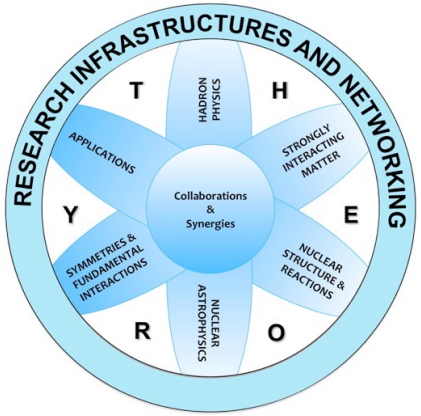
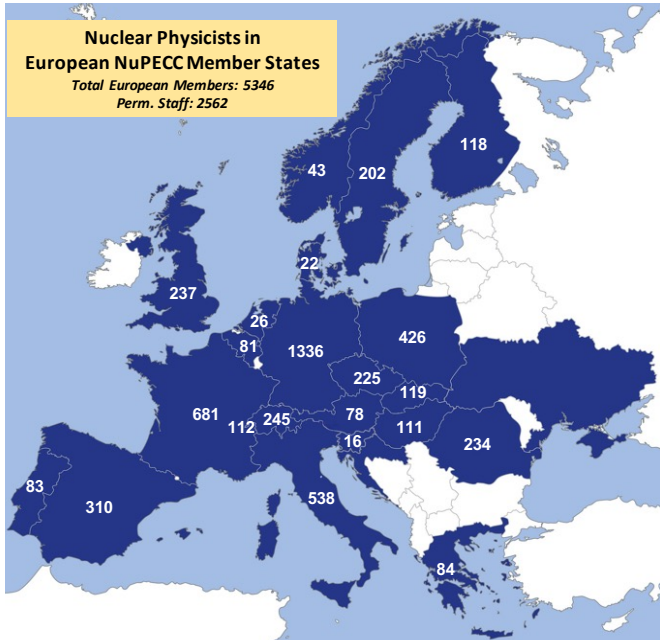
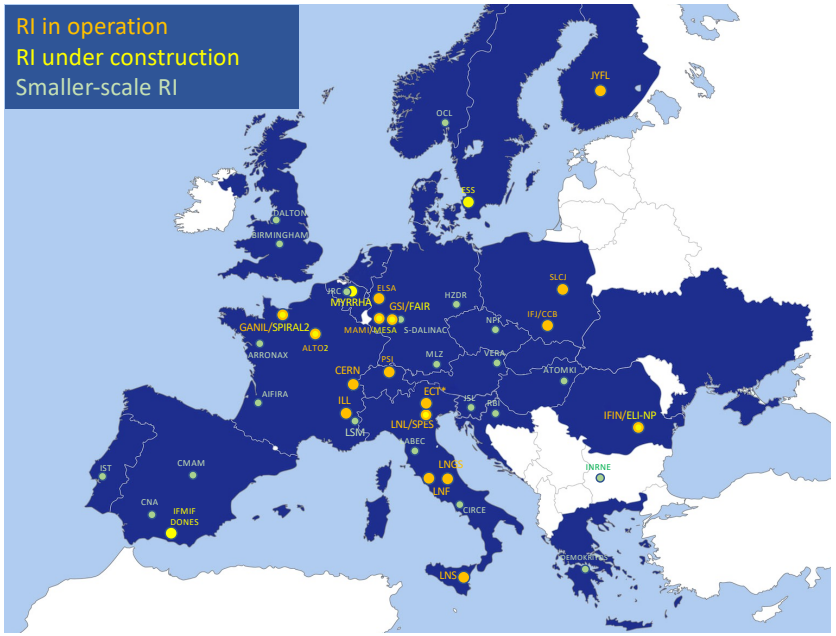


NuPECC Long Range Plan 2024
for European Nuclear Physics

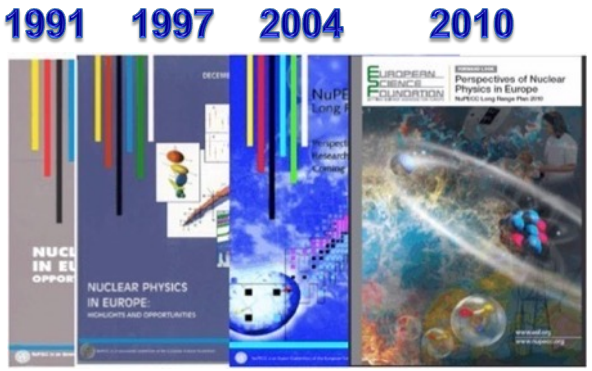
Marek Lewitowicz
Nuclear Physics European Collaboration Committee (NuPECC)



EURO-LABS Annual Meeting
October 28–30, 2024
CERN



Towards NuPECC Long Range Plan 2024



- **The LRP identifies opportunities and priorities for nuclear science in Europe**
- **The LRP provides national funding agencies, European Strategy Forum on Research Infrastructures and the European Commission with a framework for coordinated advances in nuclear science in Europe**

NuPECC LRP 2017

https://www.nupecc.org/lrp2016/Documents/lrp2017.pdf

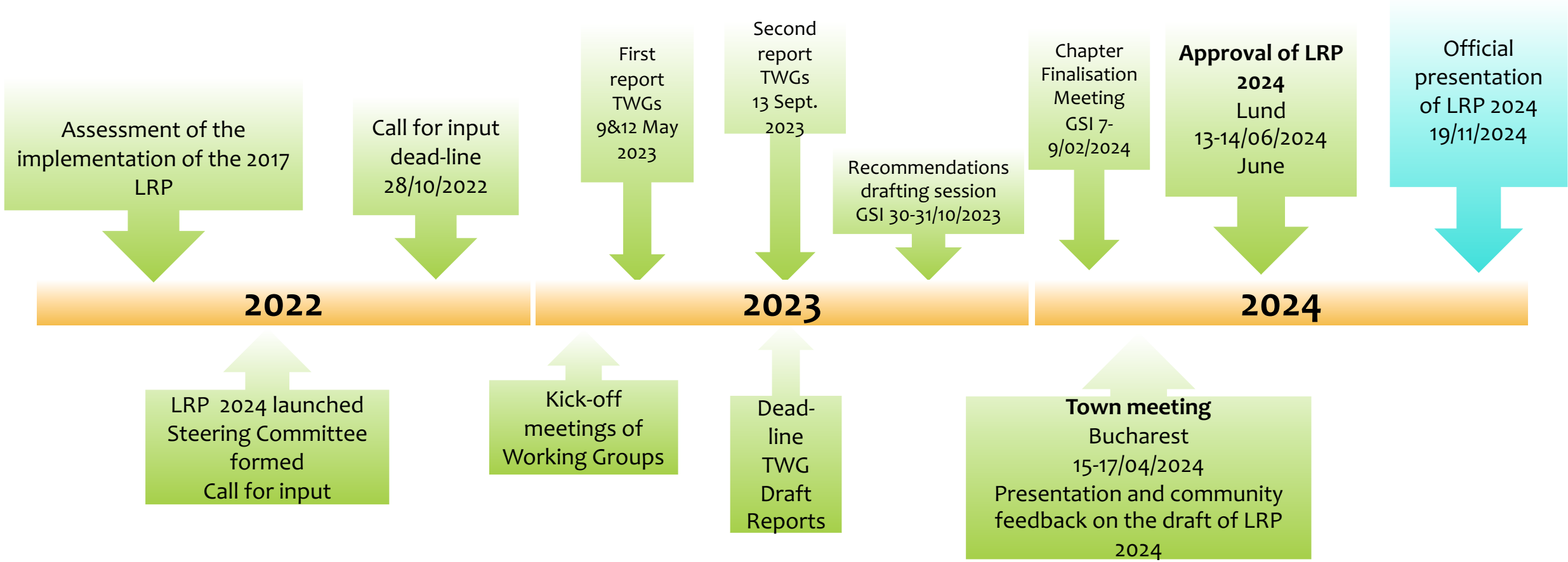
Assessment of implementation of LRP 2017

https://www.nupecc.org/2017_LRP_Assessment_of_Implementation_final.pdf

Launched in May 2022 in Madrid

NuPECC LRP 2024

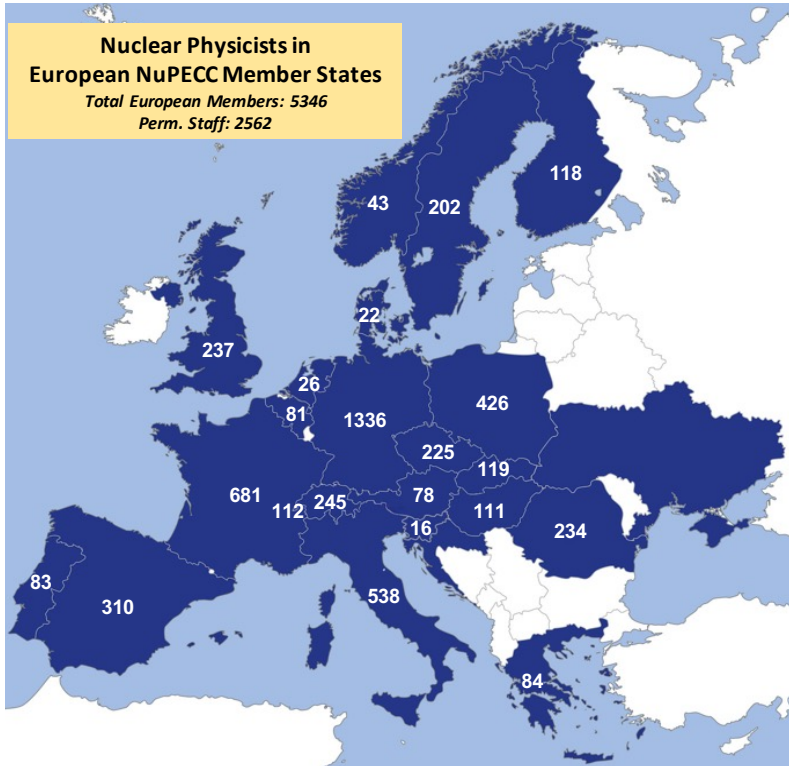
NuPECC LRP2024 Timeline

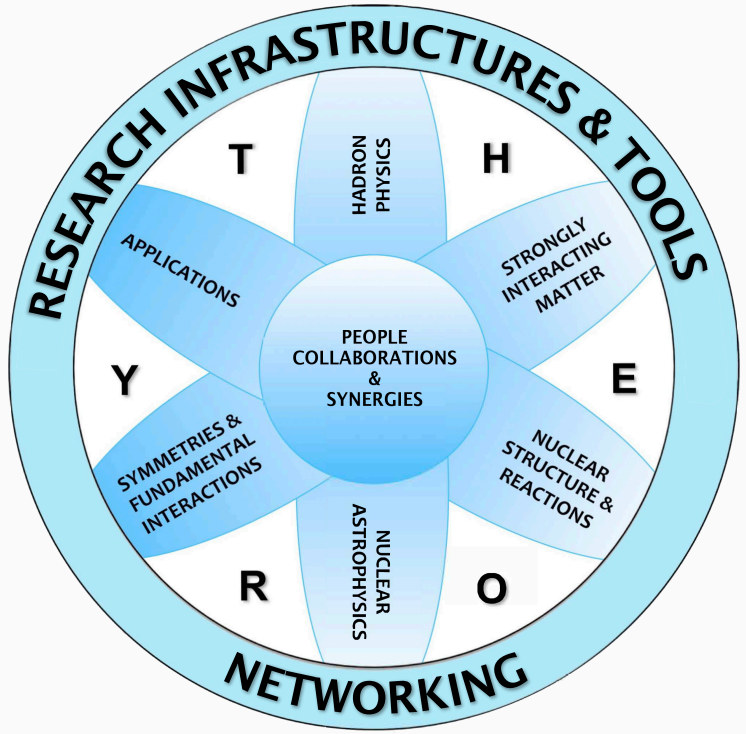


29 members of the Steering Committee
159 contributions from the community
10 Thematic Working Groups with 266 conveners, NuPECC members and contributors

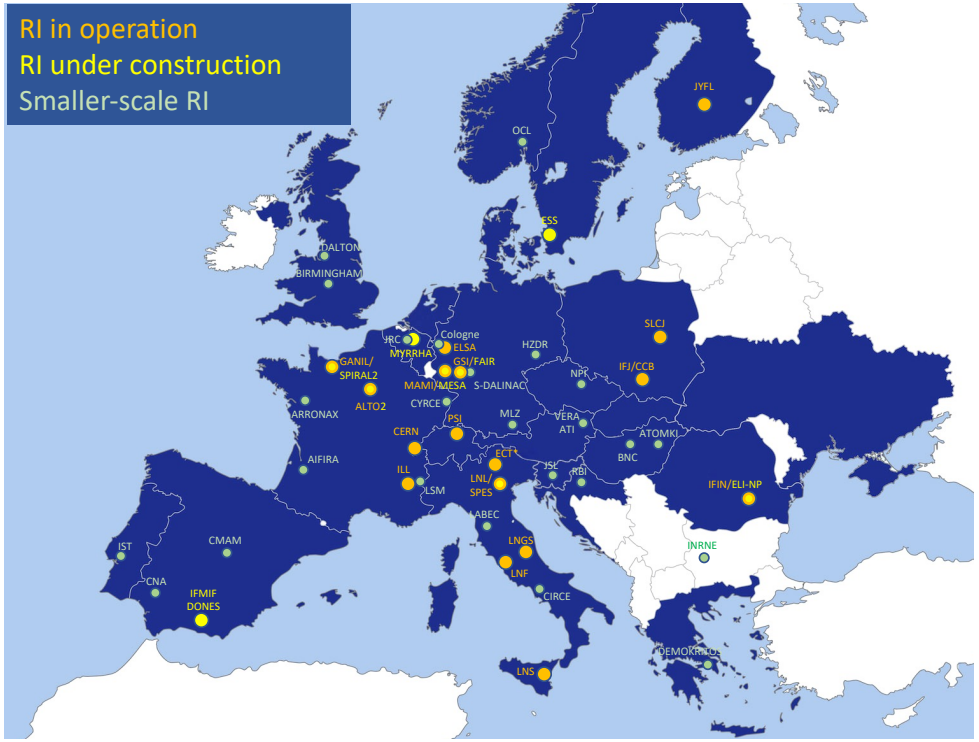
Nuclear Physics in Europe

Nuclear Physics Workforce in Europe





European Landscape of Nuclear Physics Infrastructures



5346 - total number of Nuclear Physicists (Exp. & Theory) in the European NuPECC Member States and the Associated Member CERN

2546 – *permanent staff*

2800 – *PhD students and non-permanent staff*

From NuPECC 2021& 2023 surveys

Taking data > 30;
Under construction or upgrade ≥ 9

From NuPECC LRP 2024

The NuPECC LRP 2024

Executive Summary

- Introduction
- What does Nuclear Physics stand for?
- Nuclear Physics and Society
- European landscape of nuclear physics
- ❖ **Recommendations for Nuclear Physics Infrastructures**
- International and Interdisciplinary Context
- Recommendations
  - **Fundamental Nuclear Physics**
    - Hadron Physics
    - ❖ **Strongly Interacting Matter at Extreme Conditions**
    - ❖ **Nuclear Structure and Reaction Dynamics**
    - ❖ **Nuclear Astrophysics**
    - ❖ **Symmetries and Fundamental Interactions**
  - ❖ **Applications and Societal Benefits**
  - **Nuclear Physics Tools**
    - ❖ **Detectors and experimental techniques**
    - ❖ **Machine learning (ML) and artificial intelligence (AI), Quantum computing (QC), Numerical tools, techniques and resources**
  - Open Science and Data
  - Nuclear Science - People and Society

LRP2024 approved at the NuPECC meeting in Lund 13/06/2024

➢ ***https://www.nupecc.org/lrp2024/Draft_Executive_Summary_LRP2024.pdf***

Full LRP2024 of 360 pages

Strongly Interacting Matter at Extreme Conditions

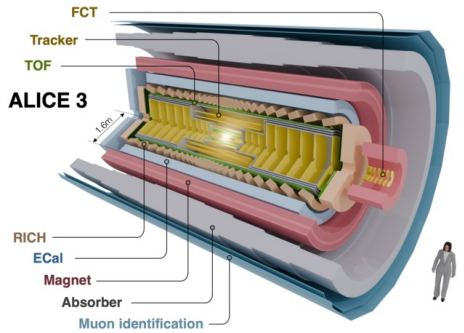
Key Questions & Goals

What are the properties of the quark-gluon plasma, which is the qualitatively novel state of nuclear matter at extreme conditions of temperature and density? Objectives: Discover in microscopic detail the material properties of the Quark Gluon Plasma at the highest temperature reached at the LHC at CERN and find the expected onset of the first-order phase transition at finite baryon density at FAIR in Darmstadt.

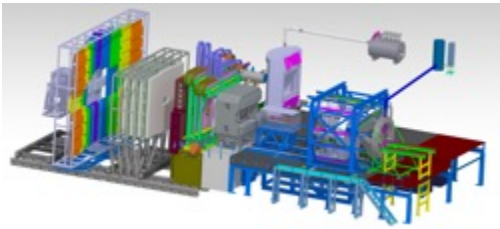
Recommendations

- **Future flagship facilities and experiments**
  - **ALICE 3** at **CERN**
  - **SIS-100** at **FAIR** and the realization of the **CBM** experiment
  - **CERN LHC** after 2035 (Run 5 and 6), the **LHCb Upgrade2** and the fixed-target setup **NA60+** detector at the **SPS**
- **Support of existing facilities and experiments**
  - maximise scientific output from the significant investment in current detector upgrades at the **LHC**
  - **HADES** and **R3B** at **SIS-18/SIS-100**, should receive full support.
  - The exploitation of **NA61** at **SPS** should receive full support
- **Theory developments**
  - Theoretical work in the field of heavy-ion collisions should be guaranteed continuous support
  - Collaborations should be particularly encouraged and nurtured in theoretical centres such as **ECT*** to strengthen the relation between heavy-ion physics and neighbouring fields

ALICE 3 @ LHC



CBM @ FAIR

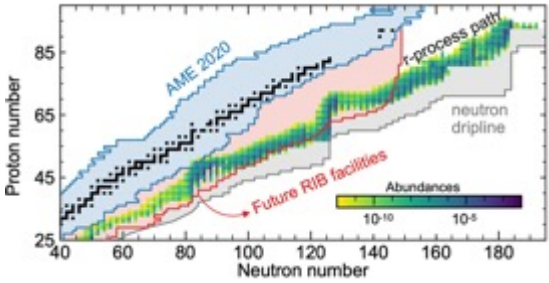


Nuclear Structure and Reaction Dynamics

Key Questions & Goals

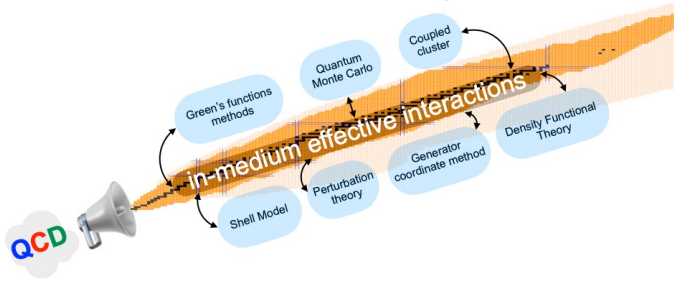
The main goals of Nuclear Structure and Reaction Dynamics in the next decade will be to answer the following questions: How do nuclei and nuclear matter emerge from the underlying fundamental interactions? What is the limit of nuclear existence and which phenomena arise from open quantum systems? How do nuclear shells evolve across the nuclear landscape, what kind of shapes can nuclei take, and what is the role of nuclear correlations? What are the mechanisms behind nuclear reactions and nuclear fission?

Recommendations



-> **EURO-LABS**

- **Support of existing facilities and experiments**
  - To ensure complementarity in experimental programs, it is essential to strongly support *large- and small-scale facilities* which guarantee access to the whole community
  - The coordinated effort amongst the **ISOL facilities** in Europe … will secure the leading position of Europe
  - The full completion of the European flagship gamma spectrometer **AGATA**-4π (with ancillaries) is mandatory
- **Future flagship facilities and experiments**
  - **FAIR** facility (with Low-Energy-Branch)**, SPIRAL2, SPES, ELI-NP, ISOL@MYRRHA, and ISOLDE** upgrades
  - Future rings at **FAIR** and **HIE-ISOLDE**
- **Theory developments**
  - Advance methods like Bayesian inference in combination with new computational techniques (e.g., Artificial Intelligence, Quantum Computing)
  - Theory centres should be strongly supported throughout Europe, in particular the **ECT*** and emerging virtual access facilities, which provide theory results for experimentalists (e.g., VA facility in the **EURO-LABS** project)



Nuclear Astrophysics

Key Questions & Goals

Nuclear astrophysics is the study of nuclear processes in astrophysical objects such as stars, covering the wide range of physical scenarios found in space. The key research questions are: How can we better understand the synthesis of heavy elements and the chemical evolution of the visible universe? What is the nature of matter in the extreme conditions of compact astrophysical objects such as mergers or pulsars?
Gravitational wave telescopes have opened a new window to astrophysics. These multi-messenger studies need a nuclear physics foundation.

Recommendations

- We recommend to strengthen nuclear astrophysics networks in Europe (e.g. **ChETEC-INFRA**) and to make them sustainable.
- **Support of existing facilities and experiments**
  - Small-scale facilities are key for nuclear astrophysics research and should be supported
  - European underground laboratories **(LNGS Bellotti** Ion Beam Facility and **Felsenkeller)** are essential
  - **CRYRING** and **ESR** storage rings at FAIR, which open important new physics cases, and **n_TOF** at CERN should be fully exploited
- **Future flagship facilities and experiments**
  - We strongly recommend the completion of Radioactive Beam Facilities in Europe, in particular the **Super-FRS** at FAIR, including the Low-Energy-Branch, the **upgrade of ISOLDE**, and **SPIRAL2**
  - A large (> 10 MV) **AMS** system is currently missing in Europe
- **Theory developments**
  - Access to large and fast supercomputing facilities in Europe is essential to perform microscopic nuclear physics calculations as well as multidimensional astrophysics simulations
  - **ECT*** in Trento is an essential place for training and networking in nuclear astrophysics

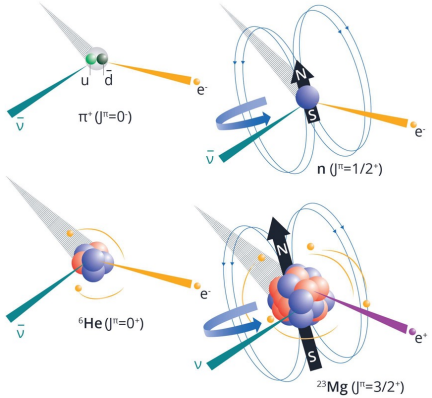
Symmetries and Fundamental Interactions

Key Questions & Goals

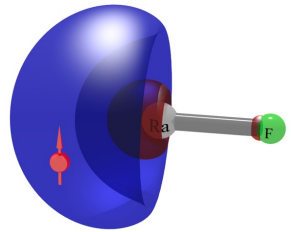
Symmetries, referred to as the invariance of the laws of physics under a given transformation, play a fundamental role in physics. They can be studied by powerful low-energy probes. As such, precision measurements are complementary to collider searches for new physics. Pioneering techniques are under development to produce, manipulate, cool and trap a diverse range of particles, including radioactive nuclei, neutrons, antiprotons, pions, muons, exotic atoms, and highly charged ions.

Recommendations

- **Support of existing facilities and experiments**
  - The multidisciplinary research infrastructures **ILL**, **FRM-II** and **PSI** provide unique opportunities. Operation of **ILL** should be ensured beyond **2033**.
  - Continued support for **ESR, CRYRING** and **HITRAP** at GSI/FAIR, and high-energy **EBITs** in other labs
  - The **AD/ELENA** physics program at CERN should be strongly supported
  - Customised instrumentation and beam time availability should be guaranteed for fundamental tests at RIB facilities like ISOLDE, GANIL-SPIRAL2, and JYFL-ACCLAB/IGISOL **-> EURO-LABS**
- **Future flagship facilities and experiments**
  - Specialization of upcoming Radioactive Ion Beam facilities such as **ISOL@MYRRHA** and **DESIR at GANIL-SPIRAL2** should be regarded as an opportunity not to be missed
  - At **ESS,** a fundamental neutron physics beamline should be installed
  - The realisation of future **CR** and **HESR** at FAIR should be vigorously pursued
- **Theory developments**
  - An inclusive theoretical framework fostering sustainable connections between nuclear theory, quantum chemistry, atomic and molecular physics, and particle physics must be encouraged and vigorously supported
  - The strong interdisciplinary program of the **ECT*** in Trento should be strongly supported



Examples of beta decays used to probe the weak interaction



Schematic representation of the radium monofluoride (RaF) molecule

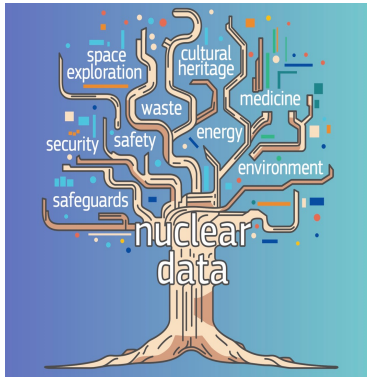
Applications and Societal Benefits

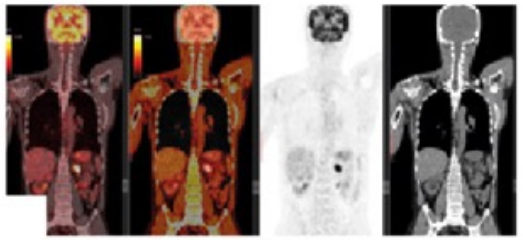
Key Questions & Goals

How might nuclear physics strengthen its role in society's sustainable development?
The United Nations Sustainable Development Goals (SDGs) call to action for all governments across the globe, but also a call for all research communities to contribute. The nuclear science community contributes to all SDGs but more specifically, it directly addresses some of these goals (#3 Good health and well-being, #7 Affordable and clean energy, #9 Industry, innovation and infrastructure, #13 Climate action) or indirectly (#4 quality education, #5 gender equality, #10 reduced inequalities) through innovative and collaborative approaches.

Recommendations

- Improving **nuclear data**, including both the measurement and the evaluation of nuclear data is needed to support research in the fields of energy, health, space, and materials science.
- **Capacity building**: in radiochemistry and radiobiology maintaining nuclear application competencies, developing the landscape of smaller-scale facilities, in coordination with the large-scale facilities.
- New generations of nuclear energy sources and the management of nuclear waste through partition and transmutation, depend on sustained technological developments in the present facilities, as well as the completion of **MYRRHA** and **IFMIF-DONES.**
- **Upscaling the production capacity of novel medical radionuclides: MEDICIS** separator at CERN, the expansion of the **EU PRISMAP** project, and the completion **ISOLPHARM** at SPES, **ISOL@MYRRHA, IMPACT-TATTOOS** at PSI, and **SMILES** at Subatech
- Completion of the first **galactic cosmic ray simulator** in Europe at GSI/FAIR
- The installation of a **high-energy AMS** in Europe (>10 MV) is recommended.
- Isotope-sensitive techniques in environmental, heritage, and materials science: sustained operation of research reactors




A PET–CT scan of the human body.

Nuclear Physics Tools - Detectors and experimental techniques

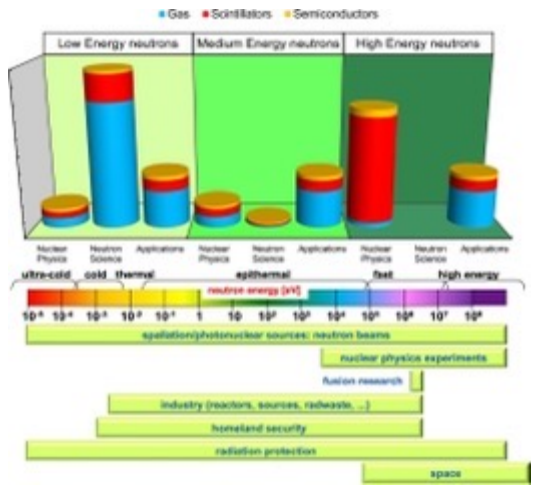
Key Questions & Goals

Advancement in the understanding of fundamental physics is intimately related to progress in the development of tools for experimental and theoretical investigations. These tools are used for detector R&D, detector operation, data acquisition and analysis, theoretical interpretation of experimental results and genuine theoretical developments.

Recommendations

-> EURO-LABS

- Elaboration of a **roadmap for detector R&D dedicated to the specific needs of low-energy nuclear physics and applications in radiation monitoring and heritage science** must be supported.
- **Strengthening of the collaborative effort in developing cutting-edge detector technology** for identified applications in accelerator experiments with respective activities in high-energy particle physics and other adjacent research fields.
- Enhance precision and efficiency in **high-resolution laser spectroscopy and mass spectrometry**, to study the structure of rare isotopes and test fundamental symmetries.
- Establish infrastructures to **ensure the provision of stable and radioactive targets**, such as **a dedicated mass separator** for providing radioactive samples and targets – **foreseen to be built at PSI**
- Secure a strategic **supply of stable enriched isotopes** for fundamental research and applications as is the case for the installation of a **European Electro-Magnetic Ion Separation facility**, providing material of the highest enrichment in rare stable isotopes.
- To develop **novel efficient neutron detectors** to replace those based on ^{3}He.



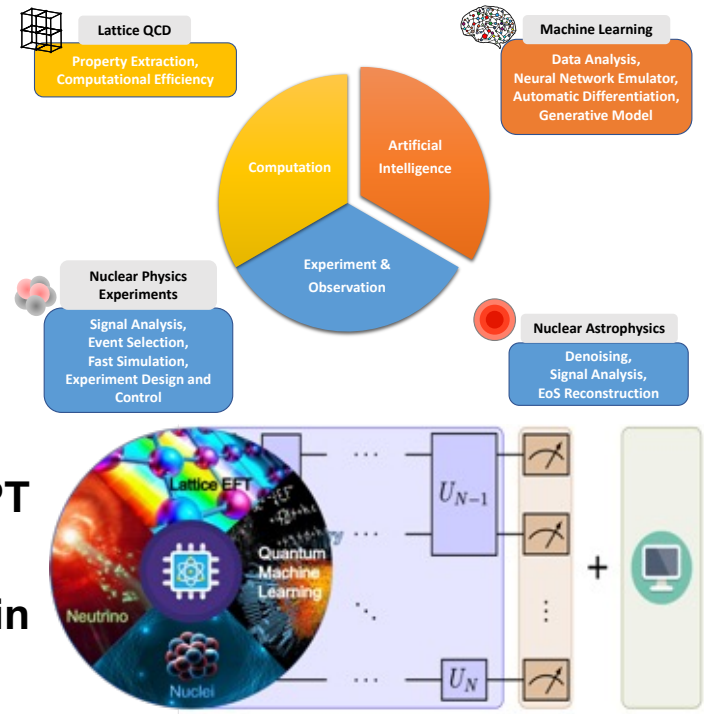
Nuclear Physics Tools – Computing, Artificial Intelligence, Machine Learning and Quantum Computing

Key Questions & Goals

The tremendous progress in the field of nuclear physics has led to the pressing need for appropriate numerical tools aimed at addressing the most relevant experimental, theoretical and technological challenges, such as those encompassed by the Joint ECFA-NuPECC-APPEC (JENA) initiatives. To this end, the advent of algorithms based on Machine Learning (ML) and Artificial Intelligence (AI) techniques, and the fast progress in the field of Quantum Computing (QC) has opened an entire new world of possibilities.

Recommendations

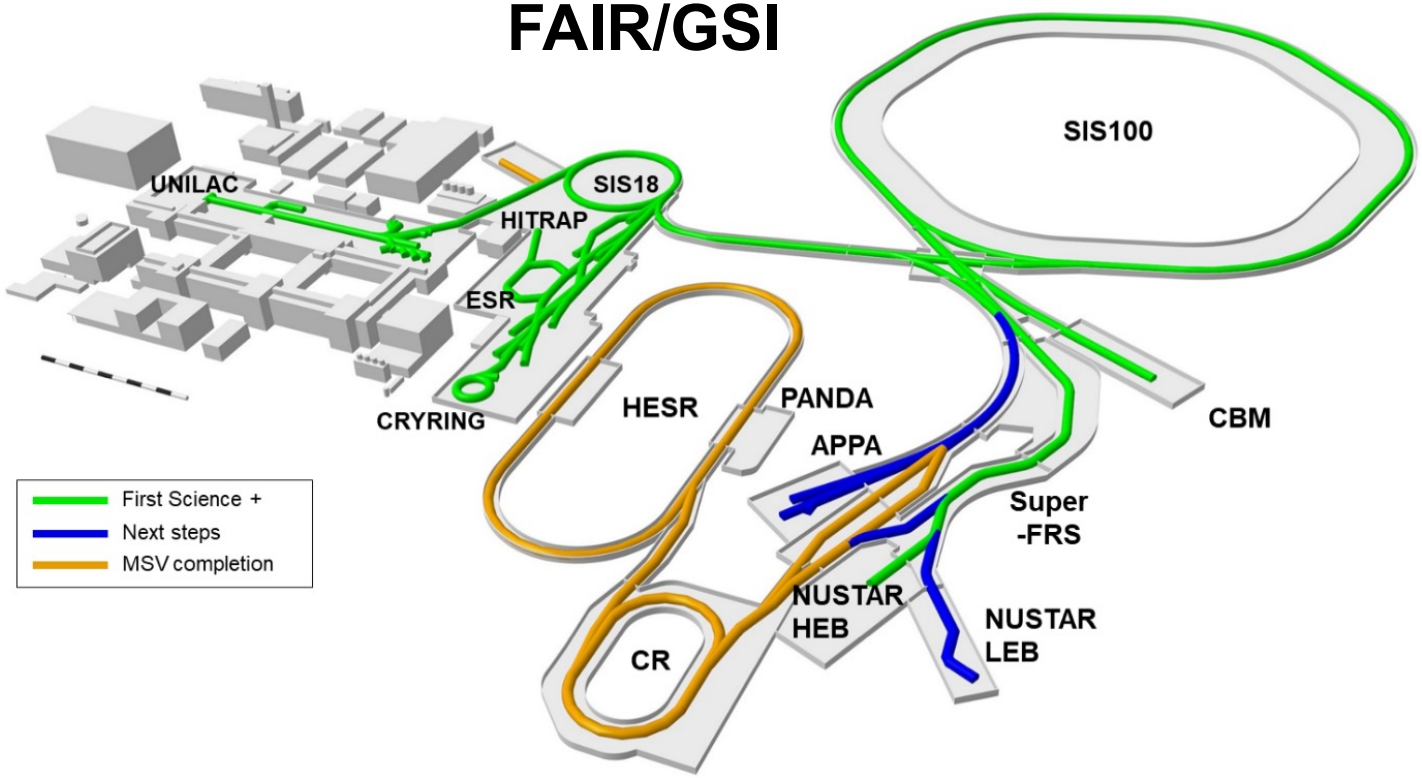
- Provide **long-term career perspectives for software developers** in the field
- Educate and train in software development
- Call for more **long-term storage solutions for gauge ensembles for lattice QCD**
- **Facilitate and strengthen access for nuclear physics researchers to large HPC centres**
- Support **virtual access infrastructures** (as in **STRONG-2020** & **EURO-LABS EU projects**)
- Transform ML prototypes into applications for production
- Invest in training and fine-tuning of models tailored for scientific purposes, such as **GPT models specialized for nuclear science.**
- Develop research into explainable AI; **Enhance transparency and interpretability in scientific AI applications in nuclear physics and adjacent fields.**
- Facilitate **access to quantum platforms**.
- Establish a **European network on quantum activities related to nuclear physics**.



FAIR facility, Darmstadt, Germany

ESFRI

- **The first phase of the international FAIR facility is expected to be operational by 2028, facilitating experiments with SIS100 using the High-Energy Branch of the Super-FRS, the CBM cave and the current GSI facilities. Completing the full facility including the APPA, CBM, NUSTAR and PANDA programs will provide European science with world-class opportunities for decades and is highly recommended.**



GANIL/SPIRAL2 facility, Caen, France

ESFRI

- **At GANIL/SPIRAL2 the Super-Separator Spectrometer S^3 is in an advanced stage of completion and the low-energy DESIR facility and heavy-ion injector NEWGAIN, will be operational from 2027/28. The refurbishing of the cyclotrons will ensure their operation for the next decades. Timely completion and full exploitation of these GANIL/SPIRAL2 projects are recommended. The future evolution of the infrastructure towards a very high-intensity reaccelerated RIB facility of up to 100 MeV/u should be actively planned.**

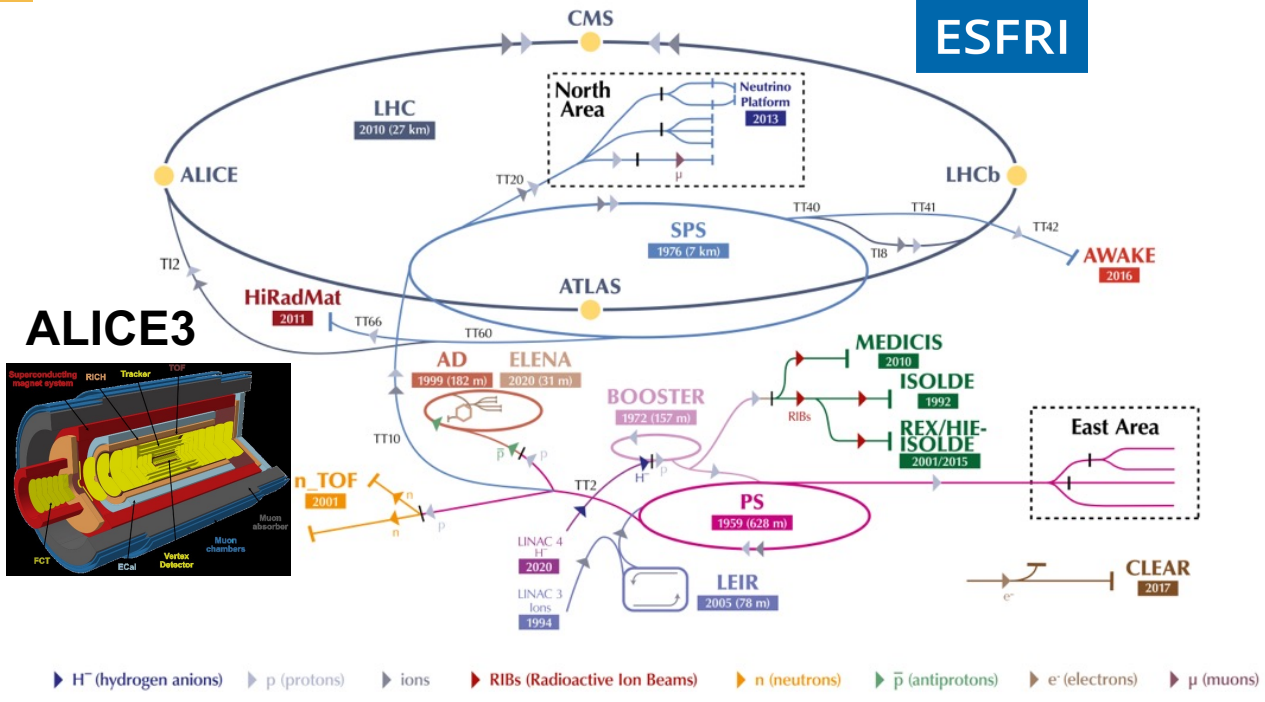
GANIL/SPIRAL2 France

CERN Nuclear Physics facilities and experiments

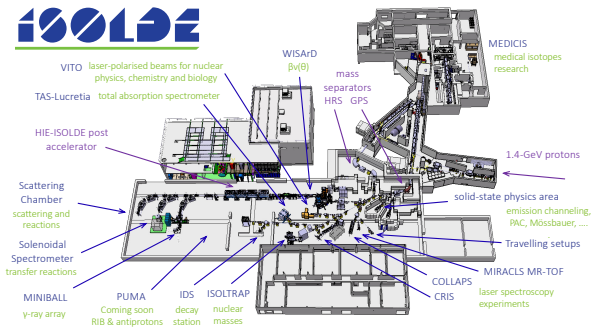
- **Nuclear physics opportunities at CERN constitute a world-leading research . The construction of ALICE 3 as part of the HL-LHC plans is strongly recommended. Continued support for exploitation and new developments are recommended to maximise the scientific output of ISOLDE, n_TOF, SPS fixed-target program and AD/ELENA. As the roadmap for the post-LHC future of CERN is developed, a strategy should be prepared to secure future opportunities for continuing world-leading nuclear-physics programmes that are unique to CERN.**

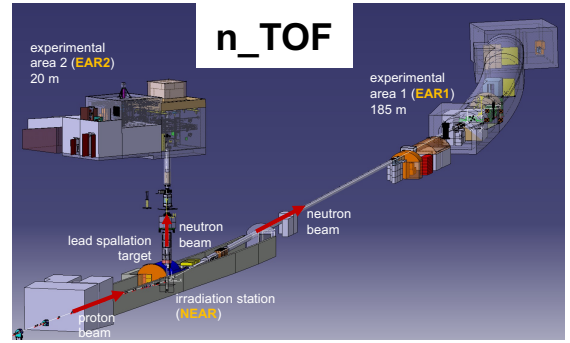
-> NP contributions to the ongoing Update of the Strategy for Particle Physics

ESFRI



ALICE3

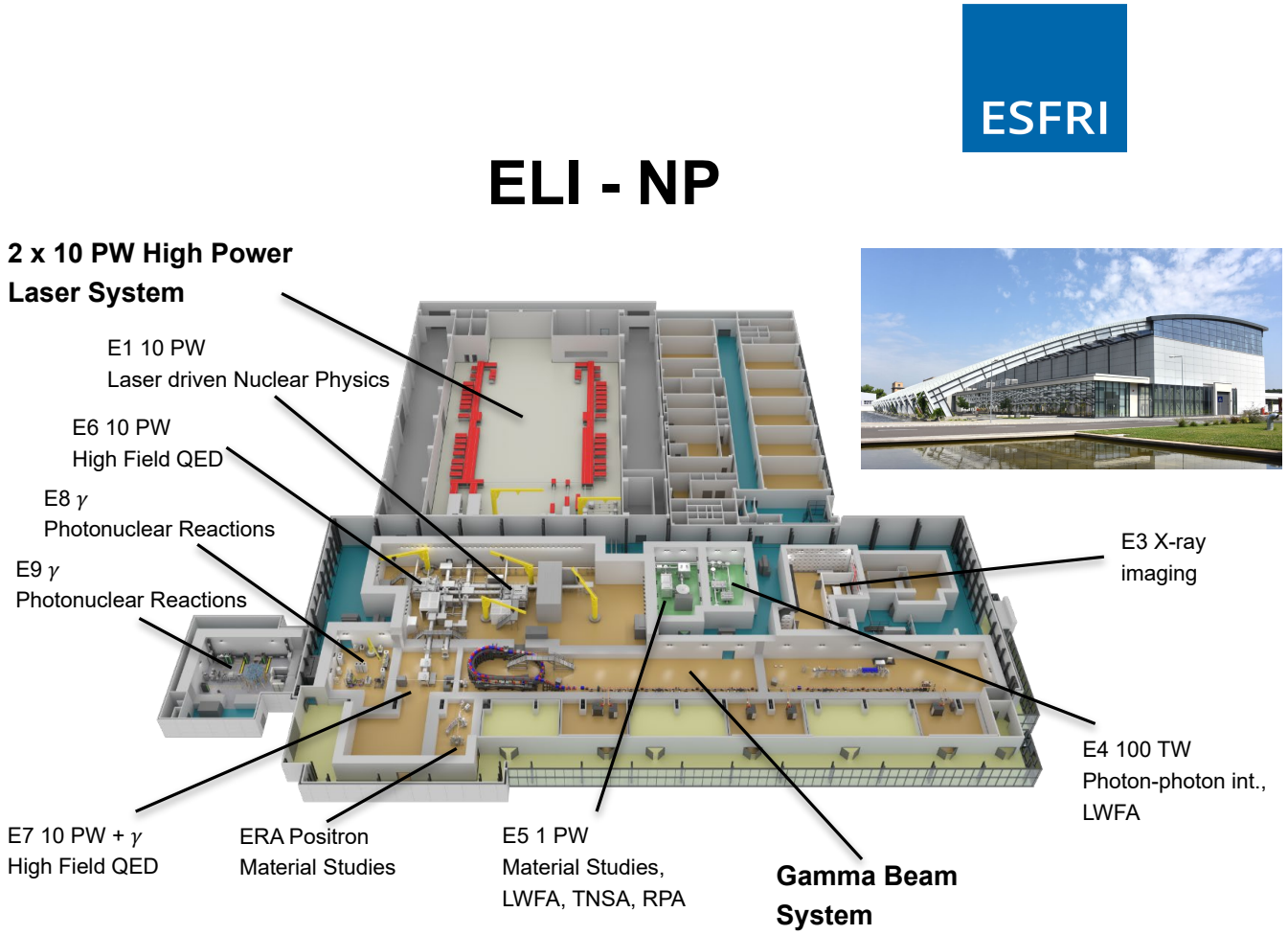




Extreme Light Infrastructure - Nuclear Physics, Magurele, Romania

ESFRI

- **At ELI-NP studies will focus on addressing key topics, such as laser-driven ion and electron acceleration. Implementing the gamma beam system to achieve the full completion of the facility to allow breakthrough results in the field of nuclear photonics is of high importance and is strongly recommended.**



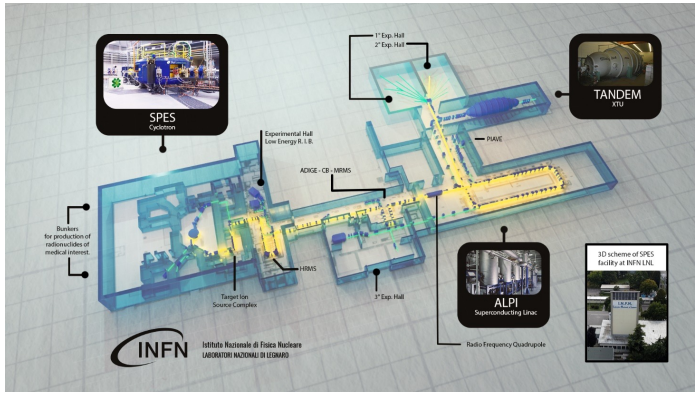
LRP 2024 Recommendations for NP Infrastructures

ISOL radioactive ion beam facilities

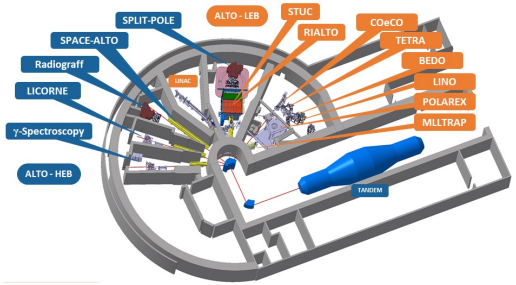
- **Timely completion of the SPES a facility and continuing coordinated efforts in developing the ALTO, IGISOL, ISOLDE, SPES, and SPIRAL ISOL facilities in Europe, will be key to maintaining their world-leading position in many areas of radioactive isotope science and are strongly recommended. Extending these efforts towards future facilities, such as ISOL@MYRRHA, TATTOOS@PSI, and RIB@IFIN, together with the development of common instrumentation, will secure the European leading position for radioisotope production, separation, and acceleration techniques, and create new avenues for the future and should therefore be actively pursued.**

-> EURO-LABS

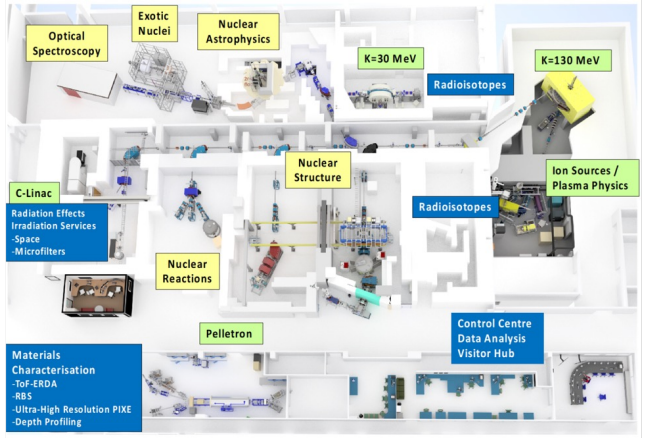
SPES/LNL Italy



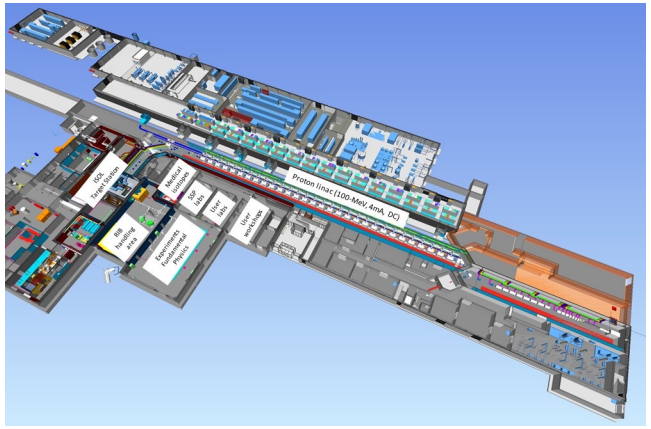
ALTO/IJCLab France



IGISOL/JYFL Finland



ISOL@MYRRHA Belgium

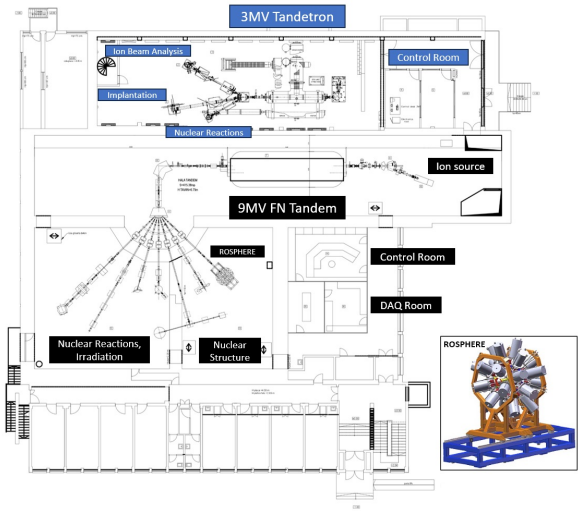


Stable Ion Beam facilities

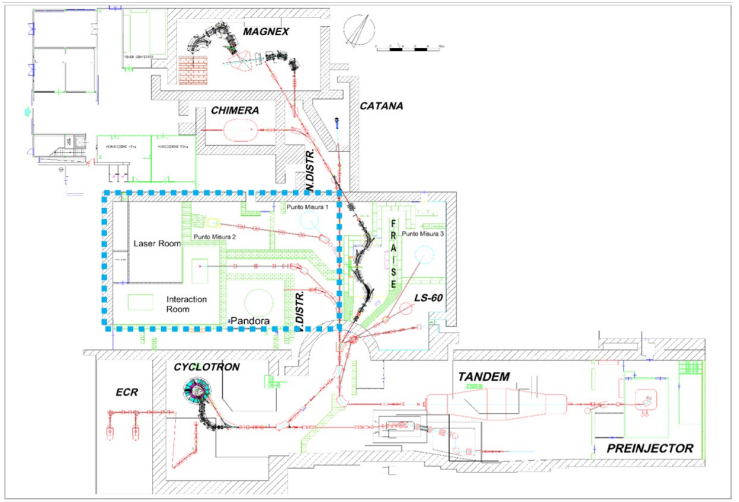
- **Large-scale stable beam facilities, such as FAIR/GSI, GANIL/SPIRAL2, IFIN, JYFL-ACCLAB, LNL, LNS, NLC (SLCJ and IFJ-PAN), and smaller ones, such as tandems, underground facilities and AMS systems, should be optimally exploited. Developments of novel and more intense beams and capabilities are also recommended to open new opportunities for basic science and applications. It is recommended that synergies between all these facilities, irrespective of size, be reinforced.**

-> EURO-LABS

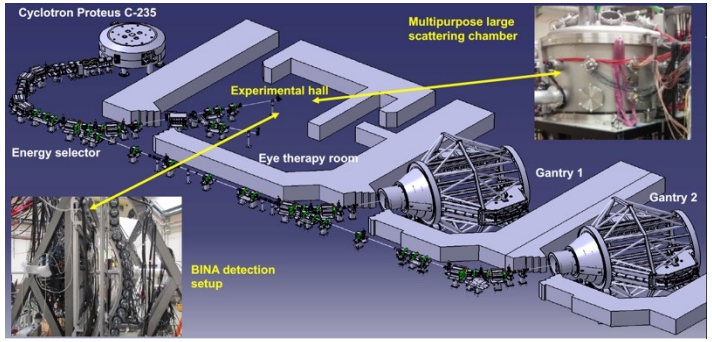
IFIN-HH Romania



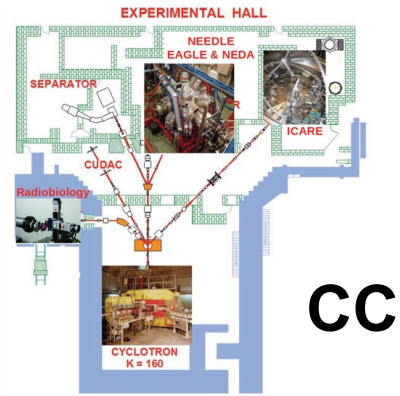
LNS Italy



NLC Poland



SLCJ

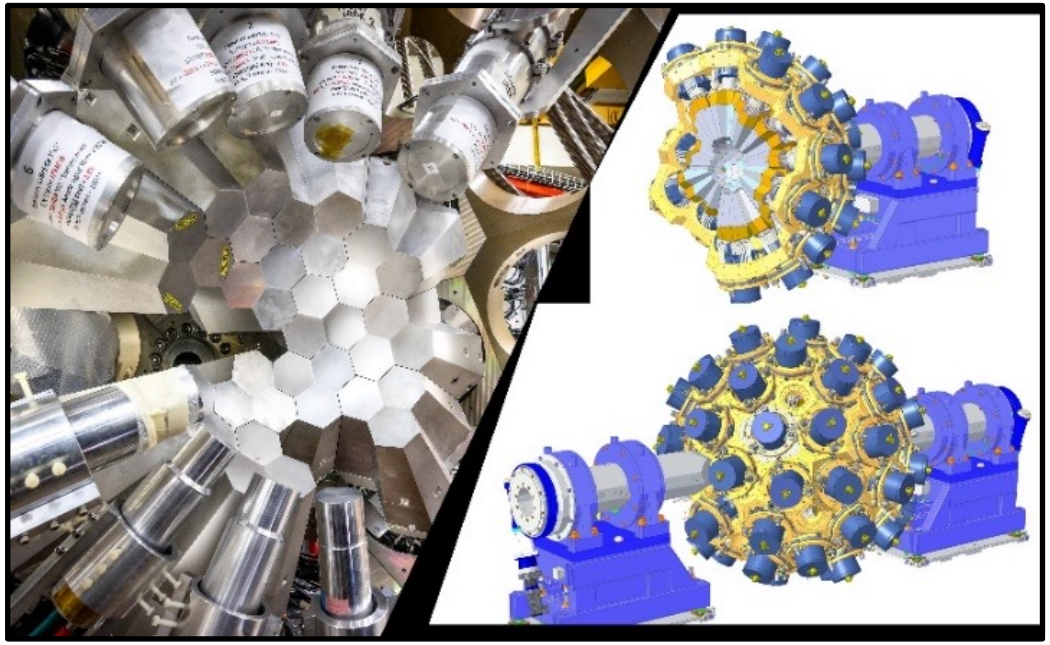


CCB

AGATA European gamma tracking array

- **It is strongly recommended to complete the AGATA gamma tracking array to its full configuration as a key instrument for studying atomic nuclei in both stable and radioactive ion beam facilities.**

AGATA

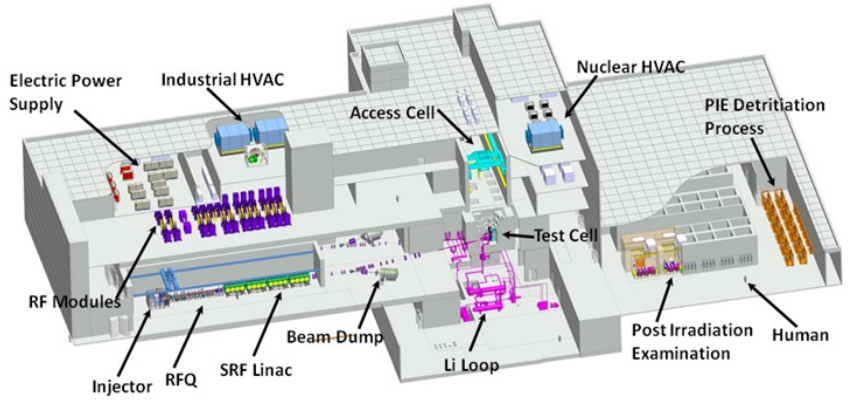


Neutron facilities

- **Neutron facilities are playing a significant role in nuclear fundamental research and applications, producing unique and valuable experimental outcomes. The new NFS facility, located at SPIRAL2, is now providing a highly intense neutron flux of fast neutrons, attracting a broad scientific community. It is crucial and strongly recommended to maintain the operation of exceptional neutron facilities like ILL and n_ToF at CERN. ESS facility and the future infrastructure IFMIF-DONES will provide advanced tools for interdisciplinary research and their unique capabilities to serve advances in nuclear physics should be explored.**

ILL France

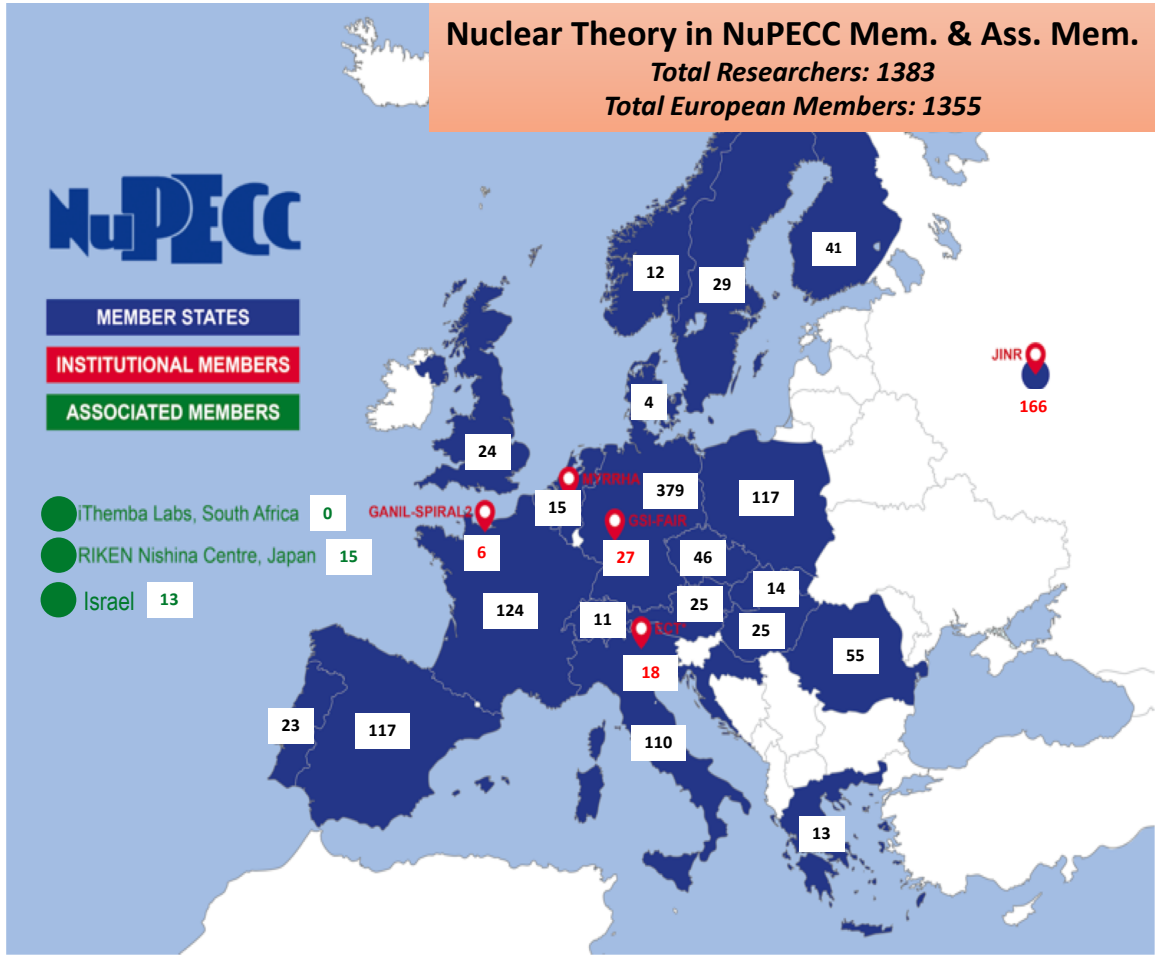
IFMIF-DONES Spain



Theory centres

- **Theory centres and groups should be strongly supported throughout Europe, in particular the European Centre for Theoretical Studies (ECT*, Trento, Italy), which is a unique European centre dedicated to theoretical nuclear physics in the broadest sense. A stronger pan-European support which will ensure that ECT* activities continue to play a strategic role in the development of nuclear physics in Europe is recommended.**

-> EURO-LABS



From NuPECC 2021 survey

ECT*

NuPECC LRP2024

- **Official presentation of LRP 2024 on 19/11/2024 at the University Foundation in Brussels**
- **Please register at:** https://indico.ph.tum.de/event/7751/

- ***Executive Summary of the LRP2024 is available on the NuPECC Web site*** ***https://www.nupecc.org/lrp2024/Draft_Executive_Summary_LRP2024.pdf***

- ***The PDF version of the full document will be available on the NuPECC Web site soon***

Implementation of the NuPECC LRP2024

- **NuPECC Task Force (directors of the NP ESFRI infrastructures) meetings with the funding agencies of the Member Countries to promote the LRP and encourage its implementation**

  9 Task Force meetings in 2017-2022

  Task Force meetings in 2023-2025:

  - Belgium in Brussels on 31/01/2023
  - Slovenia in Ljubljana on 15/03/2023
  - Austria in Vienna on 21/04/2023
  - *Scheduled for December 5th, 2024: Germany in Bad Honnef*
  - *Meetings in Slovakia, Hungary, Romania, and Sweden by 2025*

- **Use and cite the LRP2024 in the applications for funding of new projects, collaborations, EU and national grants!**
- **Make the LRP2024 recommendations known among the nuclear physics community**
- **Apply for and ensure the support of EU for nuclear physics: next EC calls!**

Warm thanks to all contributors to the NuPECC LRP 2024!

Thank you for your attention!

NuPECC LRP 2024 Town Meeting, Bucharest, April 2024