CONTENTS

PART2

LANDSCAPE ANALYSIS - SECTION1

PHYSICAL SCIENCES & ENGINEERING

PHYSICAL SCIENCES & ENGINEERING

Research Infrastructures are integral part of the day-to-day activity of Physical Sciences & Engineering. Historically and today the PSE RIs are integrated in the way research is done in these disciplines, and major advances in knowledge are achieved by the research performed at RIs. However, the RIs are much more than research tools; they are truly *Hubs of Knowledge & Innovation* with a complete multidisciplinary approach and a systematic impact on many areas beyond Physical Sciences and Engineering.

To date there are few assessments of the socio-economic impact of RIs over their lifecycle[1,2,3]. There are even fewer studies that take into account the wider impact on society; benefits which are not directly economic, such as health, a safer and fairer society, and a cleaner environment. Indeed, the methodology for such studies is still a subject of debate. However, the PSE RIs enable a vast range of science and engineering research that has an impact on almost all the identified areas of societal challenge, including health and the aging population; cleaner energy and a greener environment; better transport and improved cities; improved communications; national and personal security.

A major challenge that confronts scientists and policymakers is the increasing cost of the tools needed for achieving progress at the frontiers. Basic research as conducted today in these areas is truly international. About 30% (in some cases much more than 50%) of the users of the large and medium sized RIs are from outside the country where the facility is located. Support for the operations of these facilities has historically been provided by the host country or region with a policy of free and open access by the international scientific community and with beam-time and observation-time allocated based upon the merit of the proposed research.

Inside the PSE domain we identify three thematic subareas: **ASTRONOMY AND ASTROPARTICLE PHYSICS, PARTICLE AND NUCLEAR PHYSICS** and **ANALYTICAL PHYSICS**. In the following, the three areas will be described, with the corresponding RIs available, and the identified gaps and challenges for the near future.

Astronomy and Astroparticle Physics is evolving over recent years towards a multi-observatory approach. This new approach is contributing to our holistic understanding of the universe and its components to an unprecedented degree. Also beneficial and deep-rooted are the interactions with **Particle Physics** through the common theoretical framework and via *multi-messenger*, multi-instruments studies, covering an extraordinary range of electromagnetic wavelengths, different particles and most recently gravitational waves. Fast data analysis, together with an early alert network system, makes possible a direct observation of the same event by multiple observatories, thus elucidating the same phenomena with complementary techniques. The convergence of the different disciplines and different messengers is providing a very fertile approach and new results, which directly impact on the understanding of the physical world, from infinitely small to extremely large scales. The Astronomy and Astroparticle Physics community involves more than 12.500 scientists[4].

Particle Physics aims not only at understanding the elementary constituents of matter, but also at building a coherent theoretical framework including all fundamental forces, which would allow us to understand the evolution of the universe from its earliest instants. Probing the limits of the Standard Model of particle physics and beyond, therefore involves understanding gravitation as well as elucidating the *Dark Sector* of the Universe: Dark Energy and Dark Matter. The tools to achieve this goal are manifold, from the highest energy particle colliders and highest intensity beams to extremely low background detectors and the observation of cosmic messengers at the interface with astrophysics and cosmology, as well as ultra-high-precision experiments at the frontier with atomic physics. Some 13.000 scientists are registered as users of CERN alone.

Nuclear Physics is the study of atomic nuclei and nuclear matter and of the fundamental forces responsible for their properties and behaviour. It aims at studying the fundamental properties of nuclei from their building blocks, protons and neutrons, and understanding the emergent complexity in terms of the strong interaction from the underlying quark and gluon and their degrees of freedom within Quantum Chromodynamics (QCD). This requires detailed knowledge of the structure of hadrons, of the nature of the residual forces between nucleons resulting from their constituents and of the limits of the existence of bound nuclei and ultimately of hadrons themselves.

The significant global effort in basic nuclear physics research involves around 13.000 scientists and support staff with funding of

1. The importance of physics to the economies of Europe
https://www.eps.org/default.aspx

2. Long-Term Sustainability of Research Infrastructures, ESFRI Scripta Vol.2, October 2017
http://www.esfri.eu/sites/default/files/u4/ESFRI_SCRIPTA_TWO_PAGES_19102017_1.pdf

3. SUSTAINABLE European Research Infrastructures
https://ec.europa.eu/research/infrastructures/pdf/swd-infrastructures_323-2017.pdf

4. This number includes only the members of the International Astronomical Union

approximately 2 billion € per year. Investment in basic science results in long-term economic benefits. Advances in nuclear physics techniques and accelerator technology have made significant contributions to national and societal priorities, including new approaches in energy, national security, industry, and medicine. The discoveries and technical advancements that result from nuclear physics research make important contributions to other scientific fields and national and societal priorities. The forefront research facilities attract and train a next generation of scientists for research and national needs.

Analytical Physics includes the fine analysis of matter by scattering of beams and by spectroscopy, the nanofabrication of complex materials and systems and the *in operando* study of their functionalities. Europe is extremely competitive in this field with several world-leader **Analytical Research Infrastructures (ARIs)** facilities including sources of photon, neutron, electron and ion beams such as **Synchrotron Radiation (SR)** storage rings, **Free-Electron Lasers (FELs)**, **Neutron Scattering (NS),** advanced **Electron Microscopes (EM)**, **Nuclear Magnetic Resonance (NMR)**, high-performance lasers (**Ultra Short Pulse and High Intensity Lasers**) and **High Magnetic Fields (HMF)**.

The size of the current user community for **Synchrotron Radiation** facilities was estimated in 2017 as at least 24.000[5]. The current user community for **Free-Electron Lasers** is in its infancy and is probably less than 1.000. The size of the current user community for **Neutron Scattering** in Europe has been estimated as over 5.577 distinct users in 2017, based on data provided by the facilities[6]. The size of the current user community for **Electron Microscopy** in the physical sciences Europe was estimated[7] as 5.000 excluding proprietary industrial users. This number is likely doubled if users in structural biology are considered because of the sudden proliferation of Cryo-EM users following technological leaps in recent years which enable unprecedented resolution. The current user community for **Ultra Short Pulse and High Intensity Lasers** in Europe mainly comes under the umbrella of the LaserLab Europe network which now undergoes its 4th edition. This has a population of about 3.500 individuals from about 50 laboratories across Europe. The **ESFRI Landmark ELI** (Extreme Light Infrastructure) offers significantly enhanced research opportunities to the global academic and industrial community of users and with the increased availability of state-of-the-art beamlines, there is a potential for the growth of the scientific community. The size of the current user community for **High Magnetic Fields** in Europe can be estimated as 2.500 users and slowly growing based on the current number of users of the **ESFRI Landmark EMFL** (European Magnetic Field Laboratory). Adding up the numbers of users above quoted, a sum of approximately 45.000, including multiple users, is obtained. To the best of our knowledge, there is no quantitative study of cross-technique use across Europe, though the estimate of cross-facility use is of the order of 10%[8] wherever there are co-located facilities – for example SR and neutron scattering facilities on the same campus.

There is a tendency to develop clusters of activity and to set up complementary facilities, both large and small in scale, around **Analytical Research Infrastructures**, notably at research campuses like in Grenoble, Hamburg, Harwell, PSI Villigen, Paris-Saclay, Trieste, Barcelona and Lund. This, in turn, attracts partnerships with universities and industries which create effective hubs for research and innovation across a very wide range of disciplines and can make very significant contributions to the local economy. In most cases, ARIs also develop technologies or products as bio-products or derivatives of their core technology development. For example, in the field of laser technologies, the following areas developed: i) remote sensing for airport security and food safety; ii) medicine and medical imaging, in particular related to cancer therapy; iii) photonic devices and new laser technologies. One of the resounding success stories is Cobalt Light Systems Ltd. an STFC spin-off company, which produces the Insight100 machine[9], a bottled liquid screener that is now being used in most airports worldwide.

This Landscape Analysis does not cover the research facilities for engineering or purely applied research as they escape the exact definition of RI, often operating as test facilities or technology demonstrators. Nevertheless, there are areas - like the cleanrooms for Nanoscience and Nano-Engineering – that support both the applied industrial end users, and fundamental research programs – e.g. in the development of emerging technologies as Artificial Intelligence, Quantum Technologies and Computing.

5. Brochure for the launch of LEAPS, November 13th 2017 https://www.leaps-initiative.eu/

6. Neutron Users in Europe. Facility based insights and scientific trends - Brightness project https://bit.ly/2uqQZpS

7. As part of a survey of pan-European EM requirements for state of the art installations within the ESTEEM2 consortium. This figure excludes the life sciences and users of standard instruments who are likely to be at least equal to this number. It is important to recognise that an increase in demand for transitional access between the ESTEEM and ESTEEM2, INFRA projects, the latter offering 3.300 user days over a four-year period indicates unsatisfied bandwidth and hence provides support for consolidated (and more efficient) infrastructures and for an overall expansion of EM provision

8. Estimates of dual-use of facilities have been made in Grenoble and at Harwell

9. Insight100 machine https://www.cobaltlight.com/products/insight100series/

ASTRONOMY AND ASTROPARTICLE PHYSICS

Astronomy and Astroparticle Physics deal with the understanding of the universe and its components: from its still not well known beginnings to its growing complexity, with the formation and evolution of galaxies, stars and planetary systems, until the emergence of life. It relies on various kinds of observations, theoretical work and modelling, and more and more on laboratory experiments. The level of precision necessary to constrain models requires high-performing space, ground-based and underground observatories, mostly built and managed through international collaboration, and exploited in synergy. Observations spread well beyond the historical optical domain, to the whole electromagnetic spectrum from radio astronomy to the observation of gamma-rays, and new messengers such as gravitational waves and neutrinos. *Multi-messenger* astronomy, with its multi-wavelength, multi-instrument studies, is the new frontier to study the evolution and present phenomena of the Universe. Underground physics investigates the rarest phenomena to discover dark matter and the nature of neutrino mass.

The main science drivers are:

- understand the origin of the universe, its main constituents and the extreme conditions it hosts;
- observe the formation of galaxies and their evolution;
- understand the formation of stars and planets;
- understand the solar system and the conditions enabling life, searching for other planetary systems in our galaxy.

The recent observation of gravitational waves is the dawn of gravitational wave astronomy, a highlight which opens a new window for observation of stellar bodies and phenomena. Exoplanetary research also builds up as an inter/multidisciplinary field where a *multi-messenger* approach – e.g. landers, sample return – is taking place.

The science drivers of Astronomy and Astroparticle Physics merge with those of Particle and Nuclear Physics, linking the physics from the infinitively large to the infinitively small, giving a holistic view of the overall Research Infrastructure investment in the Physical Sciences & Engineering field.

II CURRENT STATUS

Research in Europe in this area remains at the leading edge. The intergovernmental organisations ESO[10] (European Southern Observatory) and ESA[11] (European Space Agency) enable Europe to compete at the global level in ground and space-based astronomy. Another key factor is the strong organisation of communities at national and European levels. The ASTRONET[12] and ASPERA[13] ERA-NETs have strengthened a Europe-wide collaboration between research communities and funders and are the key players proposing strategies. ASTRONET covers research from the Sun and Solar System to the limits of the observable universe, and the ERA-NET is giving rise to a co-ordinating Consortium. The APPEC Consortium[14] coordinates Astroparticle Physics research. ASTRONET and ASPERA/APPEC continuously update comprehensive studies of all the present and future activities based on scientific goals and merit.

The ASTRONET and ASPERA/APPEC Infrastructure Roadmaps, which include ESFRI Roadmap facilities, are being implemented in spite of the serious impact of the recent financial restrictions. The suite of ground-based telescopes is delivering new science. The European Southern Observatory's Very Large Telescope (VLT)[15] is the world-standard. The ALMA[16] millimetre/sub millimetre array in the Atacama Desert (Chile), the largest such facility in the world, is in full operation. The International LOFAR Telescope (ILT)[17] and the Joint Institute for VLBI ERIC (JIVE)[18] in the European VLBI Network[19], are pathfinders for the **ESFRI Landmark SKA** (Square Kilometre Array). SKA, a global collaboration with Europe in a leading role, has established a dual location in Australia and South Africa. High-energy gamma-ray Cherenkov telescopes HESS[20] and MAGIC[21] developed the observation of TeV scale photon sources into a full-fledged astronomy. The **ESFRI Landmark ELT** (Extremely Large Telescope) – ESO's giant optical-infrared telescope – was approved in 2012 and is now under construction in Chile. The **ESFRI Landmark CTA** (Cherenkov Telescope Array) is setting up the infrastructure of its two hosting sites at ESO Paranal in Chile and at the IAC La Palma, Spain. The **ESFRI Project KM3NeT 2.0** (KM3 Neutrino Telescope 2.0) is installing the first set of strings at the two Mediterranean sites of Capo Passero (Italy) and Toulon (France), aiming at higher luminosity than the IceCube[22]. The European ground-based solar community successfully proposed the **ESFRI Project EST** (European Solar Telescope) to the 2016 update of the ESFRI Roadmap.

Two ASTRONET panels, the European Telescope Strategy Review Committee and the European Radio telescope Review Committee, respectively recommended

10. European Southern Observatory
http://www.eso.org/public/

11. European Space Agency
http://www.esa.int/ESA

12. ASTRONET
http://www.astronet-eu.org/

13. ASPERA
http://www.aspera-eu.org/

14. APPEC
http://www.appec.org/

15. European Southern Observatory's Very Large Telescope (VLT)
http://www.eso.org/public/unitedkingdom/teles-instr/paranal-observatory/vlt/

16. ALMA
http://www.almaobservatory.org/en/home/

17. LOFAR
http://www.lofar.org/

18. Joint Institute for VLBI ERIC
http://www.jive.eu/

19. European VLBI Network
http://www.evlbi.org/

20. HESS
https://www.mpi-hd.mpg.de/hfm/HESS/

21. MAGIC
https://wwwmagic.mpp.mpg.de/

22. IceCube
https://icecube.wisc.edu

to optimize the science impact and cost effectiveness of small and medium size facilities[23], and reviewed the existing European radio telescopes in the context of the **ESFRI Landmark SKA.** The optical/infrared, radio, planetary and solar communities are federated respectively by OPTICON, RADIONet, EuroPlaNet and PRE-EST, succeeding SOLARNET-I3 in 2017. The APPEC 2017-2026 resource-aware roadmap recommends a strong coordination among the EU agencies involved in Astroparticle Physics in the four main research areas of *multi-messenger* astronomy, neutrino physics, dark matter searches and cosmology (CMB, dark energy). Four European networks focus on gravitational wave antennas, underground laboratories, ultra-high energy cosmic rays and dark energy.

The global network of gravitational wave interferometers (GWIC) includes advanced VIRGO[24] (EU), advanced LIGO[25] (US) and KAGRA[26] (Japan) and the forthcoming INDIGO[27] (India); all are sharing data, analysis and publications. A European FP7 design study was carried out for a novel underground 10 km-arm interferometer concept called the Einstein Telescope. The first direct observation in September 2015 of gravitational waves from the merger of a black-hole pair at LIGO and furthermore the possibility of studying the direction of the signals thanks to joining VIRGO with LIGO in data taking, set the course for a new era of gravitational and *multi-messenger* astronomy.

The network of *underground laboratories* hosts increasingly large detectors, the Gran Sasso (Italy) being the largest equipment world-wide. The ultrahigh energy cosmic ray community is gathered in Europe around the Auger Observatory in Argentina. Finally, there is a large European ground-based dark energy community with major participation in the US-led Large Synoptic Survey Telescope (LSST)[28], which is complementary to the EU-led EUCLID[29] space mission.

Excellent science continues to emerge from space missions. Herschel[30] and Planck[31] provided truly spectacular far-infrared/sub-millimetre mapping of the cold Universe and of the cosmic microwave background. Gaia performs a 3D-image of our galaxy and of star velocities. In addition, the ESA Cosmic Vision selection process has set the scene for small, medium and large projects covering: the study of the Sun (Solar Orbiter[32], launched in 2019), of Mercure (BepiColombo[33], 2018) and of Jupiter's icy moons looking for biology markers (JUICE[34], 2022), exoplanetary studies (CHEOPS 2019, PLATO 2026, ARIEL 2028), the search for dark energy (EUCLID), the study of the hot and energetic universe (ATHENA) and the study of the gravitational wave Universe (LISA)[35], this last planned to be launched by 2034, with in addition the Exomars programme (Trace Gas Orbitor[36] 2016, robotic exploration 2020). There is also an important European participation in space missions through bi- or multilateral agreements, for instance for searching for antimatter in space (AMS on the ISS) and gamma-rays (FERMI). Europe's premier space astrophysics research is planned out into the distant future thanks to the substantial stability in funding for ESA that allows maximising returns for the agencies and structuring the community as well as industry. International collaboration is also well established, in particular on the James Webb Space Telescope (WEBB/JWST)[37] near-infrared telescope, which will be launched in 2018.

The Astronomy ESFRI & Research Infrastructure Cluster project (ASTERICS) develops the cross-cutting synergies and common challenges shared by the Astronomy and Astroparticle ESFRI RIs: the **ESFRI Landmarks ELT**, **SKA**, and **CTA**, and the **ESFRI Project KM3NeT 2.0**, with liaison building up with the **ESFRI Project EST**.

A summary of the main Research Infrastructures in Astronomy and Astroparticle Physics field is shown in **Figure 1** and ESFRI contribution is depicted in **Figure 2**.

GAPS, CHALLENGES AND FUTURE NEEDS

The programme of development of new facilities is basically on track, but timelines get longer as the cost and complexity of projects increase. One challenge is to propose projects which remain doable while at the forefront to fulfil science needs. Moreover, the funding of backend instruments for the large facilities and of data science is not always included in the Research Infrastructure cost estimate, whereas the field already feels *Big Data* challenges.

The evolution of Astronomy and Astroparticle Physics projects clearly goes towards internationalisation in the construction as well as the operation of Research Infrastructures. ALMA and the **ESFRI Landmark SKA** have been the first global astronomy infrastructures. The novel *multi-messenger* paradigm implies the observation and interpretation of transient phenomena alerts and follow up by a network of telescopes and underground or underwater/ice detectors. The first detection of gravitational waves sources by the LIGO-VIRGO Consortium led to their astrophysical interpretation and their astronomical follow-up. Interest

23. Report by the European Telescope Strategic Review Committee on Europe's 2-4 m telescopes over the decade to 2020 *http://www.astronet-eu.org/sites/default/files/plaquettet2_4m-final-2.pdf*

24. VIRGO *http://www.virgo-gw.eu/*

25. LIGO *https://www.ligo.caltech.edu/*

26. KAGRA *http://gwcenter.icrr.u-tokyo.ac.jp/en/*

27. INDIGO *http://gw-indigo.org/tiki-index.php*

28. Large Synoptic Survey Telescope *https://www.lsst.org/*

29. EUCLID *http://sci.esa.int/euclid/*

30. Herschel space mission *http://sci.esa.int/herschel/*

31. Planck space mission *https://www.cosmos.esa.int/web/planck*

32. Solar Orbiter *https://www.asi.it/en*

33. BepiColombo *http://sci.esa.int/bepicolombo/*

34. JUICE *http://sci.esa.int/juice/*

35. LISA *https://www.elisascience.org/*

36. Trace Gas Orbiter *http://exploration.esa.int/mars/46475-trace-gas-orbiter/*

37. WEBB/JWST *https://www.jwst.nasa.gov/*

in gravitational-wave astroparticle/astrophysics is growing fast with the approved ESA LISA mission, the Pulsar Timing Arrays with LOFAR and in the future with **ESFRI Landmark SKA**, and developments of the Einstein Telescope.

A key topic for the future is the search for early life signature in exoplanet studies, the expansion of astrochemistry to this field and the development of astrobiology. ASTRONET and APPEC representing the major EU agencies/institutions operating in Astrophysics and Astroparticle Physics respectively have large overlaps in the Research Infrastructures they deal with. They are establishing contacts trying to develop a more solid coordination to fully exploit the synergy present in their roadmap visions.

The ASTERICS Cluster supports and accelerate the implementation of the ESFRI telescopes, to enhance their performances beyond the state-of-the-art, and to see them interoperating as an integrated, multi-wavelength and *multi-messenger* facility. It demonstrates the power of building synergies and common endeavours between the ESFRI RIs, and the necessity to establish a framework to continue to do so beyond the current Cluster projects.

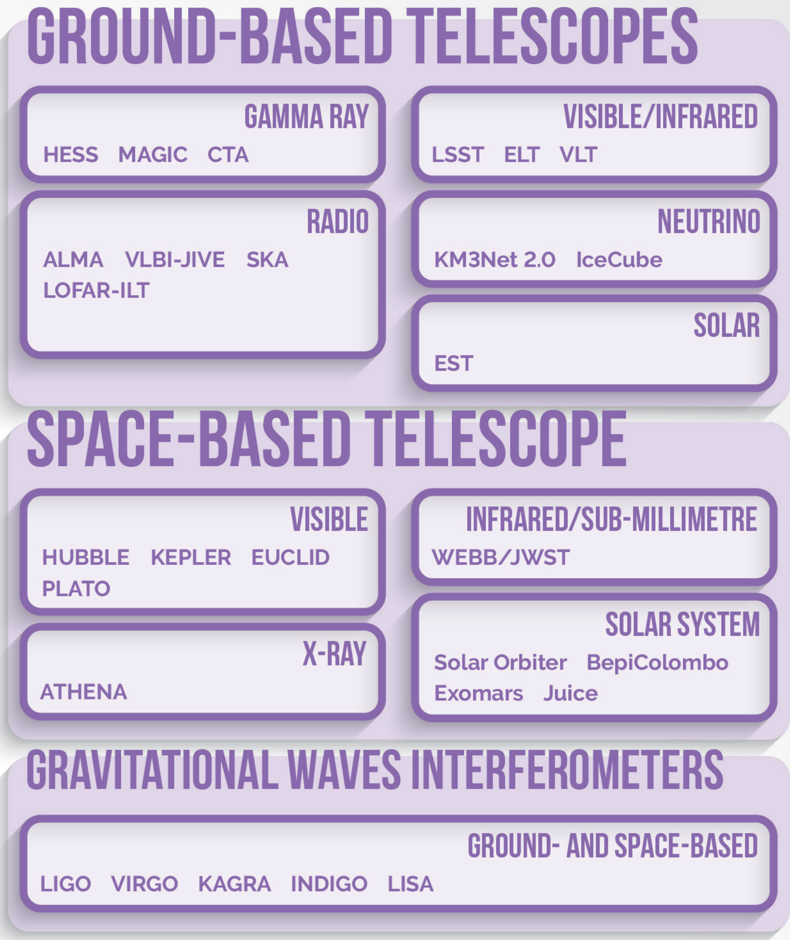

FIGURE 1.
Main Research Infrastructures in Astronomy and Astroparticle Physics

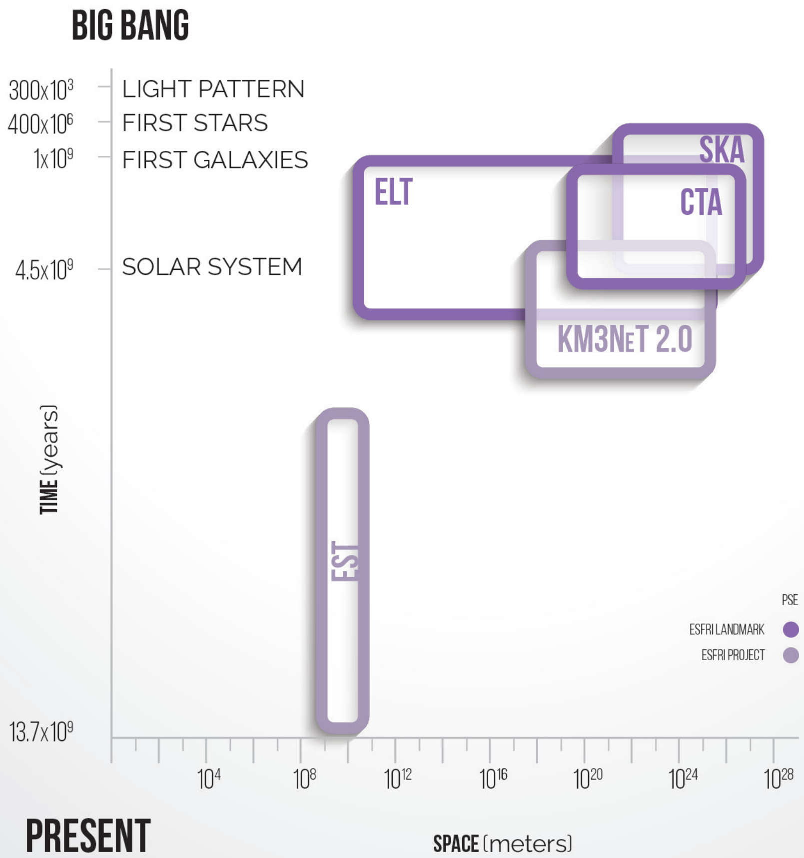

FIGURE 2.
Space and time domain of investigation of ESFRI Projects and Landmarks in Astronomy and Astroparticle Physics

PARTICLE AND NUCLEAR PHYSICS

During the last 10 years, major discoveries have shaped our vision of the building blocks of matter, their properties, their interactions and their role in the evolution of the Universe. With the discovery of the Higgs boson, the Standard Model of **Particle Physics** provides an internally consistent picture of the known elementary particles which is nevertheless known to be incomplete, since it leaves several major questions unanswered. The presence of Dark Matter in current cosmological models, and the fact that gravity is not included in the Standard Model, are two examples which push searches for physics beyond the Standard Model.

New physics models which address these questions can, for example, lead to deviations Standard Model in consistency tests or in the properties of the Higgs boson at the sub per cent level, and/or predict new particles or forces which manifest at the higher energies than currently accessible. Reaching high precision and extending the energy range are therefore crucial.

Searches for Dark Matter continue at colliders, direct detection experiment and via indirect observation via astrophysics. So far none of these have revealed any signature of new particles, though theoretical as well as experimental efforts are continuously pushing the limits. Other promising areas to look for deviations from the Standard Model include high precision measurements in flavour physics in the quark and charged lepton sectors, and the search of broken symmetries in the neutrino sector.

A key goal for **Nuclear Physics** is to develop a comprehensive understanding and a predictive theory of complex nuclei. Worldwide, this goal has driven the development of various cutting edge facilities for experiments with short-lived rare isotopes in order to provide data and discover new phenomena against which theoretical predictions have to be tested. Rare isotope beams (RIB) are obtained by complementary techniques, either through the isotope-separation-on-line (ISOL) process or through in-flight production. Such beams will allow for nuclear physics research studies aiming at answering several fundamental questions related to the phases of strongly interacting matter and their role in astrophysics, the nature of the strong force that binds protons and neutrons into stable and rare isotopes, the nature of neutron stars and dense matter, the nuclear reactions that drive stars and stellar explosions. Nuclear structure and dynamics have not only reached the discovery frontier, but are also entering into a high precision frontier with higher beam intensities and purity, along with better efficiency and sensitivity of instruments, in order to focus on essential observables to validate and guide our theoretical developments.

CURRENT STATUS

The current Particle Physics landscape is guided by the 2013 European Strategy for Particle Physics (ESPP)[38], which has been closely followed providing a coherent and broad scientific programme. The Large Hadron Collider (LHC) at CERN[39] is the major infrastructure for particle physics, with more than 7.000 physicists working on its different experiments. By the end of 2018, the LHC is in its second running period and will have accumulated an integrated luminosity of 150 fb^{-1}, corresponding to acquiring the data of roughly 10^{15} collisions and a stored data volume well in excess of 250 PB. In 2019-2020 a long shutdown is foreseen with major detector upgrades of the LHC experiments. It is foreseen to accumulate another 150 fb^{-1} in this configuration until the high-luminosity phase of the LHC will start around 2025. The **ESFRI Landmark HL-LHC** (High-Luminosity Large Hadron Collider) requires an upgrade of the accelerator complex, which has already started, and also refurbishment of the ATLAS and CMS detectors in order to maximise their scientific output in a much harsher environment.

In the field of flavour physics, the measurements provided by the LHCb experiment will be complemented and cross-checked by the results from the BELLE-2 experiments at the SuperKEKB[40] collider at KEK in Japan. Data taking of this experiment will start in 2019 and use rather low energy electron-positron beams yet at the highest intensities with the aim to accumulate an integrated luminosity of 50 ab^{-1}.

The CERN neutrino platform is a framework that allows European physicists to work on neutrino detector development. In this context, collaboration is ongoing with the next generation long baseline accelerator-based neutrino experiments: DUNE in the US (Fermi National Accelerator Laboratory FNAL[41] and Sanford Underground Research Facility[42]) and Hyper-Kamiokande[43] in Japan.

These experiments with increased beam intensities, and improved detectors, will allow unprecedented precision in measurements of neutrino oscillations and CP violation. Detector R&D as well as prototype construction for these experiments is ongoing. Accelerator based neutrino experiments are complemented by the upcoming reactor-based experiment, JUNO located in China, and measurements with atmospheric neutrinos by the ORCA-site of the **ESFRI Project KM3NeT 2.0** collaboration. Other neutrino properties are measured in Europe by smaller infrastructures, such as KATRIN at KIT for aiming at a direct neutrino

38. European Strategy for Particle Physics (ESPP)
https://cds.cern.ch/record/1567258/files/esc-e-106.pdf

39. HL-LHC
https://home.cern/topics/high-luminosity-lhc

40. SuperKEKB
http://www-superkekb.kek.jp/index.html

41. Fermi National Accelerator Laboratory (FNAL)
http://www.fnal.gov/

42. Sanford Underground Research Facility
https://sanfordlab.org

43. Hyper-Kamiokande
http://www.hyperk.org

mass measurement, and GERDA, CUORE at LNGS or SuperNemo (LSM) for determining the Dirac or Majorana nature of neutrino. European particle physicists are also pursuing precision measurements in the charged-lepton sector, at PSI and at infrastructures in other regions (US, Japan).

Complementing the searches for new physics at the LHC, experiments directly searching for Dark Matter based on various techniques such as liquid noble gas or cryogenic detectors are hosted in underground laboratories. The most stringent limits are currently provided by the XENON collaboration (LNGS), with developments ongoing on large liquid Argon based detectors (DARKSIDE) and low mass searches with cryogenic detectors.

The first generation of radioactive beam (RIB) facilities based on the complementary methods of, in flight separation (GANIL and GSI) and the ISOL approach (ISOLDE and SPIRAL1) have enabled tremendous progress in the study of exotic nuclei to be made. Both in-flight separation and the ISOL approach, combined with different post-processing of the radioactive nuclei, will form the pillars of the RIB facility network in Europe.

Major advances in the field are expected to come through the studies of extended reach in proton-to-neutron ratio of new or upgraded facilities, including the Radioactive Isotope Beam Factory (RIBF) at Rikagaku Kenkyusho (RIKEN), the **ESFRI Landmark FAIR** (Facility for Antiproton and Ion Research) at Darmstadt, the HIE-ISOLDE facility at CERN, the **ESFRI Landmark SPIRAL2** (Système de Production d'Ions Radioactifs en Ligne de 2e génération) at Grand Accelerateur National D'ions Lourds (GANIL), the facility for the Study and Production of Exotic Species (SPES) at INFN-Legnaro, the Isotope Separation and Acceleration II (ISACII) at TRIUMF, and the Facility for Rare Isotope Beams (FRIB, USA) with capabilities for fast, stopped, and unique reaccelerated beams. All these facilities provide or will provide new and important insights into the structure of nuclei and are expected to discover new phenomena that will lead to major progress towards a unified description of nuclei. Other accelerator-based probes are also important for nuclear physics research in Europe. The ELI-NP (Extreme Light Infrastructure - Nuclear Physics) facility is one of the three pillars of the pan-European **ESFRI Landmark ELI** aiming at the use of extreme electromagnetic fields for nuclear physics research.

Investigation of nuclei produced at the upcoming nuclear physics research facilities requires development of state-of-the-art detectors and detection techniques. The Advanced Gamma Tracking Array (AGATA)[44] represents a revolution in the way gamma-ray spectroscopy is performed and it will have a wide range of uses in nuclear physics from studying how elements are synthesised in stars to the understanding of the underlying shell structure of the newly discovered super-heavy elements. The basic technology of the array will also bring developments in medical imaging and diagnostic machines that produce three-dimensional images of people's bodies, providing information about the functioning of internal organs and detecting disease and tumours.

The production of exotic nuclei is closely linked to the availability of separators and spectrometers in order to select and identify the nuclei or reactions of interest. Addressing these objectives is a driving force for existing or future facilities, such as the Japan Proton Accelerator Research Complex (J-PARC), the international **ESFRI Landmark FAIR** at Darmstadt, the 12 GeV Continuous Electron Beam Accelerator Facility (CEBAF) Upgrade at the Jefferson Lab, the Mainz Microtron (MAMI), A Large Ion Collider Experiment (ALICE) at CERN, and RHIC II at Brookhaven National Laboratory (BNL), the Nuclotron-based Ion Collider fAcility (NICA) or The Super Heavy Element Factory (SHE Factory) at the Joint Institute for Nuclear Research (JINR) in Dubna (Russia).

A summary of the main Research Infrastructures in Particle and Nuclear Physics field is shown in **Figure 3** and ESFRI contribution is depicted in **Figure 4**.

44. Advanced Gamma Tracking Array (AGATA) *https://www.agata.org/*

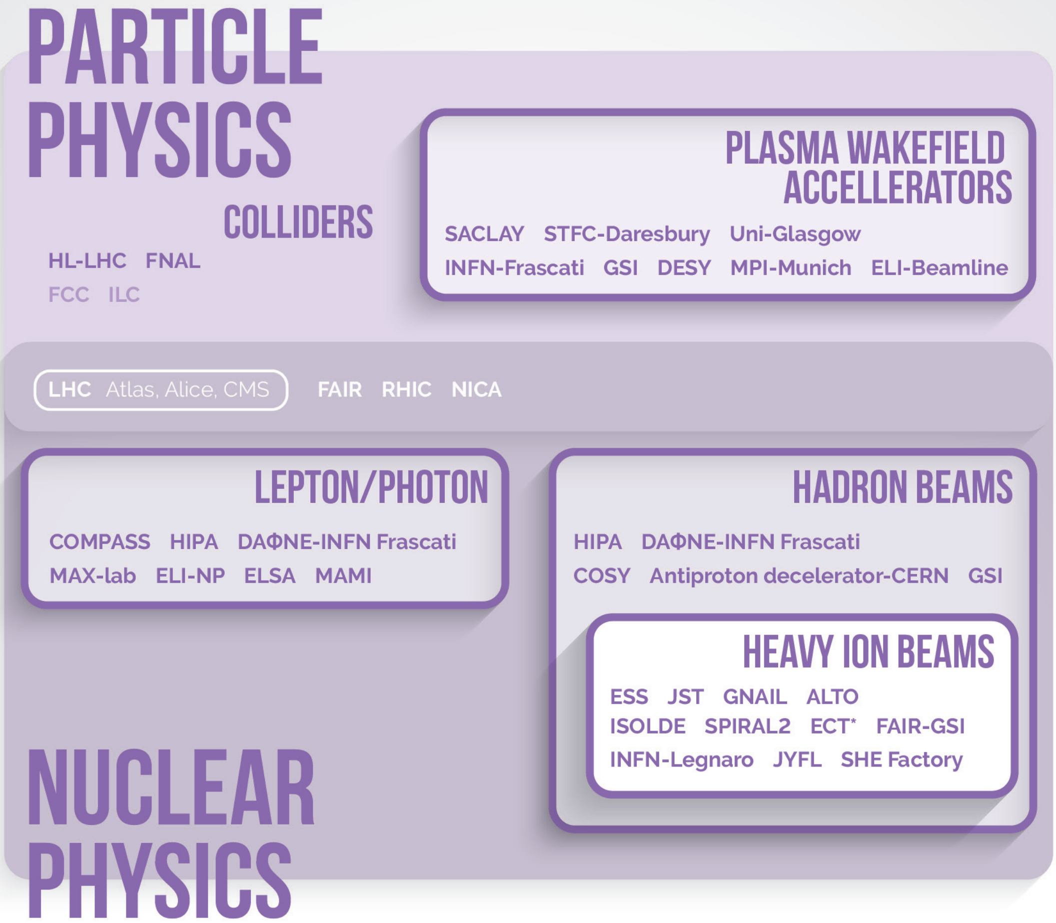

FIGURE 3.
Major Research Infrastructures in Particle and Nuclear Physics

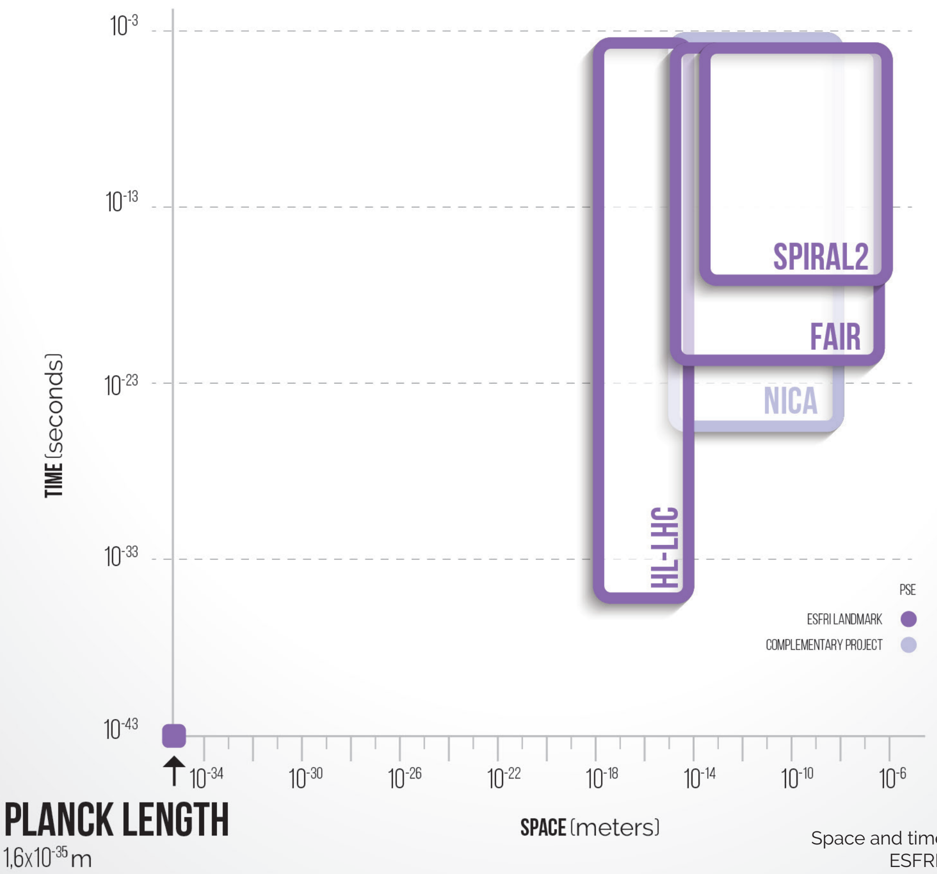

FIGURE 4.
Space and time domain of investigation of ESFRI Projects and Landmarks in Particle and Nuclear Physics

GAPS, CHALLENGES AND FUTURE NEEDS

For the near term future, the HL-LHC will be the main particle physics accelerator infrastructure, allowing detailed study of the Higgs sector and searches for new physics with 3000 fb^{-1} of data expected for ATLAS and CMS by 2035. On a similar timescale an International Linear Collider (ILC)[45] providing electron-positron collisions at a few hundred GeV energy, is a possible project to be hosted in Japan as a worldwide international collaboration. This would allow important studies of the Higgs sector and other precision measurements complementary to the HL-LHC. The ILC has long been on the strategic list of projects foreseen in particle physics, and a signal from the Japanese community indicating whether or not Japan would host such a project is expected by the end of 2018.

Further future projects would address the two main requirements for particle physics: an increase in precision and in energy. Several initiatives in accelerator R&D are addressing these challenges. In order to reach higher energies for an electron-positron linear collider, R&D for the CLIC concept using beam driven acceleration has been pursued at CERN initially aiming at energies in the multi-TeV range. However, the highest reach in energy is obtained from proton colliders, where the big challenge is the development of high field magnets, currently part of an ambitious R&D programme. Conceptual studies for a 100 km collider with about 100 TeV collision energy – the Future Circular Collider Study (FCC)[46] are underway at CERN. Such a collider would open a new window on searches for new physics and allow a conclusive study of the Higgs self-coupling. A possible stepping stone could be to install the required high field magnets in the LHC tunnel to double the LHC collision energy (HE-LHC), or to have an electron-positron collider in the FCC tunnel (FCC-ee), both of which are included in the FCC studies. There may also be interesting options to combine these technologies to collide electrons with protons, which may provide significant improvement in Higgs coupling measurements. Beyond these studies, innovative R&D programmes are ongoing on the concept of laser-plasma acceleration. Several techniques are studied in major European laboratories (Germany, Italy, UK, France and Portugal) and through the EUPRAXIA[47] design study as well as through the AWAKE[48] project at CERN.

Given the lack of theoretical guidance on where new physics could be realized, it is important to, as much as possible, cover all options. A new Physics Beyond Colliders[49] initiative is looking at ways of profiting from the CERN infrastructure and expertise to leave no stone unturned in the search for new physics. For example, studies include searches for axion-like particles in beam dump based experiments benefitting from the upgrade of the LHC injectors. By the end of 2018 documents on all the above projects will be available for the next ESPP discussion, from which a set of recommendations will be released in 2020 to define the strategy for particle physics research for the proceeding 5-10 years.

For Nuclear Physics on a long term perspective a novel ISOL facility in Europe (EURISOL) is needed, which will provide wide range of beams with much higher intensities compared to what is available at present. Meanwhile, by integrating the ongoing efforts and developments at the major ISOL facilities of HIE-ISOLDE, SPES and SPIRAL2, the planned ISOL@MYRRHA facility, and the existing JYFL and ALTO and COPIN facilities and the planned ELI-IGISOL facility an advantage should be taken use the synergies and complementarities between them and build a programme of research to bridge the gap between present facilities and ultimate EURISOL facility.

Based on the collaboration between nuclear physicists and plasma physicists, the ELI project will develop laser–plasma electron accelerators, based on the wakefield principle, and ion beams accelerators. Such devices have the potential to accelerate a range of particle and ion species in table-top distances. These innovative acceleration methods will open new perspectives for a range of applications such as: more efficient production of radioisotopes required for nuclear medicine and beams for testing the latest designs of sensors for use in medical imaging, new methods for identification and remote characterization of nuclear materials with applications in homeland security and nuclear material management, testing of materials for space science.

Research and development programmes, are being pursued to investigate the concept of precision storage rings to search for charged particle electric dipole moments (EDM), based on the ongoing studies at COSY; the design of a polariser ring to produce high intensity polarized antiproton beams as one upgrade option for HESR at FAIR; the implementation of sympathetic laser cooling techniques to cool systems like the proton, antiproton and highly charged ions to temperatures as low as a few mK; the design of advanced high intensity lasers for precision spectroscopy of exotic atoms, such as antihydrogen, muonic hydrogen, pionic helium, and muonium.

45. International Linear Collider
http://www.linearcollider.org/

46. Future Circular Collider Study
https://fcc.web.cern.ch/Pages/default.aspx

47. EUPRAXIA
http://www.eupraxia-project.eu/

48. AWAKE
https://cds.cern.ch/record/2221183/files/SPSC-SR-194.pdf

49. Physics Beyond Colliders
http://pbc.web.cern.ch/

ANALYTICAL PHYSICS

Analytical Research Infrastructures primarily comprise powerful sources of photon or particle beams. Light sources based on electron accelerators with storage rings for **Synchrotron Radiation** or **Free-Electron Lasers** provide brilliant soft to hard X-ray beams enabling nanoprobes of the structure and chemical composition of materials, including trace analysis down to ppb concentration, over many length scales – from atomic to macroscopic (10^{-10} - 10^{-1} m) – and time scales – from femtoseconds (fs, 10^{-15} s for FELs) or picoseconds (ps, 10^{-12} s for SR) to milliseconds (ms, 10^{-3} s) or steady states. **Neutron Scattering** sources based on proton accelerators or nuclear reactors provide unique and complementary probes of the structure of materials, particularly for light elements such as H and subtle magnetism, and lower energy scales for slow dynamics – typically ~µs. Moreover, the neutrons constitute, because of their high penetration power, a single probe for analysis on large volumes, or non-destructively on small internal volumes in an industrial piece for example.

The broadly distributed laser spectroscopy, high resolution **Electron Microscopy** and **High Magnetic Field** facilities also operate as ARIs. EM complements SR, FELs and NS, probing down to 50 picometers (pm, 10^{-12} m) spatial resolutions with element specificity, comparable energy resolution (10 meV or less) and temporal resolutions that can approach 10 fs. **Laser RIs** probe or manipulate matter with ultra-short or ultra-high intensity pulses from ~ 100 attoseconds (as, 10^{-18} s) to 100 fs with millijoule (mJ) to tens of joule (J) energies, or cover the complementary time-energy region up to 10 kilojoule (kJ) and 10 nanosecond (ns, 10^{-9} s). Materials may also be manipulated using HMFs to provide unique insights into electronic and magnetic phenomena.

The very broad range of analytic capabilities provided by ARIs provides an equally broad range of drivers across many areas of fundamental and applied science: structure and function of biological macromolecules implicated in disease and therapy; materials for cleaner, greener transport, energy and chemical synthesis; complex electronic and magnetic materials, for next generation ICT; synthesis and performance of materials during manufacture and under *operando* conditions; environmental systems and planetary science; and climate, natural and cultural heritage artefacts.

Integration of European ARIs is occurring at different levels, impacting materials science and nanoscience both for fundamental research and for innovation: the CERIC-ERIC[50] is a distributed RI providing access to fine analysis with complementary methods – electrons, neutrons, X-rays, synchrotron-light; the EU IA Initiative NFFA-Europe[51] offers integrated access to nano-foundry, characterization, theory and fine analysis at major European facilities and research institutions.

II CURRENT STATUS

SYNCHROTRON RADIATION AND FREE ELECTRON LASER FACILITIES

There are currently twelve SR facilities and six FELs open for transnational access across Europe (**Table 1** and **Table 2**). Among SR facilities most have storage ring energies of 3 GeV and are among the best in class in the world – while the **ESFRI Landmark ESRF EBS** (European Synchrotron Radiation Facility Extremely Brilliant Source) have helped maintain it as best in class of any SR facility in the world and the 6 GeV facility PETRA III has also undergone extensive upgrades[52]. Most recently, Europe has seen first operations of the MAX IV Facility[53] based on novel, disruptive MultiBend Achromats (MBA) technology for the storage ring that will offer unprecedented brightness and coherence. The **ESFRI Landmark ESRF EBS** will provide 100-fold increase in brilliance and coherence – significantly closer to the physical (diffraction) limit for hard X-rays – by 2019 through a MBA upgrade, several other national facilities also plan MBA upgrades in the period 2020-2025. Complementary improvements in detector technology have also been transformative, while accelerated throughput and increased remote access in techniques such as crystallography, and construction of more beamlines at some national facilities helps meet the increasing demand for access.

50. Central European Research Infrastructure Consortium CERIC ERIC
http://www.ceric-eric.eu/

51. NFFA-Europe
http://nffa.eu

52. PETRA
http://photon-science.desy.de/facilities/petra_iii/index_eng.html

53. MAX IV
https://www.maxiv.lu.se/

FACILITY	LOCATION	ELECTRON ENERGY (GeV)	EMITTANCE (nm rad)	FULLY SCHEDULED BEAMLINES (CONSTRUCTION/COMMISSIONING)	START OF USER OPERATIONS
ESRF (EBS)	GRENOBLE (FR)	6	4 (0.13)	30+14 CRGS*	1994 (2020)
PETRA III	HAMBURG (DE)	6	1.1	16 (24)	2010
ALBA	BARCELONA (ES)	3	3.6	7	2012
DIAMOND	HARWELL (UK)	3	2.7	31 (33)	2007
MAX IV	LUND (SE)	3	0.34	16 (29)	2016
		1.5	9	0 (5)	2016
SOLEIL	ST. AUBIN (FR)	2.75	3.74	29	2008
SWISS LIGHT SOURCE	PSI, VILLIGEN (CH)	2.4	4.4	16	2001
ELETTRA	TRIESTE (IT)	2.0/2.4	7.0/9.7	26 (2)	1994
BESSY II	BERLIN (DE)	1.7	6.4	47 (31)	1998
SOLARIS	CRACOW (PL)	1.5	6	2	2018
ASTRID2	AARHUS (DK)	0.58	12	10	2014
MLS	BERLIN (DE)	0.24-0.6	100	11	2008

*Collaborating Research Groups managing quota of access

TABLE 1.
Summary of European SR facilities

FACILITY	FELS LINES OPERATING IN PARALLEL	LOCATION	START USER OPERATION	ELECTRON ENERGY	PHOTON ENERGY	PULSE PROPERTIES	NUMBER OF END STATIONS
European XFEL	SASE-1 SASE-2 SASE-3	HAMBURG / SCHENEFELD, GERMANY	2017 2018 2018	8.5-17.5 GeV	3.0 to >20 keV 3.0 to >20 keV 0.25-3.0 keV	1-100 fs 10x2.700 pulse/s	2 2 2
SwissFEL	ARAMIS ATHOS	VILLIGEN, SWITZERLAND	2018 2020	2.1-5.8 GeV	4.0-15 keV 0.25-2.0 keV	5-100 fs 100 Hz	2 2
FERMI	FERMI-1 FERMI-2	TRIESTE, ITALY	2012 2016	1.5-1.8 GeV	15-90 eV 80-400 eV	20-90 fs 10-50 Hz	5
FLASH	FLASH FLASH-2	HAMBURG, GERMANY	2005 2016	1.25 GeV	30-300 eV 30-300 eV	20-150 fs 10x800 pulses/s	4 3
CLIO	CLIO	PARIS, FRANCE	1993	40 MeV	10-400 meV	0.5-5 ps 60 MHz pulsed: 25 Hz	
ELBE	FELBE TELBE	DRESDEN, GERMANY	2005 2016	40 MeV	0.5-250 meV	0.5-30 ps 13 MHz cw	7 1
FELIX	FELIX 1/2 FLARE FELICE	NIJMEGEN, NETHERLANDS	1993 2013 2007	15-50 MeV 10-15 MeV 15-50 MeV	8-400 meV 0.8-12 meV 12-250 meV	0.5-200 ps 1/3 GHz pulsed: 20 Hz	12 4 2
TARLA		ANKARA, TURKEY	2019	40 MeV	5-400 meV	0.5-30 ps 13 MHz cw	

TABLE 2.
Summary of European FELs, in operation or under construction

The **ESFRI Landmark European XFEL** (European X-Ray Free-Electron Laser) and SwissFEL[54] are hard X-ray FEL facilities that saw their first experiments in 2017, complementing a suite of complementary IR, UV or soft X-ray FEL user facilities already in operation. The TARLA facility is being built in Turkey and further projects are planned (MAX IV-FEL, POLFEL).

CALIPSOplus[55] supports co-ordinating activity for SR and FEL facilities, overlapping with the remit of the European Cluster of Advanced Laser Light Sources (EUCALL)[56]. The League of European Accelerator-based Photon Sources (LEAPS)[57] co-ordinates activity for SR and FEL facilities, FEL activities join forces in the consortium FELs of Europe[58] and the EC funded the PaNdata[59] initiative for integrated data infrastructure for European photon and neutron facilities, and for the future EOSC is under discussion.

NEUTRON SCATTERING FACILITIES

Thirteen NS facilities operate in Europe, comprising two world-leading sources – the **ESFRI Landmark ILL** (Institut Max von Laue-Paul Langevin), and the accelerator-based ISIS neutron and muon Facility[60] – and an array of high quality medium flux facilities (**Table 3**). This landscape will change greatly in the next decade: the future neutron source for Europe, the **ESFRI Landmark European Spallation Source ERIC** begins its user program on world-leading instruments initially planned for 2023 while two reactor-based facilities – BER-II[61] and Orphée-LLB[62] – will stop in 2019. ILL whose current agreement between the partners expires in 2023, is one of the key facilities to maintain at a very high level the European community of neutron scientists and users, especially before ESS reaches its nominal operation. These evolutions of the European neutron landscape will lead to a significant shortfall in the provision of neutron facilities relative to needs from the start of the next decade[63]. EC currently supports such facilities, including integrating activity, through SINE2020[64].

FACILITY	LOCATION	SOURCE	POWER (MW)	FULLY SCHEDULED INSTRUMENTS	START (END) USER OPERATIONS
ILL	GRENOBLE (FR)	REACTOR	57	30+10 CRGs*	1971
ISIS	HARWELL (UK)	SPALLATION	0.2	21+10 CRGs*	1984
LLB	SACLAY (FR)	REACTOR	14	21	1981 (2020)
FRM-II (MLZ)	GARCHING (DE)	REACTOR	20	25	2004
BER-II	BERLIN (DE)	REACTOR	10	10	1973 (2019)
SINQ	VILLIGEN (CH)	SPALLATION	1	13	1996
JEEP II	KJELLER (NO)	REACTOR	2	2	1967
REZ	REZ (CZ)	REACTOR	10	8	1957
BNC	BUDAPEST (HU)	REACTOR	10	15	1959
DELFT	DELFT (NL)	REACTOR	2	4	1963
SACAVEM	SACAVEM (PT)	REACTOR	1	3	1961 (2016)
VIENNA	VIENNA (AT)	REACTOR	0.25	4 CRGs*	1962
ESS	LUND (SE)	SPALLATION	5	15**	2023

* Collaborating Research Groups managing quota of access
** Instruments under design and construction to be operational in the period 2022-2028

TABLE 3.
Summary of European Neutron Scattering facilities

54. SwissFEL
https://www.psi.ch/swissfel/

55. CALIPSOplus
http://www.calipsoplus.eu/

56. EUCALL
https://www.eucall.eu/

57. LEAPS
https://leaps.desy.de/

58. FELs of Europe
https://www.fels-of-europe.eu/

59. PaNdata
http://pan-data.eu/

60. ISIS Muon and Neutron Source
https://www.isis.stfc.ac.uk/Pages/home.aspx

61. Research Reactor BER II
https://www.helmholtz-berlin.de/quellen/ber/ber2/index_en.html

62. Orphée-LLB
http://www-llb.cea.fr/en/Web/hpr_web/HPRWEB1.php

63. Neutron scattering facilities in Europe - Present status and future perspectives Author. ESFRI Physical Sciences and Engineering Strategy Working Group - Neutron Landscape Group, ESFRI Scripta Volume 1, 2016
http://www.esfri.eu/sites/default/files/u4/NGL_CombinedReport_230816_Complete%20document_0209-1.pdf

64. ENSA Brochure, 2017
https://www.sine2020.eu/news-and-media/ensa-brochure---second-edition.html

ELECTRON MICROSCOPY FACILITIES

About 100 mid- to high-end EM instruments operate in Europe (most of which include aberration correction of the probe forming or imaging optics). From these 15 leading laboratories and some SMEs form a networked infrastructure, ESTEEM2 (FP7)[65], to be replaced by ESTEEM3 (H2020). An EU Design Study (DREAM) to explore the creation of a pan-European Research Infrastructure for advanced EM at a scale similar to SR and Neutron facilities is being planned, including two of the highest spatial resolution microscopes in the world (at Juelich[66] and Harwell[67,68]) and several instruments capable of providing sub 10 meV energy resolution (Daresbury[69] and Orsay[70]). The recent development of direct electron detectors has helped to revolutionise the use of cryo-EM in structural biology, with an exponential growth in installations that increasingly complement X-ray protein crystallography, and in the physical sciences through faster frame-rates and significantly improved detector resolution.

HIGH PERFORMANCE LASERS

Laser RIs are distributed across Europe with user access and joint R&D coordinated mainly through the EU integrated Initiative LaserLab IV (LLIV)[71] with 33 organisations from 16 countries and also part of EUCALL. The **ESFRI Landmark ELI**, which aims to host the highest performance laser systems worldwide, is currently developing at three sites with complementary capability to each other and the rest of LLIV: the ELI-ALPS[72] pillar combines USP and UHI at very high repetition rates; the ELI Beamlines pillar[73] will provide ultra-short secondary radiation (X and γ-rays) and particle (electrons, ions) sources; ELI-Nuclear Physics[74] offers a unique combination of the most powerful laser sources worldwide (2 x 10 PW) with a fully tuneable γ-ray source (up to 19.5 MeV).

HIGH MAGNETIC FIELDS

All high magnetic field activities in Europe are organised through the **ESFRI Landmark EMFL** facilities, with a common user access program, outreach, training and technical developments. Maximum field strengths are increasing, with two hybrid magnets designed to exceed 43 Tesla (T) field, under commissioning in 2018 (Grenoble and Nijmegen) while in Toulouse, a semi-destructive pulsed field installation now offers fields of 100-200 T. All HMF facilities have been either fully renewed since 2000 or have had major upgrades and are internationally competitive. Two of them are directly coupled to a THz FEL (Nijmegen and Dresden), allowing unique joint operation.

GENERAL

European activity should also be considered as part of a network of global partnerships, both among our nearest neighbours (for example Russia, which has a number of existing and planned facilities available for international users such as the IBR-2 reactor[75] and the support of the Commision through the Cremlin project[76], as well as the middle East with initiatives such as SESAME[77]).

A summary of the main Analytical Research facilities representing the Analytical Physics Landscape is reported in **Figure 5** and ESFRI contribution in **Figure 6**.

65. ESTEEM 2 *http://esteem2.eu/*

66. ER-C *http://www.er-c.org/centre/centre.htm*

67. Harwell ePSIC *http://www.diamond.ac.uk/Science/Integrated-facilities/ePSIC.html*

68. Harwell eBIC *http://www.diamond.ac.uk/Science/Integrated-facilities/eBIC.html*

69. SuperSTEM-Daresbury *http://www.superstem.com/*

70. LPS-Orsay *http://www.lps.u-psud.fr*

71. LASERLAB *https://www.laserlab-europe.eu/*

72. ELI-ALPS *https://www.eli-hu.hu*

73. ELI-BEAMS *https://www.eli-beams.eu*

74. ELI-Nuclear Physics *http://www.eli-np.ro/*

75. IBR-2 reactor *http://ibr-2.jinr.ru/*

76. Cremlin project *https://www.cremlin.eu/project/*

77. SESAME *http://www.sesame.org.jo/sesame/*

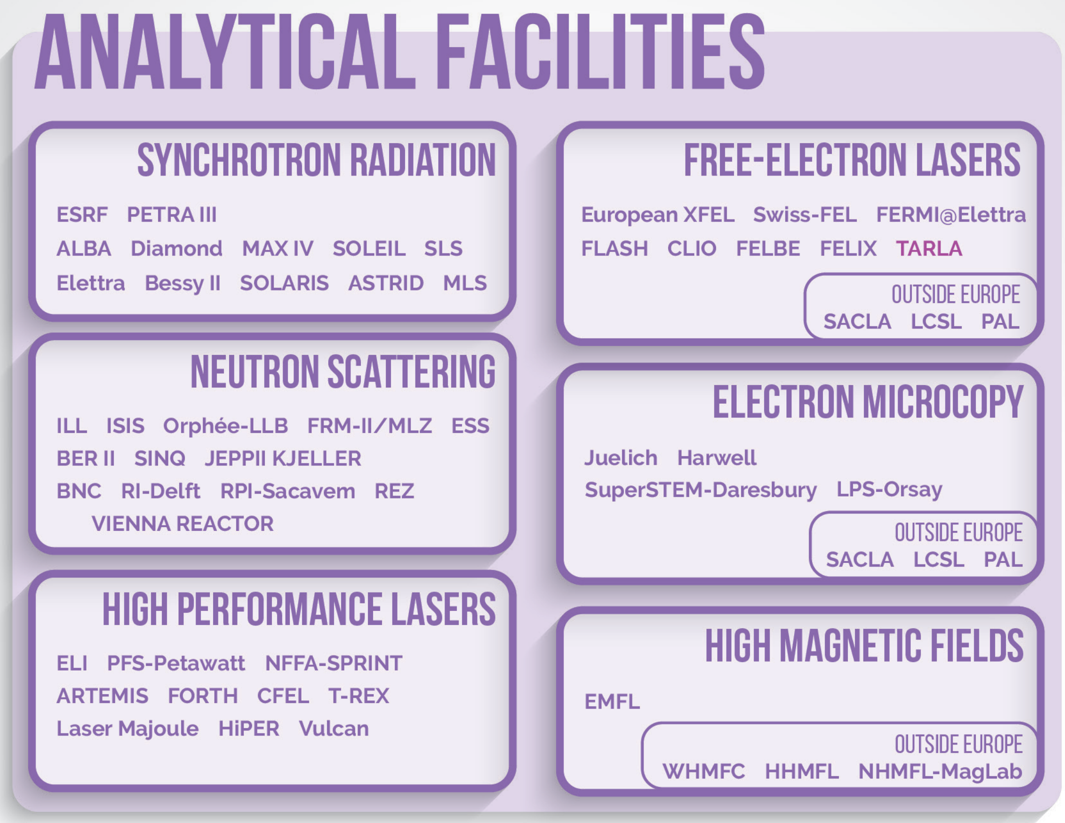

FIGURE 5.
Main Research Infrastructures in Analytical Physics

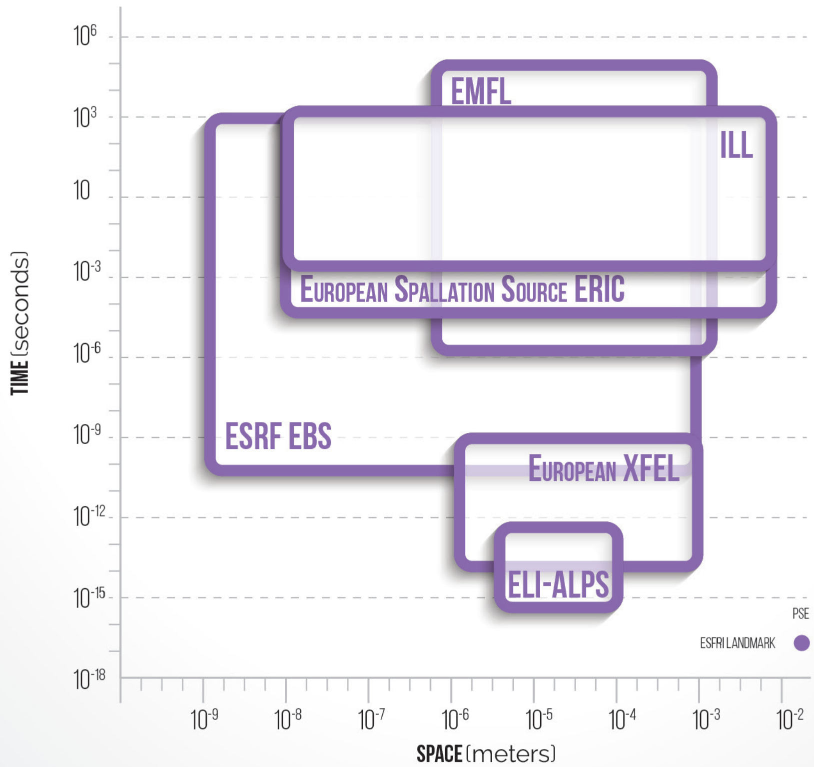

FIGURE 6.
Space and time domain of investigation of ESFRI Projects and Landmarks in Analytical Physics

GAPS, CHALLENGES AND FUTURE NEEDS

Brighter sources and faster detectors produce larger, often more complex data sets that are becoming more challenging to process and analyse, both during the experiment to make informed decisions about how best to proceed, and afterwards, increasingly across multiple probes. This requires not only significant investment in hardware to transfer, store and process data but also coherent development of software with greater exploitation of AI techniques, and many more people – data scientists – expert in such methods.

Many ARIs require more powerful, compact accelerator sources and better detectors, both of which could involve highly synergic collaborations across types of RIs. There are technical challenges specific to individual types of ARI: diffraction limited storage rings for SR for harder X-rays offering coherent imaging down to 10's of nm, and study of fluctuations to 100 ps; new medium-power high-brilliance NS installations; coherent pulsed sources for EM that operate in both stroboscopic and single shot modes, also requiring detector development. Improvements to high performance lasers will require new materials for robust optical components, a new generation of online, single-shot, *in situ* diagnostics of the laser fields, to control the experimental environment fully, and increase laser peak power at least 100 times by shortening pulses or superposing beams from several sources to create and study electron-positron pairs from the vacuum. For HFM, co-ordinated development across RIs (CERN, NS, etc.) is needed to develop a 30+ T high T_c superconducting (HTSC) magnet and address the very high electricity costs of operation, as well extend fields to the region 55-60 T, closer to the point where charge carriers in HTSC materials decouple.

Increasing demand for SR facilities could be met over the next decade through the upgrade of existing facilities and building additional national or regional facilities. Exploitation of complementary FEL facilities is still at a relatively early stage but likely to grow strongly in this period. A co-ordinated European plan to provide sufficient NS capacity before the ESS ramps up should be developed. The very strong growth in demand for Cryo-EM will require an increase in the number of instruments and the development of higher throughput methods. For high-performance lasers a key challenge is to transform existing networks into more robust and reliable user-oriented operations at or approaching 24/7.