applied to a wide variety of physical phenomena. However, feedback (e.g. star & planet formation, supernovae, cooling and damping including cosmic expansion on largest scales, etc.) results in specific adaptation and more importantly coupling between scales, making this field rich, valuable, intricate and complex.

The theme is one of the international leaders in this topic, both on tools provided and observations. It is a key contributor to the high-precision full-sky era with surveys such as Euclid (from the instrument to pipelines and analysis tools, to underlying theoretical models and supporting numerical simulations), and VERA RUBIN

Observatory. This puts IRFU in a leading position to exploit data from the new generation of cosmological surveys. Numerical simulations of structure formation are at the top international level in terms of included physics, resolution, and simulated volumes, which is central to ultimately test different cosmological models. Simulations performed by the theme's researchers stand at the very top of HPC.

Projects like ALMA and JWST, as well as the strong involvement of IRFU in pioneering surveys (e.g. CEERS) pave the way to an understanding of the emergence and evolution of the so-called cosmic web of galaxies and supposedly associated invisible structures of dark matter. The history of galaxy formation is currently unveiled by a variety of techniques towards earlier and earlier, up to the re-ionization epoch. Here as well, the teams of the theme are among the leaders in this topic.

On the smaller scales of stars and exoplanet formation, the tools developed have unveiled the strong couplings at work, with magnetic fields regulating star formation that are strongly intricated with the growth of dust grains in protoplanetary disks. Cutting-edge models of dust grain growth in the disk are currently being developed. All these results offer amazing upcoming perspectives for IRFU to start ab initio simulation of protoplanetary disk formation, along with star formation. In the coming decade, this research will be able to describe the initial conditions of exoplanet formation and evolution, yet another very active field.

This science is supported by the strong involvement of IRFU in major instrumentation on the short to long terms in the ground and space: ELT/METIS, VLT/BlueMuse, and ATHENA. Another major advantage and resource is the leading expertise in multi-scale simulations, with the continuous improvement of major codes such as RAMSES and the development of next-generation codes such as Dyablo for exascale supercomputing. This deep experience of the teams in using first-class supercomputers also serves the involvement into the SKA observatory.

All this contributes to the strong attractiveness in this theme with new recruitment and several recent incoming mobility from CNRS, CNAP and Université Paris-Saclay. Associated with its success in securing funding for students and postdocs, it places the theme in good position to continue playing a world-leading role in these active and emerging fields.

However, the topics detailed here overlaps with other scientific themes (5, 7 and 11) that should be taken into consideration for an improved structuration among the research themes of IRFU (see recommendations hereafter).

RECOMMENDATIONS TO THE THEME

In the light of the emerging science of gravitational waves, and the related involvement of IRFU into LISA, the formation of intermediate mass and supermassive black holes must be investigated, with the objective of providing prospects for future observations.

Special attention and research efforts must be pursued on disentangling numerical effects (like weak resolution) from a change in cosmological parameters, like what has been done for the apparent discrepancy of compact galaxies at high redshifts from the vanilla LCDM concordance model. This is particularly important since it is hoped to unveil the nature of dark energy and dark matter from large-scale structures observables with future surveys like Euclid and DESI.

Despite the excellence of the science produced, the committee recommends a rearranging of the topics: large-scale structure, galaxies and star formation (currently theme 6); energy content of the universe (theme 7) and scientific computing/data analysis/simulation (theme 11). Science and observational aspects should be merged under one flag theme as well as all aspects regarding simulations and code developments to be regrouped under another flag theme. This appears to us as a necessary rationalization as it will allow a better balance and readability between the many different research themes at the level of the IRFU institute. Keeping theme 6 separated does not appear to be justified since themes 5 and 7 are using numerical results of theme 6 while theme 11 focuses on the development of software like Dyablo.

Theme 7: Energy content of the universe

Name of the supervisor: Mr Christophe Yeche, Mr Jean-Luc Starck

TOPICS OF THE THEME

This theme is spanning research areas in cosmology such as dark matter, dark energy and gravity, primordial universe (including early gravitational waves emission and inflationary processes) and cosmic microwave background. Methodological developments include: matter clustering through weak lensing and large-scale spectroscopic galaxy surveys; statistical inference; machine learning; multi-scale multi-physics state-of-the-art numerical simulations of large-scale galaxy formation; mock catalogues; future CMB polarization maps; and direct search of dark matter (WIMPs and axion-like). Teams are involved in international projects: space-based (Planck in the past, Euclid currently and LiteBird for future); ground-based (DESI and CFIS/UNION); simulations (Extreme-Horizon).

CONSIDERATION OF THE RECOMMENDATIONS OF THE PREVIOUS REPORT

The previous report recommended improving the collaboration and synergies between astroparticle physicists and astrophysicists.

This has been partly addressed by the organisation of joint prospective workshops on forthcoming projects, joint research seminars and cross participation in recruitment committees. The concerned teams have also engaged into co-supervision of PhD thesis (cosmological simulations, modelling of galaxy density field and quasar Lyman-alpha Forest) and collaboration in international projects such as Euclid and DESI around galaxy clustering with interdisciplinary efforts. Remarkably, this also leads to success in joint ANR application, showing the gain of this enhanced cross-collaboration.

WORKFORCE OF THE THEME: in physical persons at 31/12/2023

Catégories de personnel	Effectifs
Professeurs et assimilés	Not applicable to the classification of IRFU personnel
Maitres de conférences et assimilés	Not applicable to the classification of IRFU personnel
Directeurs de recherche et assimilés	Not applicable to the classification of IRFU personnel
Chargés de recherche et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui à la recherche	Not applicable to the classification of IRFU personnel
Sous-total personnels permanents en activité	Not applicable to the classification of IRFU personnel
Enseignants-chercheurs et chercheurs non permanents et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui non permanents	Not applicable to the classification of IRFU personnel
Post-doctorants	Not applicable to the classification of IRFU personnel
Doctorants	14
Sous-total personnels non permanents en activité	
Total personnels	

EVALUATION

Overall assessment of the theme

The theme units the research teams with activity in the area of cosmology spanning over a wide range of space and ground -based topics and which benefit of scientific and technical expertise required to produce achievements at the highest international level. The teams stand at the cutting-edge of modern science, including some strategic aspects such as machine learning and more generally artificial intelligence.

The committee nevertheless makes some suggestions to the teams that should: prospectively question the future of CMB science in space; anticipate the breathlessness of precision cosmology after the results of incoming space missions like Euclid; and especially define a strategy and perspectives concerning the interplay with astroparticle physicists. The committee also noticed the identified perspectives on gravitational-wave astronomy are too weak, especially in the light of the involvement of IRFU into the future LISA mission.

The question of gender balance should also be considered as a top priority to ensure the benefits of diversity in the working environment as well as the scientific and creative processes.

Strengths and possibilities linked to the context

The teams of the theme are deeply involved and key actors of several ongoing and forthcoming state-of-the-art international mission or collaborations, for instance the spectroscopic and photometric surveys thanks to a significant longstanding contribution to SDSS-CFHTLenS. Their expertise is as vast as impressively skilled, particularly multidisciplinary: from statistics in cosmology for reconstructing the signal to theoretical interpretation of dark energy, alternatives to general relativity, nature of dark matter, neutrino mass, etc. The teams are collaborating with good emulation, avoiding non-productive internal competitions.

The environment of CEA is excellent in providing technical and engineering support for development. This gathering of scientific critical mass, skills variety, excellence and team work is quite exceptional, which must be emphasised. It is also the necessary condition to produce such high-level science in such international competitive collaborations, where foreign partners often have more financial resources, better salaries, political support or manpower.

Remarkable opportunities with excellent potential perspectives include the support of a next-generation CMB mission, scientific and R&D involvement into axion searches (MADMAX collaboration), key involvement in SKA through computing expertise and future spectroscopic surveys both in the US (Spec-S5) and in Europe (WST).

Weaknesses and risks linked to the context

There is no established team around CMB studies, and this lack is pointed by the teams themselves. The Planck space mission has pushed the CMB measurements towards technological, if not physical, frontiers of the experiment. There is no real successor, and therefore unclear ambitious strategy for the future of the CMB studies.

Ageing of the research teams is also an issue since it will imply a loss of expertise and could imply a decrease in the workforce.

Analysis of the theme's trajectory

The teams of the theme plan to focus on the key scientific goals of cosmology for the next decade: unveiling the physical nature of so-called dark energy, probing gravity on extragalactic scales, exploring the many roles of dark matter on several scales, and questioning the physics of the very early universe.

This will be achieved through essential scientific and technical participation to large-scale surveys such as LSST, Euclid, DESI and SKA. 4th generation CMB projects are hopefully expected to unveil physical mechanisms behind cosmic inflation and astrophysical constraints on neutrino mass.

Starting after 2025, the DESI-II spectroscopic galaxy survey will focus on high-density surveys of low-z galaxies, a probe of the non-linear gravitational collapse regime that also allows exploring phenomena such as galaxy-galaxy lensing. It will also provide an extensive survey of high-z galaxies above redshift 2, giving access to novel tracers of matter like Lyman Break Galaxies (LBG) and Lyman-alpha Emitters (LAE). These first galaxies directly probe the onset of Dark Energy through transition form, the so-called dark ages, as well as investigate primordial non-gaussianities stemming from inflation. IRFU has proven its expertise with the DESI survey and will contribute both to the science and to the upgrade of the spectrographs for DESI-II by modifying the cryostats built by IRFU for DESI. Possibilities for future surveys are under investigation at the perspective of the following decade (after 2035) with possible contribution in the construction of instruments where it already has a strong expertise, like cryostat design and construction.

About the Euclid space telescope and Vera Rubin Observatory, IRFU will be strongly involved into analysing and interpreting weak lensing data. Teams have developed important and innovative high-order statistical tools, supported by numerical simulations, to constrain the cosmological parameter.

This will be made in synergy with involvement into Sky Kilometre Array (SKA) in the radio domain, for which the team has developed data analysis tools and interpretation of subtle weak lensing effects. SKA will offer a glimpse into the so-called epoch of reionization, a topic in which the team has a strong expertise through long-term involvement on CMB foreground studies for the Planck mission.

Research on the CMB will focus on the measurement and characterisation of its polarisations through 4th generation experiments that are currently emerging but still at the level of prospective study or assembling. The current involvement focuses on galaxy clusters and studying correlations between CMB lensing and large-scale structure, with participation in the Simon Observatory, a precursor to CMB-S4. Besides involvement in the data analysis and interpretation, the teams will also contribute to the development of the instrumentation, notably through superconducting cables. Involvement in LiteBird, a forthcoming Japanese-led space-based experiment focusing on the B-mode of the CMB polarisation, is underway, with contributions to control electronics and cryogenics. While both projects are complementary and benefit from good internal collaborations, the IRFU teams are not in a leading position, though they will provide significant and decisive contributions.

On the other hand, the teams of the theme are strongly involved into the design and exploitation of dark matter direct searches experiments, through both astronomical and ground-based methods. The team has been involved into the EIDELWEISS experiment (WIMP search) through the development and running of cryogenic detectors and data analysis with final delivery in 2020. Continuation of the expertise is ongoing through a partnership into the ANR project CRYOSEL.

In addition, IRFU has been engaged in the search for axions for decades. In 2020, the theme was awarded ERC funding for the G-LEAD project (with two experiments under construction). These are innovative both in terms of science and related technology. A patent application around the assembly of permanent magnets is pending.

These perspectives are excellent. For large-scale structures, the teams will be involved in the scientific exploitation that their previous involvement into mission preparation has allowed. They are in a leading position for data analysis and interpretation. For the CMB, important significant contribution to data analysis and instrumentation is planned for ground-based and space-based projects, although the teams are not in a leading position. This is identified as a weakness by the teams themselves. For DM searches, the IRFU is in a leading and innovative position around axion searches.

RECOMMENDATIONS TO THE THEME

Prospective joint workshops should investigate and question the future of CMB science, using out-of-the-box reasoning to favour the emergence of innovative future experiments, with a part of scientific risk but potentially high gain in technology. While contributions to 4th generation experiments on the CMB are planned (e.g. LiteBird or CMB-S4), there appears a need for a more ambitious large-scale program which could take the form of a European-lead space-based mission with edge-cutting and innovative technologies developed by the teams.

While the teams are preparing the future surveys of the next decades, it is also important to anticipate the future of cosmology, beyond the current stage of precision science with statistical tools. The fear is that cosmology could somehow be slowed after experiments like Euclid and SKA because the gain in statistics will saturate or the results will not be able to rule out the vanilla concordance model. This model has indeed little explicative value until some come with a candidate for dark matter and a theory for weighing vacuum energy. It is therefore important to anticipate innovative approaches for future experiments in cosmology, beyond the current trend of precision science.

The committee points out a lack of perspectives in the trajectory concerning the interplay with astroparticle physicists. However, this could be made around dark matter searches and related cosmological abundances, for instance, as well as unified dark matter-dark energy candidates with axion physics. In addition, it is also recommended to enhance collaborations with theme 8 on GW science and multi-messenger astronomy (CTA, Einstein Telescope, LISA, etc.).

The identified perspective on gravitational-wave astronomy is too weak (only the mention of indirect GW imprints on CMB polarisations). Since this is expected to be a major emerging era of research in the forthcoming decades, it is recommended to investigate participation into projects like LISA, Einstein Telescope and Cosmic Explorer, but also the emerging field of electromagnetic detection of GW in the MHz-GHz range. The latter directly probes the cut-off of the stochastic GW background spectrum typically with similar apparatus as those dedicated to axion searches. This is a possible innovative perspective of IRFU teams for which they have a direct significant expertise from past and current research. The G-Lead experiments could include a search for such very high frequency GW with moderate adaptation.

It is also important to prepare forthcoming retirements by ensuring the renewal of positions and the expertise and knowledge transfer, while bringing new skills and networking for future development. The question of gender balance should also be considered a priority to ensure the benefits of diversity in the working environment as well as the scientific and creative processes.

Theme 8: Exploration of transient universe

Name of the supervisor: Mr Fabian Schussler, Mr Bertrand Cordier

TOPICS OF THE THEME

The topic addressed in theme 8 is the exploration of transient universe, which can be more precisely defined as the study of: time-varying emissions and flares; and novel, unpredictable phenomena from astrophysical sources. The field has benefited from the emerging discovery of multi-messenger events that provide new insight into the transient universe.

Within the wide-ranging and global activities, the theme focuses on three scientific aspects:

- detection of transient phenomena with various ground- and space-based detectors for different messengers, some of which are operational, some of which have stopped taking data and some of which still need to be built for the future;
- follow-up observations of transient events also by preparing services and tools for real-time multi-measurement observations;
- theoretical studies of the transient Universe.

CONSIDERATION OF THE RECOMMENDATIONS OF THE PREVIOUS REPORT

The recommendations of the last report were taken seriously and have been implemented to a large extent, within the limit of the resources devoted to this theme. Three recommendations have been particularly considered by the committee:

- Closer collaboration between the Astrophysics, Cosmology and Astroparticle Physics teams at IRFU: Cross-cutting activities on the research topics of the theme have started between the departments, in particular in the form of joint seminars, partly joint analyses, shared coordination (on particular, department overarching activities within CTA) and joint funding applications such as common ANR projects in observational cosmology and EU Horizon projects (ACME) in multi-messenger observations. However, all these activities were conducted on initiatives of individuals but not driven by the strategy of IRFU departments.

- Development of a strategic plan on which and how to pursue the messengers: The teams made the effort to consider how to deal with the limited resources and available expertise (which permanent scientist on which research topic?) globally on cosmic messenger activities. However, due to global delays in most funded and starting projects, it turned out that final strategic decisions with timelines and prioritisations could not be taken. Anyway, a plan was developed on how to be engaged in gravitational waves and the upcoming facilities, where LISA is the favoured GW project. High-energy gamma rays will be pursued by science with CTA and for lower energies (GRB) THESEUS is the fostered satellite program. The decision was also taken that high-energy neutrino activities will not be continued (e.g., with KM3NeT) due to lacking resources.

- Instrumentation of CTA: The decision by the CTA collaboration to select NectarCam for the CTAO mid-size telescopes, is a big success for IRFU which is in charge of the construction of nine cameras. The Institute will also take the responsibility for calibration and operation. This is a great recognition for the teams, with high international visibility. It will bind resources for several coming years.

WORKFORCE OF THE THEME: in physical persons at 31/12/2023

Catégories de personnel	Effectifs
Professeurs et assimilés	Not applicable to the classification of IRFU personnel
Maitres de conférences et assimilés	Not applicable to the classification of IRFU personnel
Directeurs de recherche et assimilés	Not applicable to the classification of IRFU personnel
Chargés de recherche et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui à la recherche	Not applicable to the classification of IRFU personnel

Sous-total personnels permanents en activité	Not applicable to the classification of IRFU personnel
Enseignants-chercheurs et chercheurs non permanents et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui non permanents	Not applicable to the classification of IRFU personnel
Post-doctorants	Not applicable to the classification of IRFU personnel
Doctorants	19
Sous-total personnels non permanents en activité	
Total personnels	

EVALUATION

Overall assessment of the theme

The theme transient Universe, more comprehensively expressed as multi-messenger time domain Astrophysics, is a cutting-edge area aiming at understanding the physics of high- and highest-energy processes in the Universe. IRFU is well internationally positioned with visible contributions and has the potential to become one of the worlds leading institutes in this astrophysics field. The overall programme consists of a good mix of contributions to flagship experiments such as SVOM and CTA, and a number of smaller experimental and phenomenological activities, which together form a well-rounded picture. The strategic thinking for the next decade is well balanced and IRFU shares high potential to play a pivotal in international projects of the field. However, prioritization is necessary in order to decide in which experiments, missions and topics the finite resources of the IRFU could make the highest possible impact.

Strengths and possibilities linked to the context

The teams of the theme are involved in large-scale international projects with significant, visible and unique contributions. These contributions to the theme come from several IRFU departments, which is a clear strength in international benchmarking, providing broad expertise in the entire life cycle of experiments from design to construction and data analysis.

This is true for the SVOM project where the strong contribution of the theme to this international project benefits of the high potential of IRFU; involved from the beginning, major contributor to the design, responsible for instrumentation, calibration and operation, and cumulatively in the service and operation of the French SVOM Science Centre, and with the associated liabilities for the entire lifetime of the mission. It should be noticed to the role of the instrument PI of an IRFU scientist.

SVOM is a flagship experiment of IRFU and will remain so in the coming years. The fact that the first GRBs have already been observed and analysed at IRFU after the launch in 2024 (and alerts have also been sent from IRFU) fits in here. A large number of scientific publications will follow.

The activities in the TEV-Gamma area follow a similar pattern than in HESS with a successful transition to CTAO, currently in the set-up phase with a significant contribution to the camera of the mid-size telescopes. Here, the strength of IRFU will lie in not suffering a break in existing expertise in the transition from construction to data analysis of CTA. It should be reminded that the team's most important publications were made with H.E.S.S.

Another mainstay is the exploitation in future space missions, in particular directed to the THESEUS satellite as well as gravitational wave activities, which are oriented towards the LISA mission, but where also a synergy with the Pulsar Timing Array in Nancay is exploited. Here, both the scientific expertise is currently being expanded and the foundations for possible hardware contributions are being laid.

AstroColibri is an interesting project for the Institute since it builds on expertise from the SVOM mission and provides an essential service to the real-time multi-messenger astrophysics community that only a large research centre like IRFU can provide. The fact that this project is now embedded in the large EU HORIZON-INFRASERV project ACME is a real success. The gained expertise also opens the possibility to participate in current and future missions, like the CATCH program. IRFU can also make further visible contributions to the long-term archiving of relevant data required for this. In addition, the topic is well suited for outreach and citizen science projects, although such possibilities have not yet fully utilized.

The theme activities are complemented by dedicated phenomenological and theoretical work in astrophysics, in particular the ERC project MagBURST, which is an excellent fit for SVOM and multi-messenger astrophysics.

Weaknesses and risks linked to the context

The cross-departmental pursuit of large international projects in this area is both a strength, a weakness but also a risk. The matrix-like workforce involvement makes a consistent strategy in and for long-term projects difficult, as other topics also have to plan resources and individual scientists want to focus their expertise on their own topic.

This is currently best seen in the SVOM project, where the hardware work has been completed and the team for the data centre has been established. Although the necessary resources for this have been secured, it is currently a problem that the data analysis and thus the scientific analyses are not being carried out on site, as the necessary resources are lacking. This applies in particular to the application of modern methods such as artificial intelligence and real-time analyses (also based on AstroColibri). More intensive collaboration with Theme 11 (Multi-scales data analysis & simulation) could help here.

There is a certain risk of getting bogged down in too many smaller projects, the expertise being undoubtedly available. This can happen if large-scale projects are delayed and teams therefore commit to smaller, but also long-term experiments. To this end, the IRFU long-term strategy must be discussed across a range of topics without jeopardising the strength of its broad positioning.

Presenting the topic or composition of the theme as activities relating to the transient Universe restricts strategic development is somewhat unnecessarily. An example of this is the preparation of CTAO and also the science with data from H.E.S.S.; the scientific portfolio of experiments is much broader than just understanding the transient Universe. This harbours a certain risk as to whether the available resources are used optimally and efficiently for the greatest possible scientific output.

Another weakness of the theme is that strategic developments and decisions are made dependent on whether the opportunity for significant third-party funding can be allocated, on the one hand, and whether it matches the expertise of newly recruited personnel on the other. For example, it was decided to withdraw from high-energy neutrino astronomy and to focus on the LISA project as a future activity.

Analysis of the theme's trajectory

The theme has a rich physics program with the overarching goal of achieving a better understanding of the early Universe via multi-messenger time domain astrophysics. Although there is expertise in observing all kinds of messengers, the teams have to focus the activity on a few large international projects due to resource constraints. These are currently SVOM (in transition from construction to operation) and CTA (still under construction), whereby the entire breadth of multi-messenger astrophysics is covered by the provision of important data management tools in the context of, among others, AstroColibri and phenomenological work.

The near future of the activities is strategically secured by the fact that with SVOM a unique and irreplaceable contribution is made by the IRFU teams, and with CTA for which a long-term commitment is foreseeable. The overarching work on a user-oriented service for multi-messenger astrophysics (with efficient in-house use) can also be expanded in a versatile and highly visible way.

The teams of the theme are also working on a strategy for participating in other major projects (particularly THESEUS and LISA), whereby the currently foreseeable timeline would suit them perfectly, as there are always 1-2 projects under construction and 1-2 projects in the operational and data analysis phase. Delays in international decisions naturally harbour a risk for strategic planning, but IRFU teams have sufficient expertise to be able to react flexibly and rethink local plans.

This strategy is seen as very positive and fulfils the IRFU mission to make significant contributions to large-scale and global science. However, for long-term continuity, it must be assured that there are no major breaks in the available resources, both in the scientific burden and in the development of instruments. Then the IRFU teams and their activities will constitute an irreplaceable building block in the promising future of multi-messenger physics at international level.

RECOMMENDATIONS TO THE THEME

SVOM is now in full swing with IRFU as the central hub with its SVOM Data Centre. In addition to securing resources for this centre, it is recommended to set up an in-house data analysis group dedicated to SVOM to benefit directly from the scientific harvest. Furthermore, it is recommended to strategically consider how to proceed in case of deteriorating political relations with China.

Prepare for integration and merging of CTAO related activities, i.e. closer cooperation between staff involved in the construction, in the future operation, in the gamma-ray astrophysics and the multi-messenger physics in CTAO.

Analyse and exploit to structurally strengthen the activities related to the development of services and tools for real-time multi-messenger astrophysics, eventually in cooperation with Theme 11 (Multi-Scales Data Analysis & Simulation).

The committee recommends that the proposed far-sighted strategy of participating in future projects such as THESEUS and LISA be pursued further, although the risks should be analysed in detail in terms of opportunity management and underpinned with alternative scenarios that are discussed with the IRFU management at an early stage.

The committee recommends defining in the near future a coherent approach (at least among themes 6, 7 and 8) for gravitational wave physics, based on the unique contributions that IRFU can make to gravitational wave research, how these are embedded in the structure of IRFU and how many resources are available for this. This approach should include space-based experiments such as LISA as well as ground-based observatories such as the Einstein Telescope.

Theme 9: High energy and high intensity accelerators

Name of the supervisor: Mr Jérôme Schwindling

TOPICS OF THE THEME

The teams of this theme are active on development and construction of high energy and high intensity accelerators and participate in international accelerator projects covering both the frontiers of high energy and high intensity, providing contributions of highly recognized level and quality. The team's expertise is based on two major technological pillars, low energy and high intensity injectors including radio frequency quadrupoles, and superconducting RF cavities including couplers, tuners and cryomodules. The related competences include beam dynamics in linacs and rings, beam diagnostics and controls, and accelerator installation and operation. In parallel, IRFU maintains an R&D programme in superconducting coatings, in additive-manufactured cavities and components, and is developing light ion sources, robots and AI applications to accelerators. The teams are also involved in the design of advanced accelerators as muon colliders and has a small participation in laser-plasma based systems. IRFU owns a large technological platform that is a strong asset for contributing to future projects, requiring a continuous effort in terms of development and maintenance.

CONSIDERATION OF THE RECOMMENDATIONS OF THE PREVIOUS REPORT

The last evaluation has formulated three recommendations, related to the criticality of depending on external projects, the difficulty of attracting young people on mature technologies, and the possible reduction of future large projects contributions.

The teams addressed these recommendations, but some of the criticality remains. The dependency on large international projects is acknowledged by the teams that are constantly active in international collaborations to identify and engage themselves in new projects. During the reference period, this has been partially successful. Some new projects have been or are being launched, but the critical dependency on external projects remains. An important move has been made towards projects for design, construction, and operation of compact accelerator-based neutron sources at low energies that might become an important source of activities in the medium- and long-term future. The situation remains, however, critical over the long term, depending particularly on the plans for future particle physics projects, and will have to be regularly re-evaluated.

The teams acknowledge that their R&D programme on superconducting cavities led to a valuable increase in PhD thesis. However, the total number of PhD students remains relatively small despite an outreach effort on accelerator R&D.

WORKFORCE OF THE THEME: in physical persons at 31/12/2023

Catégories de personnel	Effectifs
Professeurs et assimilés	Not applicable to the classification of IRFU personnel
Maitres de conférences et assimilés	Not applicable to the classification of IRFU personnel
Directeurs de recherche et assimilés	Not applicable to the classification of IRFU personnel
Chargés de recherche et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui à la recherche	Not applicable to the classification of IRFU personnel
Sous-total personnels permanents en activité	Not applicable to the classification of IRFU personnel
Enseignants-chercheurs et chercheurs non permanents et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui non permanents	Not applicable to the classification of IRFU personnel
Post-doctorants	Not applicable to the classification of IRFU personnel

Doctorants	7
Sous-total personnels non permanents en activité	
Total personnels	

EVALUATION

Overall assessment of the theme

The IRFU accelerator teams have developed over the past decades a strong and internationally recognized expertise on two technological pillars of modern accelerators, high intensity and low energy linear accelerators and superconducting RF cavities. For both, IRFU has the capabilities to conceive, design, build, install/commission and operate complete state-of-the-art systems including specialised components (e.g. RFQs) and ancillaries. This expertise is supported by a robust background in beam dynamics, providing the tools to address complex problems and to participate in the design of future accelerators, and by strong competences in diagnostics and controls that allow integrating all elements into complete turn-key accelerator systems. The success of the theme, proven by the participation in the most relevant accelerator projects worldwide and by a number of measurable achievements, is the result of the precise strategy of focusing on selected high-level accelerator components where IRFU can maximise its impact. A major example in this sense is the recent conversion of the IPHI test stand into a powerful state-of-the-art compact neutron accelerator source that successfully integrates the expertise of several IRFU teams and departments into what will become an operational accelerator user facility, the first on the Saclay site after the closure of Saturn.

Pursuing an accelerator R&D programme is acknowledged as a strategic issue for the theme, to remain competitive over the long term. Despite the fact that some actions are embedded in European research programmes, progress remains slow because of competition with ongoing projects. The selected R&D topics are limited, yet appropriate, in line with the theme's scientific strategy. They provide an excellent way to attract PhD students in the field. Broadening and giving them more priority would increase their impact and ensure the long-term competitiveness of IRFU for future accelerator projects.

The teams maintain and operate a powerful technological infrastructure that is a strong asset to contribute to future projects. It is appreciated by the constant effort to keep it operational and up to date, but it requires substantial financial and human resources.

Many permanent staff have recently retired or will retire before 2030. A recruitment plan to transmit the competences is announced and for the moment successful but it needs to be carefully monitored with special care to ensure the transfer of specific expertise. The fact that the recurrent budget is not sufficient to cover salaries induces a strong dependence on external resources enhancing the risk of limited recruitment and consequent loss of competences.

The IRFU contribution to GANIL operation was not presented at all at this review and could not be assessed. This might be the subject of a future and separate assessment of the GANIL facility.

The team heavily relies on internal resources for constructing the sophisticated equipment required by their partnership projects. A larger involvement of industry as a subcontractor or as technology transfer partner might enhance the impact of the IRFU accelerator teams on high technology industry and on society at large.

Strengths and possibilities linked to the context

Strengths of the theme include the recognised expertise in crucial accelerator technologies, at the core of present and future accelerator systems. Together with the experience in managing quality and with in-kind procurement aspects of large-scale contributions to international projects, these competences should make it possible for IRFU to maintain in the near future its strategy of relying on external projects to support the staff and to maintain and improve the technical infrastructure.

The world-class asset of technological platforms will remain a strong asset in this strategy. The diversification of the technologies covered by the teams ensures the resilience to adapt to any possible direction taken by the particle physics community.

New opportunities are appearing, where IRFU is exploiting its expertise and is developing its reach towards new projects and initiatives. A notable example is that of compact accelerator-based neutron sources at low energy, where IRFU accelerator teams have the potential to become a recognised world leader. The new user facility in construction on the Saclay site will provide a useful operational culture and a welcome connection with industrial users. Other applications of low-energy beams could be explored, if required, to complement present projects, in the frame of medical and industrial applications of low-energy ion beams.

Weaknesses and risks linked to the context

The dependence on external projects is a manifest medium- and long-term risk for the theme, enhanced by the fact that the recurrent budget is not sufficient to cover the salaries of permanent staff. In the present world political and scientific environment, construction of large international research infrastructure might be slowed down. This is a long-term threat for the IRFU teams.

Possible mitigation are diversification towards smaller projects and industrial or medical applications, as well as an increased focus on R&D, with the multiple goals of making the IRFU technologies more competitive, of attracting young talents, and absorbing the personnel resources that might be free from projects. The move in the direction of compact neutron sources is an excellent example of diversification towards a new field, leveraging on the competences acquired by the team. Yet it should be complemented by enhanced participation to accelerator R&D.

The staff plan and its evolution over the next five years are an important concern. It is important to continue the recruitment of expert staff to maintain and transmit the competences.

The number of PhD students is not optimized, particularly in accelerator activities. The number of DACM scientists with a HDR (Habilitation à Diriger des Recherches) is too low as well as the involvement in the teaching at the national and European JUAS accelerator level.

The risk of downsizing the technological infrastructure because of lack of resources (personnel and budget), or of leaving it slowly into obsolete, is real and mitigation need to be carefully prepared.

Analysis of the theme's trajectory

Recent contributions to large accelerator projects have strengthened the teams and their competences and have reinforced the IRFU reputation worldwide, especially in several European projects and international collaborations.

The theme is now entering a transition period, with some large-scale projects with important IRFU contributions being completed or coming soon to completions (SARAF, ESS, IFMIF-EVEDA, SPIRAL2), others starting or in the ramping-up phase (PIP-II, new GANIL injector, IFMIF-DONES, FCC, MuCOL). For the new projects, however, only for PIP-II and the new GANIL injector production of high-level technological components has been defined and agreed upon.

The engagement on the new neutron source project referred to as in the paragraphs above and in general on compact neutron sources represents a clear move towards a direction exploiting the competences in high intensity and low energy, leveraging the large past investment on IPHI, and making possible synergies and collaborations inside CEA and with other IRFU departments. The CANS activity fits very well with the expertise of the teams and might further increase its impact on science and on society. But in terms of R&D, it is mostly dedicated to high-power targets.

Other contributions are related to projects not yet approved or only in a design phase, requiring only limited resources and only partially exploiting the strong technical infrastructure available. There is a risk that the level of resources coming from external projects might decrease in the medium and long-term future, with possible consequences on the staffing and on the operation of the technological infrastructure.

The contribution to R&D for future accelerators is important but could/should be further increased; thanks to a possible reduction in project activities.

The R&D topics are relevant. However, the level of resources devoted to each topic is not evident. Studies on laser plasma technology are limited to beam optics analysis. Thin film technology and additive manufacturing are critical for the future of superconducting RF. It is not clear whether the support given to activities that are aimed at maintaining the attractiveness of IRFU is sufficient.

The long-term survival of the wide technological infrastructure supporting the activities of the theme is a clear concern. When the plans for future high-energy European accelerators are defined, it might be necessary to streamline the assembly and test capabilities as a function of the choices of the particle physics community.

RECOMMENDATIONS TO THE THEME

Broaden, intensify and speed up R&D activities on accelerator technologies that will be crucial for future accelerator projects.

Attract more PhD students, boost the number of HDR and involvement in teaching (JUAS).

Build an accurate staff plan to anticipate the retirement of critical personnel and ensure the transfer of competences.

Improve connections with industry, as subcontractors and as partners in R&D initiatives. Define and implement a knowledge transfer policy.

Continue to explore opportunities for participation in future accelerator projects, in the direction of large initiatives for particle physics as well as in the direction of industrial and medical applications, as successfully achieved for neutron production.

Maintain and improve the technological infrastructure that is a strong asset for the team. Opening infrastructure to industry and attracting some forms of European support might be directions to generate resources for its operation.

Theme 10:	High field superconducting magnets
Name of the supervisor:	Mr Clément Lorin, Mr Philippe De Antoni

TOPICS OF THE THEME

Theme 10 consists of about 60 FTE in the DACM department and 20 FTE from the DIS department of IRFU. The activity is technology oriented, with participation to a variety of projects related to superconducting magnet technology, covering the core mission of IRFU and beyond. The teams of the theme are directly involved in large national projects, e.g. Iseult and Nougat for MRI, Suprafusion for non-circular HTS magnets and LNCMI outsert magnets, where the expertise on superconducting magnet technology can be exploited. The collaboration with CERN for accelerator and detector magnets is a major pillar of the theme portfolio, lasting through decades with various projects, e.g. with FRESCA II (Nb_3Sn), Eucard (HTS) and HL quadrupole (NbTi).

CONSIDERATION OF THE RECOMMENDATIONS OF THE PREVIOUS REPORT

The previous report made five recommendations for the unit.

Two of them, "the enhanced role in education" and "test facilities", have been well addressed by the theme. The number of students has been substantially increased in the scope of the agreement with Université Paris-Saclay and the test facilities STAARQ and MATTRICS were put into operation.

The recommendation "to include superconductors R&D in the palette of projects" is only partly addressed because it is somehow considered outside the scope of the theme. This point of view is acceptable as long as IRFU maintains good links to other national and international laboratories more specialized in superconductors R&D.

The other two recommendations, "seek the possibility to define internal projects with longer life spans" and "considering a dedicated internal mechanism to select and sustain some level of R&D independently of external support" actually address the same issue (see also below), related to the negative effects of the work load fluctuations from large external projects. In this sense, it should be observed that Suprafusion, quoted in the self-assessment document as an internal project, is actually a broad national effort involving 20 institutes. Internal support for R&D remains modest, at the level of 80 k€ for PhD students and post-doc.

WORKFORCE OF THE THEME: in physical persons at 31/12/2023

Catégories de personnel	Effectifs
Professeurs et assimilés	Not applicable to the classification of IRFU personnel
Maitres de conférences et assimilés	Not applicable to the classification of IRFU personnel
Directeurs de recherche et assimilés	Not applicable to the classification of IRFU personnel
Chargés de recherche et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui à la recherche	Not applicable to the classification of IRFU personnel
Sous-total personnels permanents en activité	Not applicable to the classification of IRFU personnel
Enseignants-chercheurs et chercheurs non permanents et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui non permanents	Not applicable to the classification of IRFU personnel
Post-doctorants	Not applicable to the classification of IRFU personnel
Doctorants	2
Sous-total personnels non permanents en activité	
Total personnels	

EVALUATION

Overall assessment of the theme

The activity of this theme is based on the participation to large national and international projects of limited duration. The achievements of IRFU are commended with recognition from the international community. After 2021, many key projects like Iseult, Nougat, LNCMI outsert and Macqu were successfully completed. The fluctuation of the work load from the national and international projects calls for a dynamic adjustment of the field of activities for a number of specialized FTE, e.g. with enhanced activity on infrastructure. The discontinuity of the external funding from the large projects is bridged by internal subventions. Starting in 2024, the new project Suprafusion brings fresh funding and motivation to the teams.

IRFU maintains and operates the winding workshop, the large cryogenic infrastructure and the magnet test facilities. The fusion community did access the services of the magnet test facility for the acceptance tests of the W7-X and JT60 TF coils. These facilities are a valuable asset for the IRFU, but also need a number of dedicated FTE, independently on the fluctuations of the work load due to the discontinuity of the large projects.

Strengths and possibilities linked to the context

One strength of the theme is the technical infrastructure, mainly the cryogenic magnet test facilities and the winding workshop. Capitalizing on the investments from the JT60 magnet test, IRFU is now equipped with a large multi-purpose cryostat, named MATTRICS, completed with supercritical helium supply, a large valve box and connected high current source. MATTRICS may attract in future the interest of industry and other communities for the acceptance test of large magnets. The winding workshop has played an important role in the collaboration with CERN, both for advanced NbTi winding (Fresca II) and recently for the R&D on the Nb3Sn quadrupoles for the HL upgrade of LHC. The experience with Eucard winding (HTS Roebel cable) will be a valuable know how for the Suprafusion project.

The professional skills of the technicians and engineers are the other major strength of the theme. The expertise accumulated over decades of R&D on superconducting magnet technology is successfully transferred to the younger generation.

Weaknesses and risks linked to the context

The fluctuations of the work load due to the discontinuity of the large projects can be considered a weakness for the theme: on one hand, the motivation of the professionals follows those fluctuations and, on the other hand, the budgetary dependence on external funding is obviously a burden.

Since the former branch of Alstom closed the department for superconductors and magnets, the lack of this industrial privileged partnership, after decades of tight links, is an issue. The exchange with the industrial manufacturer is of paramount importance, for a technology department to learn and address the real open problems in the technology and for the industry to introduce and validate the R&D innovations. In the past, the loss of such a partnership has been the reason of major crises in Germany (KFK/Siemens) and in Switzerland (SIN/ABB) in the eighty and ninety years.

Analysis of the theme's trajectory

IRFU is active in the area of high field superconducting magnets. It developed an autonomous, effective, technology service centre for the whole community of high field magnets. The links with the other departments of IRFU remain weak, with the exception of DIS, whose services are instrumental.

The users of IRFU facilities and technological capabilities in the field range from the physics institutes (mainly CERN, but also Max Plank), to the medical MRI, nuclear fusion and high magnetic field institutes. The STAARQ and MATTRICS facilities may enhance in future the portfolio of users, attracting not only HEP and fusion institutes, but also industrial customers for the acceptance test of magnets.

RECOMMENDATIONS TO THE THEME

Few recommendations are meant to address the weakness while valorizing the strength of the theme:

The two magnet test facilities STAARQ and MATTRICS are now fit for operation, with important cost in terms of human resources, electricity and maintenance of the equipment. For an optimum exploitation of the facilities, it is recommended to promote the services of those facilities towards the whole community of magnet manufacturers, including industries. A leaflet with magnet specification, interface requirements and operating range could be prepared and made available on the web and conferences.

In Europe, the R&D for HTS magnets for fusion is managed for over one decade by the EUROfusion consortium of laboratories, funded by the EU. Since EUROfusion is also involved in HTS conductor development and design of HTS model coils, the committee recommends that the Suprafusion coordinator liaises with the EUROfusion WPMAG coordinator to promote the exchange and exploit project synergies.

The loss of the preferential partnership with the former branch of Alstom is perceived as a weakness for the theme. We recommend establishing new partnerships with national or international manufacturing industries, possibly with bilateral agreements to regulate intellectual property and legal aspects.

The fluctuation of the work load due to large projects with limited duration is surely an issue, both at organizational and financial level. The committee acknowledges from the replies to the previous report recommendations that a long term fully internal project and/or a solid R&D internal program may not be realistic instruments to mitigate those fluctuation effects, intrinsically linked to the organization and trajectory of the department. Nonetheless, the committee recommends addressing the work load fluctuations by a careful, long-term planning of the commitments, an internal mobility plan within CEA for at least a fraction of the technical staff, and a plan of subventions to bridge the gaps of external funding.

Theme 11: Multi-scales data analysis & simulation

Name of the supervisor: M. Shebli Anvar

TOPICS OF THE THEME

The theme serves as a cross-cutting focus across six of the seven IRFU departments. Activities are primarily organized around two main use cases: multi-scale simulations, especially in the field of astrophysics, driven by computational needs; and complex data analysis, driven by data needs.

Among the challenges addressed in this theme, a key issue is the adaptation of advances in hardware platforms, such as increases in processing units and data volumes. The aim is to achieve exascale capabilities and solve scientific computation problems arising from complex research applications and help to answer challenging scientific questions in physics. To manage the complexity associated with code, architecture, and frameworks, it is also necessary to develop adaptive and portable software components.

CONSIDERATION OF THE RECOMMENDATIONS OF THE PREVIOUS REPORT

According to the self-assessment document, all recommendations of the previous report have been addressed.

In particular, the previous committee questioned whether the hiring and salary plans were sufficient to attract well-trained computer scientists and engineers, especially given the need for significant developments in response to emerging software and hardware technologies.

The IRFU strategic response has resulted in the creation of two additional permanent high-performance computing (HPC) engineer positions. This has led to the recruitment of two highly qualified young engineers, bringing the HPC team to three permanent engineers and between two and four Ph.D. students or temporary contracts. In addition, as IRFU is the NumPEx project coordinator for software development activities, this could be an excellent opportunity to potentially recruit some other computer scientists.

WORKFORCE OF THE THEME: in physical persons at 31/12/2023

Catégories de personnel	Effectifs
Professeurs et assimilés	Not applicable to the classification of IRFU personnel
Maitres de conférences et assimilés	Not applicable to the classification of IRFU personnel
Directeurs de recherche et assimilés	Not applicable to the classification of IRFU personnel
Chargés de recherche et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui à la recherche	Not applicable to the classification of IRFU personnel
Sous-total personnels permanents en activité	Not applicable to the classification of IRFU personnel
Enseignants-chercheurs et chercheurs non permanents et assimilés	Not applicable to the classification of IRFU personnel
Personnels d'appui non permanents	Not applicable to the classification of IRFU personnel
Post-doctorants	Not applicable to the classification of IRFU personnel
Doctorants	6
Sous-total personnels non permanents en activité	
Total personnels	

EVALUATION

Overall assessment of the theme

The scientific production of this theme results from state-of-the-art research activities at the top international level. Software development is fully driven by use cases for physics issues and reaches production-level quality. Among all the achievements during the assessment period by the software development team, the following contributions, in connexion with dedicated themes, can be highlighted.

Regarding data-driven applications:

- the use of neural networks to extract information from experimental/observational data (themes 1 and 3), such as data analysis for embedded real-time software (SVOM) and machine learning for the signal and image processing algorithms (LENA);
- the design of new algorithms and methods, the introduction of AI in the context of asteroseismology (theme 5) and the application of AI methods to huge cosmological data sets (theme 7);
- the achievement of distributed applications for the massive data processing of Galactica databases (theme 6) and the storage of large data sets (theme 8) for multi-messenger time domain astrophysics;
- the development of Astro-Colibri, an open platform for time domain astrophysics.

Regarding computational-driven applications, the emphasis was placed on multiscale and multiphysics simulations using adaptive mesh refinement (AMR) on structured meshes for astrophysics, particularly within themes 5, 6, and 8. These efforts have enabled impressive results with complex AMR frameworks, demonstrating remarkable scalability on GENCI machines and other major international supercomputers. This work significantly impacts fields such as solar science, cosmology, galaxy and star formation. Notably, only a few simulation codes in France can scale effectively on Tier-1 or Tier-0 supercomputers, most being developed in CEA institutes. Although not explicitly mentioned in the self-assessment document, this work is closely associated with the "Maison de la Simulation" and the CeXA programme.

It can also be noted that emerging topics such as quantum computing, including the hybrid quantum initiatives at the TGCC, provide opportunities for IRFU to remain engaged in this area where it could play a significant role.

Strengths and possibilities linked to the context

Participation in the NumPEx PEPR for the development of the Dyablo code provides a valuable opportunity to leverage national software development efforts around this code. In addition, IRFU provides researchers with the flexibility to focus on extensive development work without the immediate pressure to publish, allowing them to devote significant effort to achieving the ambitious goals required to perform cutting-edge simulations addressing both academic and industrial research challenges.

In order to achieve production-level quality in software development, it's essential to incorporate DevOps tools for continuous integration and continuous deployment (CI/CD). These tools streamline the software development lifecycle by automating the integration, testing, and deployment processes to ensure that software updates are reliable and efficient.

The researchers of the theme have access to computing facilities in two ways, on one hand HPC clusters hosted by CEA, such as supercomputers at CEA/TGCC, on the other hand local HPC clusters for development and testing purposes before deployment and production use.

In addition, a computing committee has been established to plan and coordinate the development of the Institute's infrastructure.

Several of the permanent members are involved in teaching software engineering and signal processing at engineering schools and universities, which increases the institution's attractiveness for students.

Weaknesses and risks linked to the context

Managing the rapid evolution of high-performance computing architectures, especially as they move toward exaflop capabilities designed primarily for AI computations, presents significant challenges. This evolution involves a shift from traditional GPUs to more specialized processing units such as TPUs, which are optimized for AI tasks and often use reduced or mixed-precision computations. The CPU components themselves are evolving with the introduction of new chips with unified memory architectures that allow both CPUs and GPUs to share a single pool of memory, reducing data transfer times and improving performance.

Technical debt is a critical issue for objects that are expected to exist for the next 20 to 40 years, but the theme is aware of this challenge and understands the cost implications of rewriting code. To address this issue, IRFU plans to use DevOps and agile methodologies, together with selecting mature technologies that offer sustainability guarantees, such as those supported by Linux Foundation projects.

Although the self-assessment document highlights a concern about the competitiveness of salaries compared to the industry, this can be offset by the attractive environment offered by IRFU.

Analysis of the theme's trajectory

The trajectory is clearly exposed and consistent with the objectives of the theme, which aims to meet the needs of research projects in the different areas of physics in which IRFU is involved.

It emphasizes the tools and methods of modern software development and the challenges associated with the evolution of hardware architectures to meet the needs of complex simulations and data processing, by focusing on projects such as LISA, ATHENA and SKA.

RECOMMENDATIONS TO THE THEME

The Dyablo code has been taken over by expert computer scientists. While modern C++ is a widely used and effective language for developing new code, it requires a complex learning curve and its rapidly evolving standards can be challenging for non-computer scientists. Therefore, it's important to support physicists who will need to contribute to the code. Special attention should be paid on training, tutorials, workshops and coaching for newcomers or non-computational physicists to bring them more efficiently towards the exploitation of the Dyablo code.

The Kokkos framework may not significantly help with data distribution and task scheduling between nodes, so while it is a strategic choice due to its maturity and sustainability, it should not be the sole way for achieving exascale simulations.

It's unclear whether the SKA project is fully aligned with the astrophysics themes, but there is interesting potential that could be addressed within Theme 11, using the expertise gained from SVOM and more globally data analysis.

As this theme is a cross-cutting activity with all other IRFU themes, dissemination is an important issue. Sharing best practices in software development, such as DevOps and agile methodologies, and addressing challenges in reproducibility are recommended.

In anticipation of the rise of AI, which is becoming essential for all activities involving data analysis, it is crucial to maintain internal expertise in this area. Strengthening links with Université Paris-Saclay (Data AI cluster) around machine learning for data analysis is recommended.

It is also important to avoid fashion effects resulting from technological breakthroughs, such as big data before and now AI, and to ensure that the right tools are used efficiently for the target applications.

The partitioning of IRFU activities between themes 5, 6, 7, 8 and 11 is debatable. As mentioned in the recommendations of theme 6, science and observational aspects could be merged under one flag theme, and all aspects related to simulations and code development could be grouped under another flag theme.

CONDUCT OF THE INTERVIEWS

Dates

Start: The 9th of December 2024 at 09 am

End: The 12th of December 2024 at 01 pm

Interview conducted: on-site

INTERVIEW SCHEDULE

Lundi 09 décembre	09 h 00 - 09 h 15 Huis Clos : Réunion de préparation du comité
	09 h 15 - 09 h 20 Session plénière: présentation des membres du comité
	09 h 20 - 10 h 30 Session plénière: présentation du directeur de l'IRFU
	10 h 30 - 11 h 00 Session plénière: questions
	11 h 00 - 11 h 15 Pause-café
	11 h 15 - 12 h 30 Theme 1: Coherence tests of standard model of particle physics Présentation 45 min + 30 min de questions
	12 h 30 - 14 h 00 Déjeuner
	14 h 00 - 15 h 15 Theme 2: Structural tests of standard model Présentation 45 min + 30 min de questions
	15 h 15 - 15 h 30 Pause-café
	15 h 30 - 16 h 45 Theme 3: Dynamics of quarks and gluons Présentation 45 min + 30 min de questions
	16 h 45 - 17 h 45 Visite de plates-formes
	17 h 45 - 18 h 30 Session fermée du comité
Mardi 10 décembre	09 h 00 - 10 h 15 Theme 4: Nuclear structure and dynamics Présentation 45 min + 30 min de questions
	10 h 15 - 10 h 30 Pause café
	10 h 30 - 11 h 45 Theme 5: Stars and planetary systems Présentation 45 min + 30 min de questions
	11 h 45 - 12 h 45 Visite des plateformes du département d'astrophysique
	12 h 45 - 14 h 00 Déjeuner
	14 h 00 - 15 h 15 Theme 6: Evolution of structures, galaxies and stars Présentation 45 min + 30 min de questions
	15 h 15 - 15 h 30 Pause-café
	15 h 30 - 16 h 30 Rencontre avec les doctorants et post-doctorants
	16 h 30 - 17 h 45 Theme 7: Energy content of the universe Présentation 45 min + 30 min de questions
	17 h 45 - 18 h 30 Session fermée du comité
Mercredi 11 décembre	08 h 30 - 09 h 45 Theme 8: Exploration of transient universe Présentation 45 min + 30 min de questions
	09 h 45 - 10 h 00 Pause-café
	10 h 00 - 11 h 15 Theme 9: High energy and high intensity accelerators Présentation 45 min + 30 min de questions
	11 h 15 - 12 h 15 Rencontre avec les chercheurs
	12 h 15 - 13 h 00 Déjeuner
	13 h 00 - 14 h 00 Rencontre avec le personnel technique
	14 h 00 - 15 h 15 Theme 10: High field superconducting magnets Présentation 45 min + 30 min de questions
	15 h 15 - 15 h 30 Pause-café
	15 h 30 - 16 h 45 Theme 11: Multi-scales data analysis & simulation Présentation 45 min + 30 min de questions
	16 h 45 - 17 h 45 Session fermée du comité
	17 h 45 - 18 h 45 Réunion avec la tutelle
Jeudi 12 décembre	09 h 00 - 10 h 00 Réunion avec l'équipe de direction
	10 h 00 - 13 h 00 Session de travail du comité

GENERAL OBSERVATIONS OF THE SUPERVISORS

The institution responsible for submitting the application, which is also responsible for coordinating the response on behalf of all the research unit's supervisors, did not submit any general observations.

The Hcéres' evaluation reports are available online:
www.hceres.fr

Evaluation of Universities and Schools
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19 rue Poissonnière
75002 Paris, France
+33 1 89 97 44 00