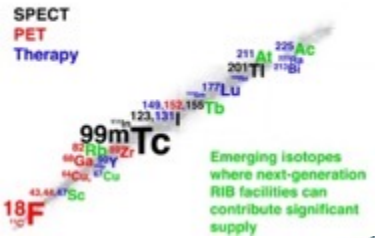
Nuclear Physics Roadmap
(in Europe)

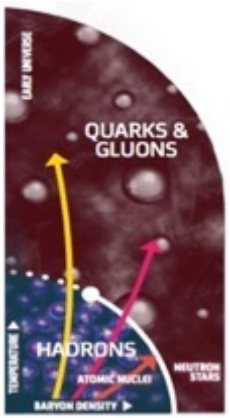
SAM meeting
Kraków 9-11/10/2023

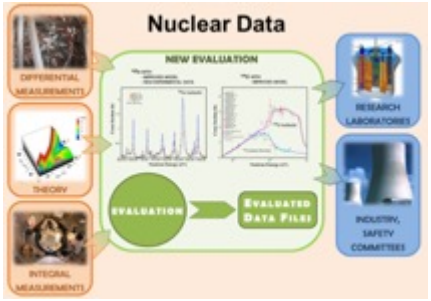
- **European Nuclear Physics Research - Recent Results (examples) and strategic issues**
- **NuPECC and 2024 Long Range Plan for Nuclear Physics in Europe (appetizer)**

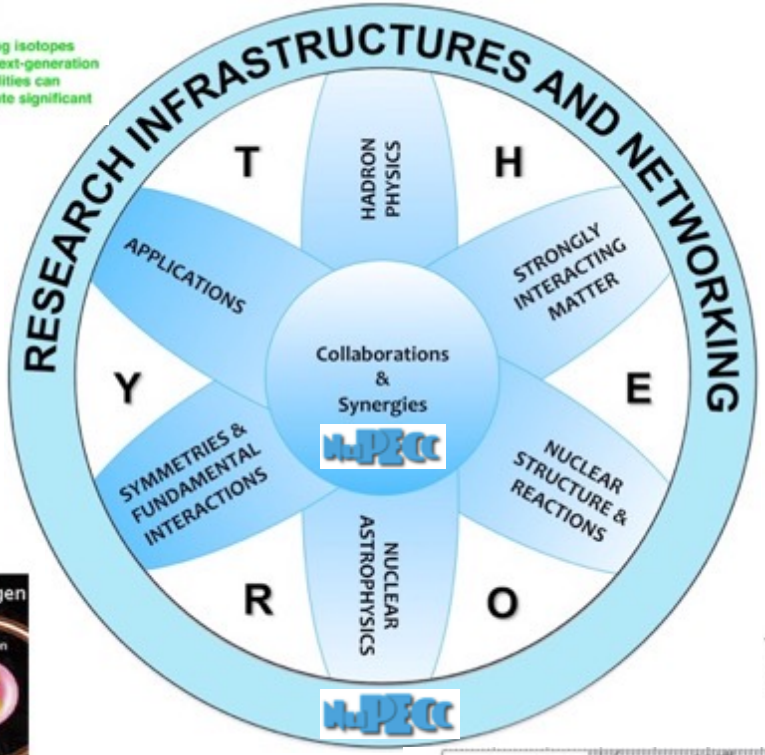
Recent Results from European Nuclear Physics Facilities

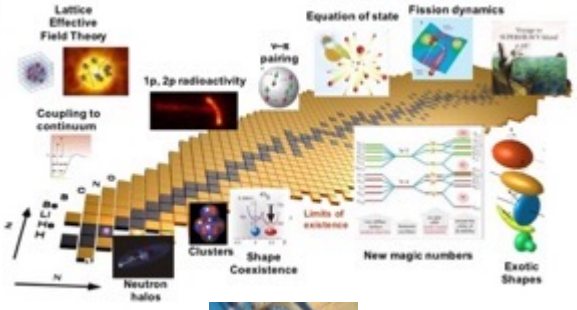
http://www.nupecc.org

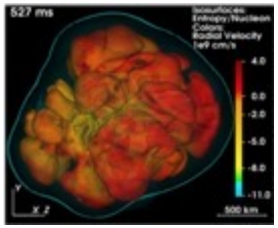


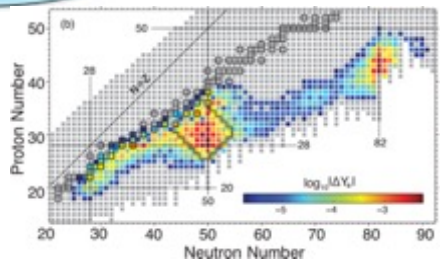












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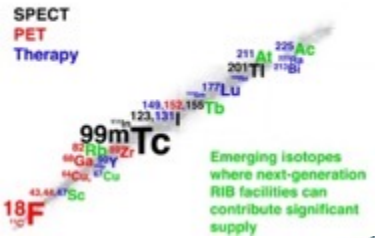
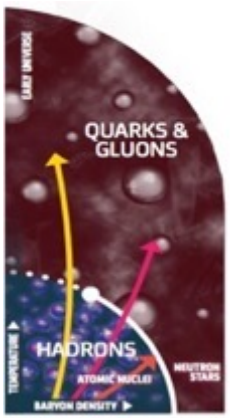
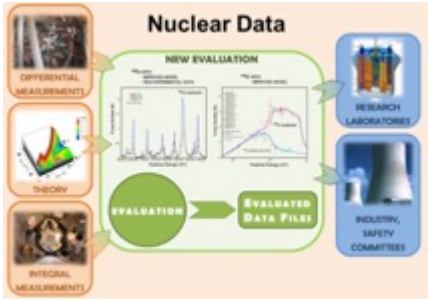
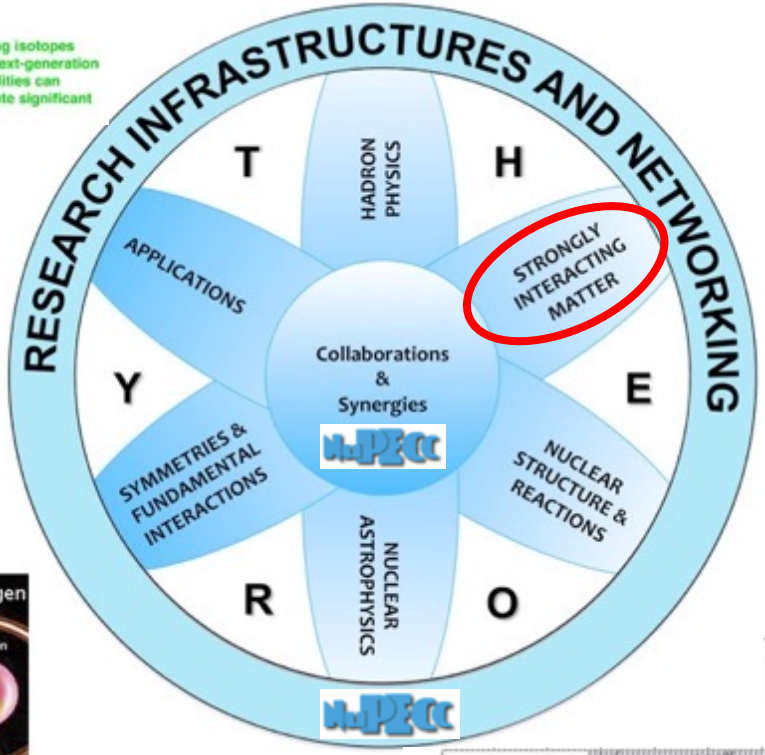
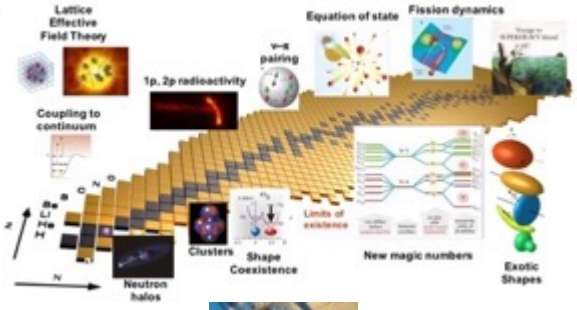
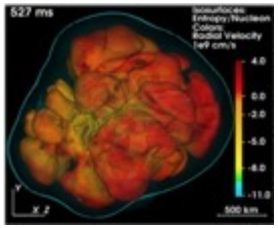


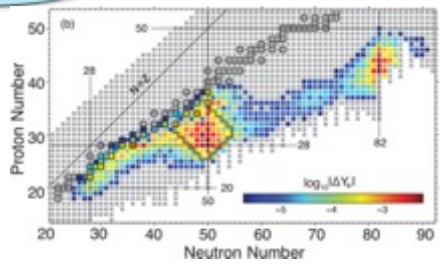






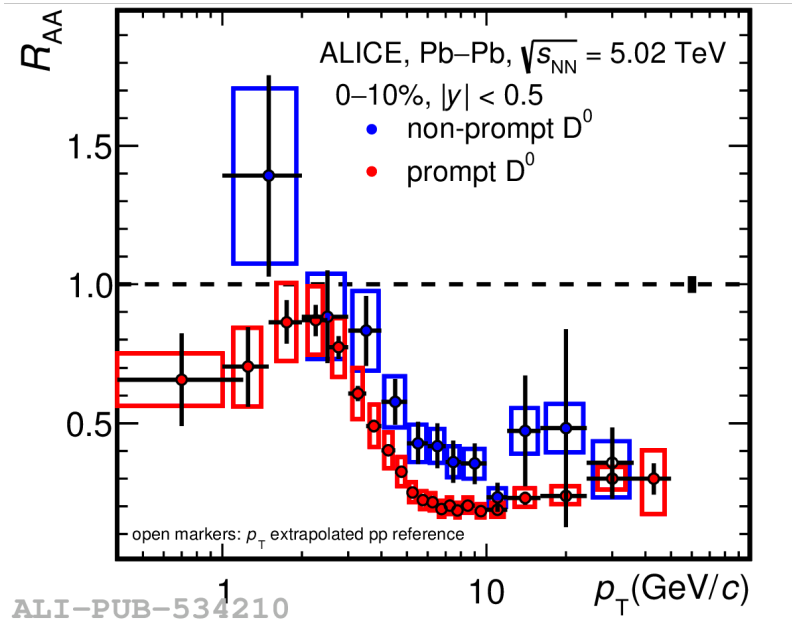




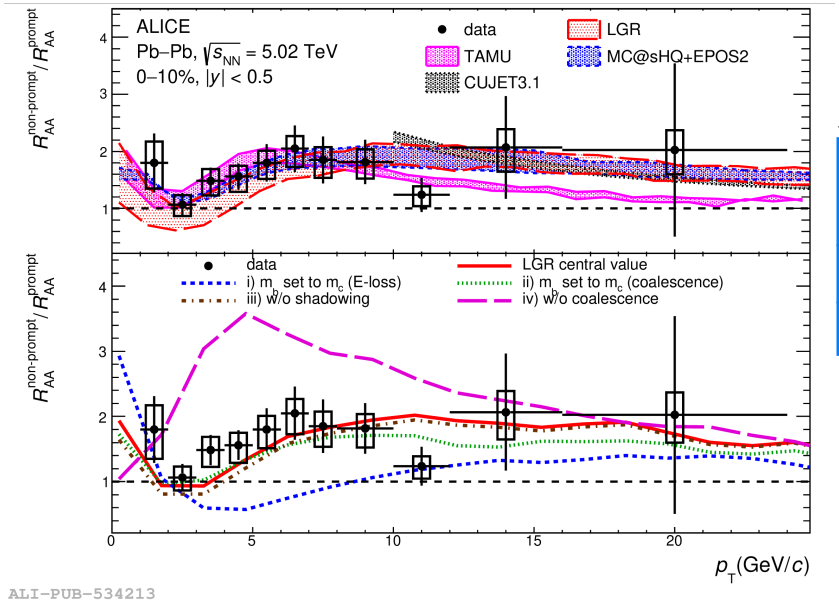


Probing the QGP with Heavy Flavour particles at ALICE/LHC

Charm and beauty: prompt and non-prompt D mesons



Non-prompt/prompt ratio



ALICE, JHEP 12 (2022) 126

Beauty (non-prompt D mesons) less suppressed than charm: large mass quarks lose less energy
Qualitatively in line with both collisional an radiative energy loss; model calculations to determine mechanism

Courtesy of M. Van Leeuwen

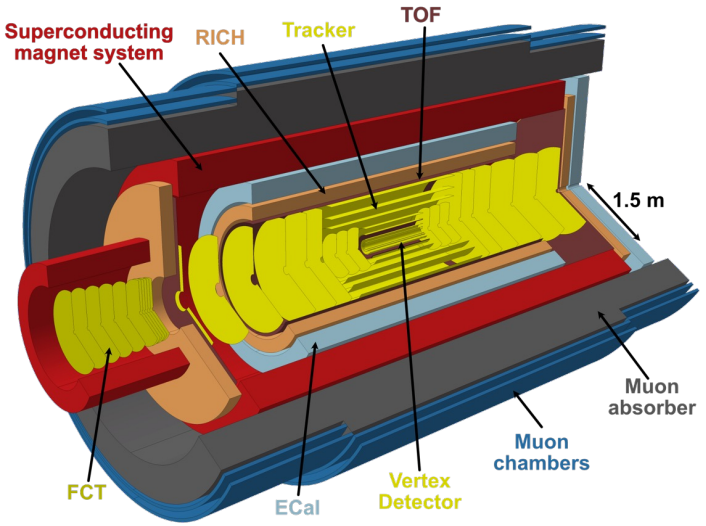
ALICE 3: next-generation heavy ion program at LHC

ALICE 3 design:

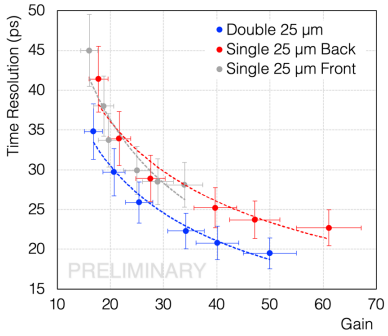
- Compact and lightweight all-silicon tracker
  - Excellent pointing resolution with a retractable vertex detector
- Extensive particle identification: TOF, RICH
- Large acceptance

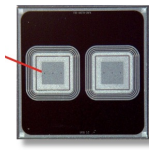
Detector and sensor R&D has started:

- tracking, timing, and photon detection



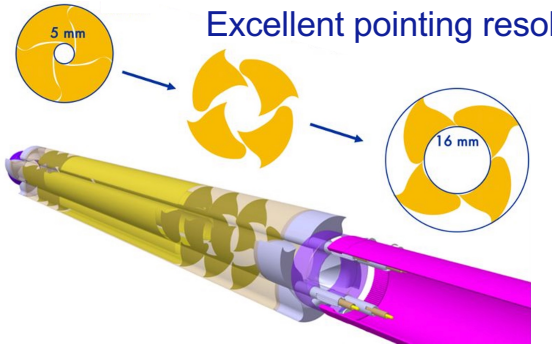
Time resolution: thin LGAD





F. Carnesecchi et al, EPJ Plus 138 1, 99

Excellent pointing resolution: retractable vertex tracker



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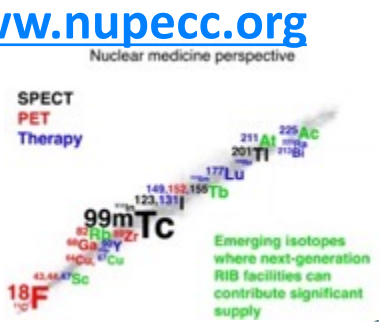
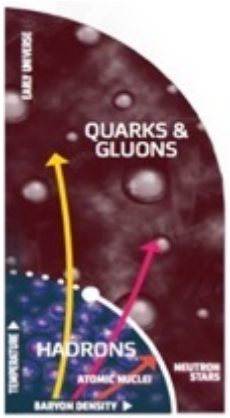
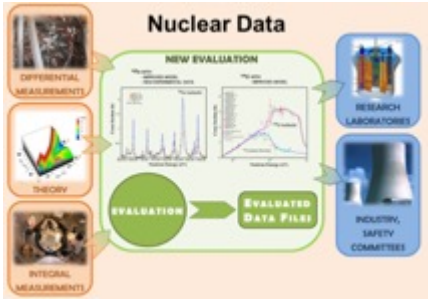
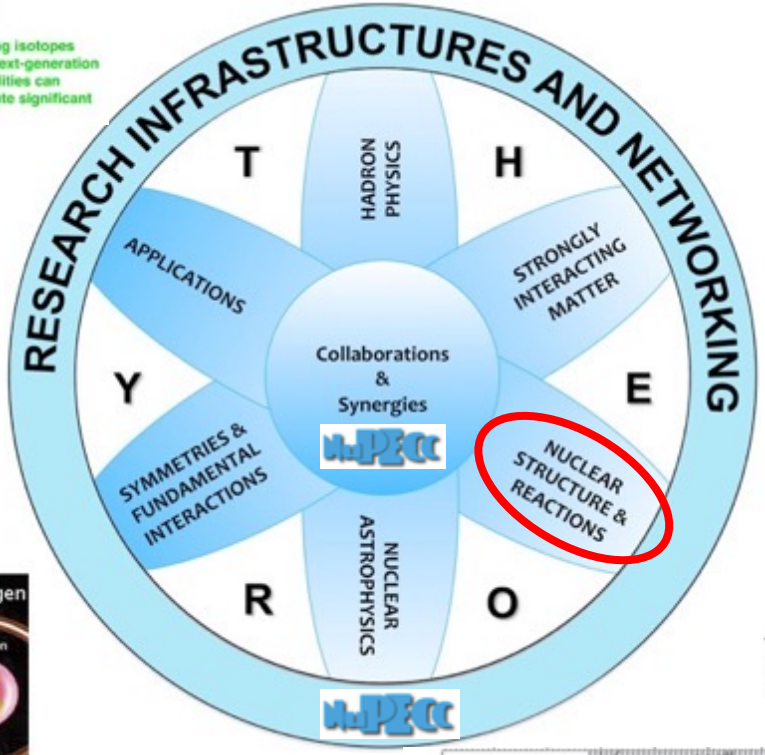
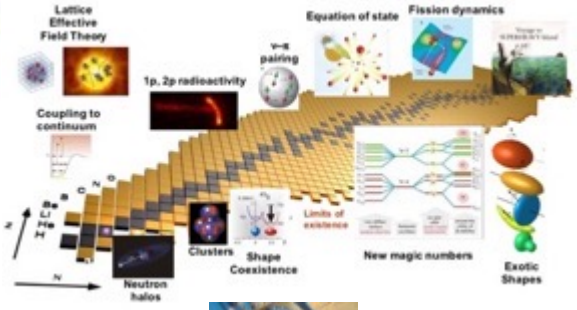
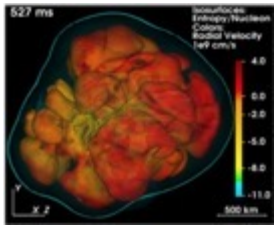


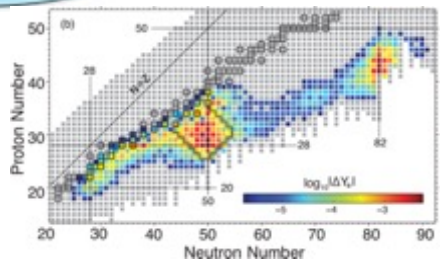








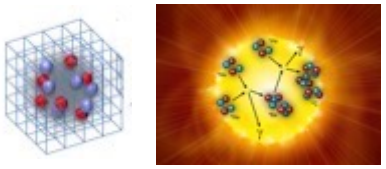




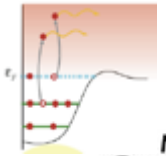
Structure of complex nuclei

- How does the complexity of nuclear structure arise from the interaction between nucleons?
- What are the limits of nuclear stability?

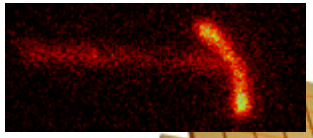
Lattice Effective Field Theory



Coupling to continuum



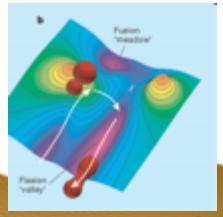
1p, 2p radioactivity

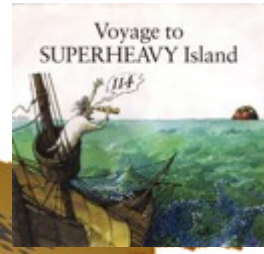


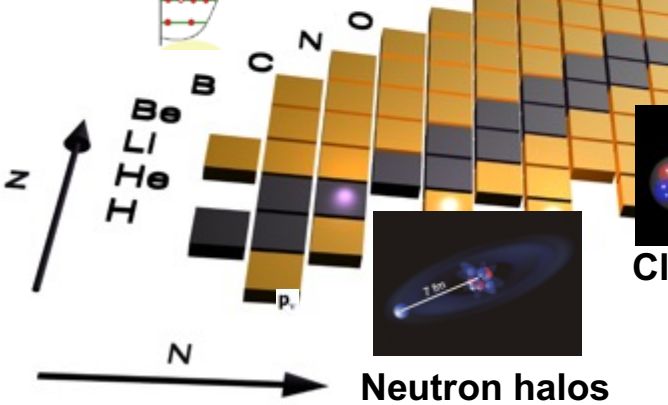
ν–π pairing

Equation of state

Fission dynamics

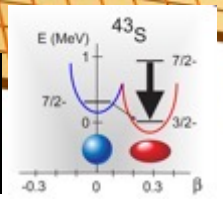






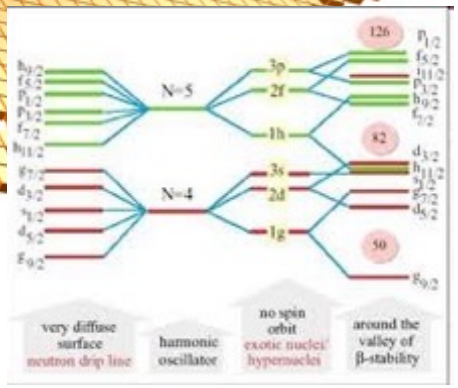
Neutron halos

Clusters

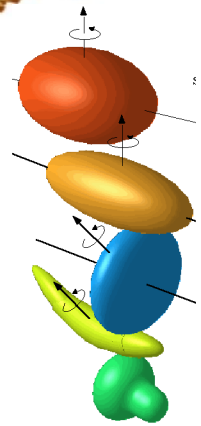


Shape Coexistence

Limits of existence



New magic numbers



Exotic Shapes

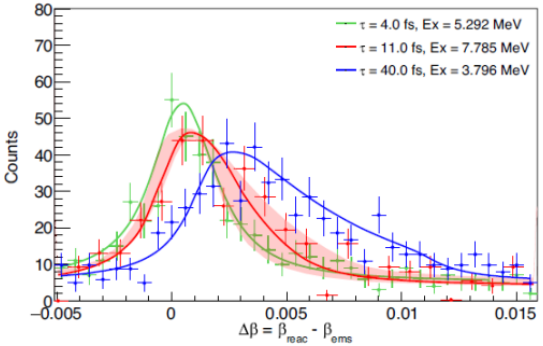
Recent Results from European Nuclear Physics Facilities

AGATA@GANIL

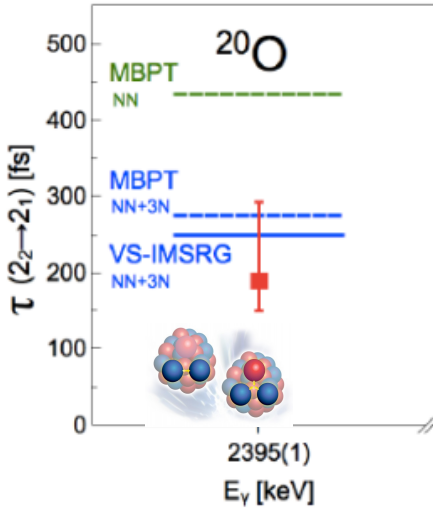
- 27 peer-review paper published including 30% high impact letters
- 16 PhD theses have been defended or in preparation
- 0.5 Pbytes of data recorded

Search for ^{22}Na in novae supported by a novel method for measuring femtosecond nuclear lifetimes

Constraining the ^{22}Na(p, γ)^{23}Mg reaction from the spectroscopy of the 7785.0(7) keV resonance in ^{23}Mg.

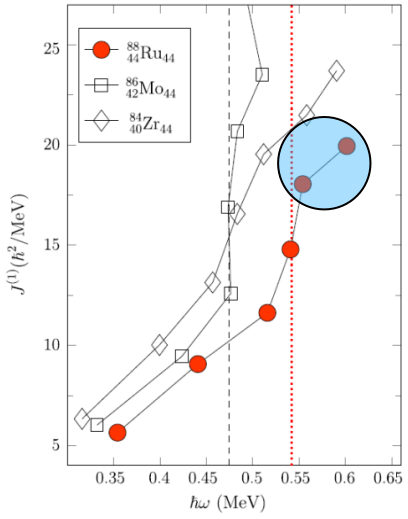


Ch. Fougère et al
Nature Communications volume 14, 4536 (2023)



The obtained results agree well with predictions from MBPT and ab initio VS-IMSRG for ^{20}O, showing that 3N interactions are needed to accurately describe electromagnetic observables in neutron-rich nuclei.

M. Ciemała et al, Phys. Rev. C101, 021303(R) (2020)



Direct observation of a "delayed" rotational alignment in a deformed N = Z nucleus (^{88}Ru), in agreement with theoretical predictions related to the presence of strong isoscalar neutron-proton pair correlations.

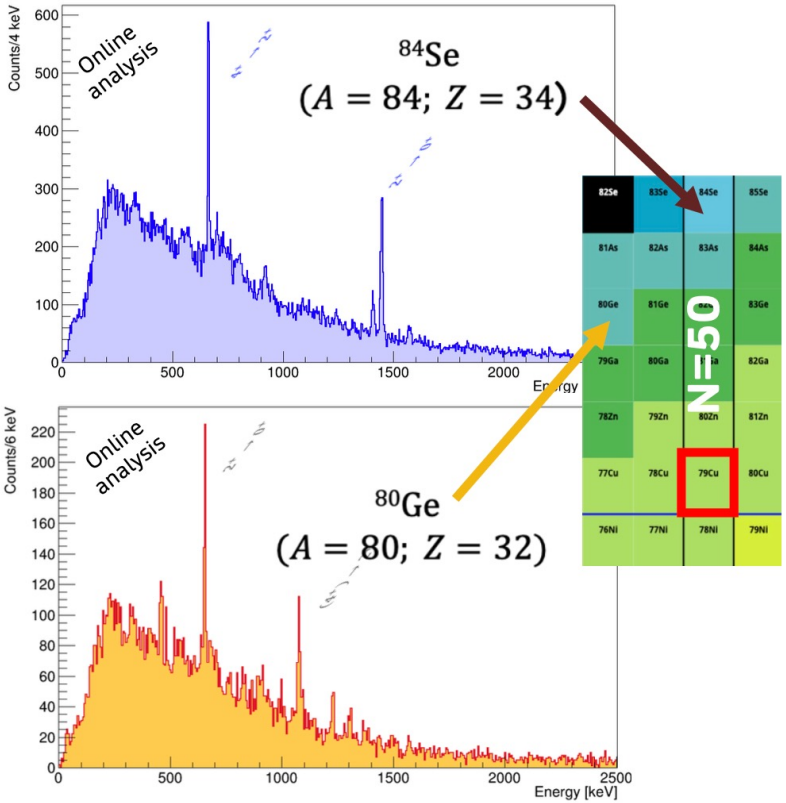
B. Cederwall et al, Phys. Rev. Lett. 124,062501 (2020)

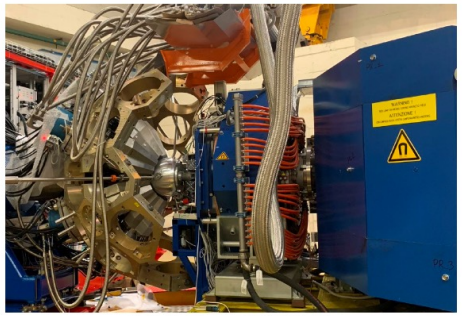
Courtesy of E. Clement

First AGATA Physics Campaign at LNL Italy

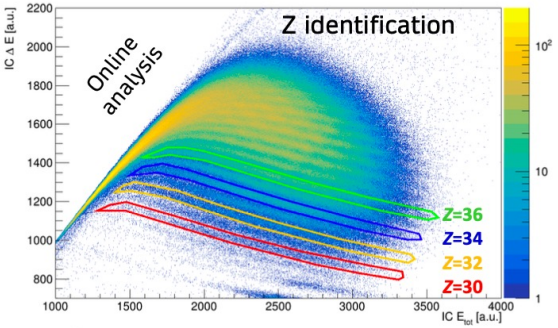
Fusion-Fission reactions for N=50 studies

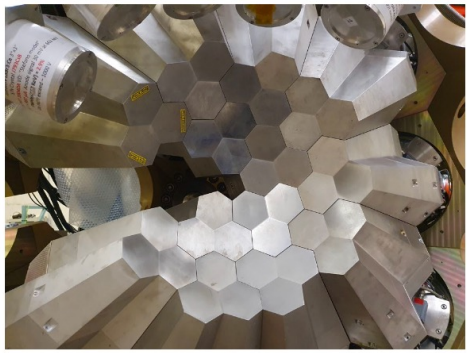
1.3 GeV ^{208}Pb + ^{9}Be



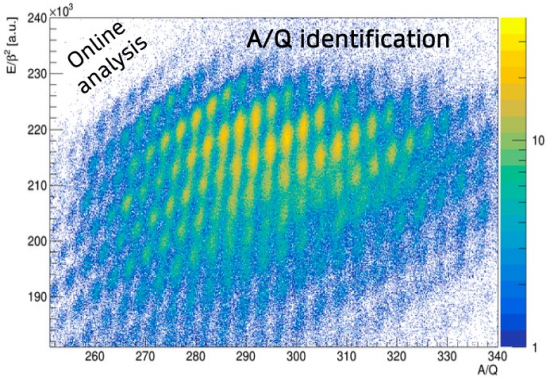


AGATA + PRISMA





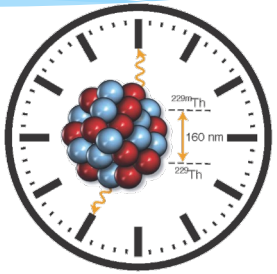
View of AGATA from the target position



Courtesy of T. Marchi

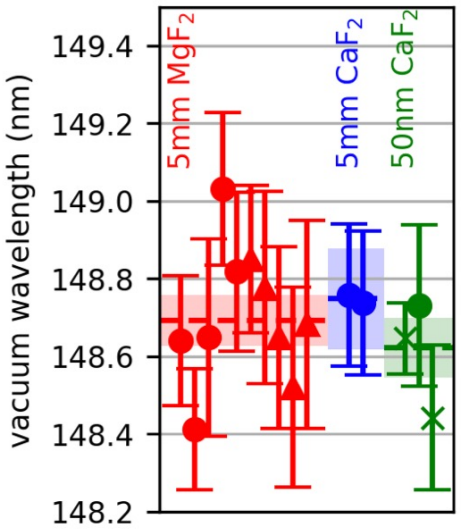
^{229m}Th and its Application as a Nuclear Clock

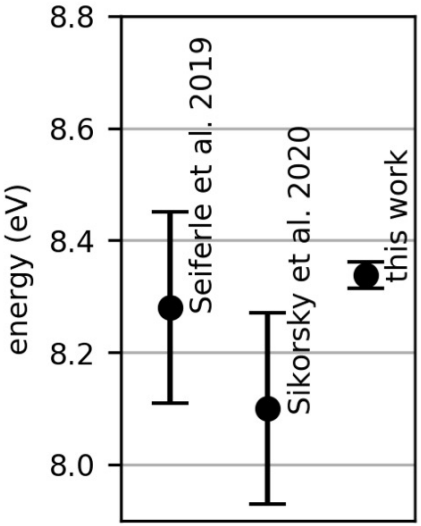
Observation of the radiative decay of the ^{229}Th nuclear clock isomer

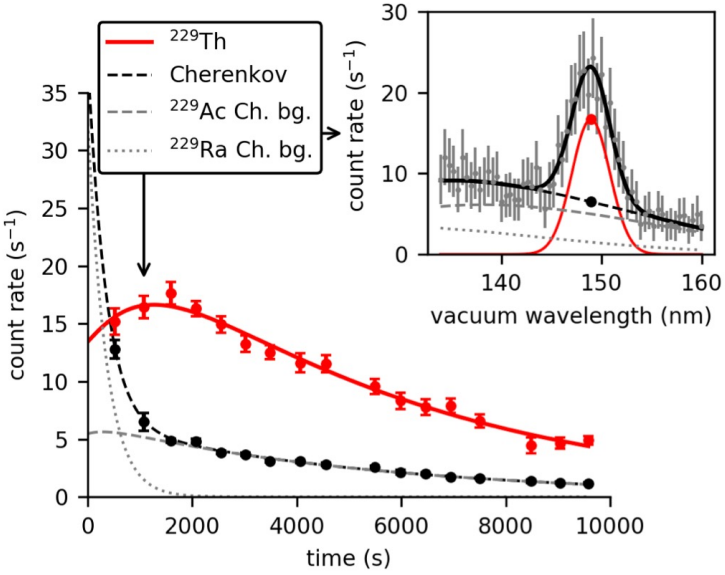


Kraemer, S. *et al. Nature* 617, 706–710 (2023)

- ^{229m}Th properties: E* = 8.338(24) eV
- half-life of ^{229m}Th embedded in MgF_2 is determined to be 670(102) s







Courtesy of P.G. Thirolf and S. Freeman

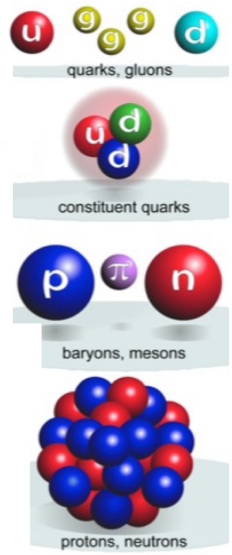
Structure of complex nuclei
New Era of Nuclear Theory

Quantum Chromodynamics (QCD)

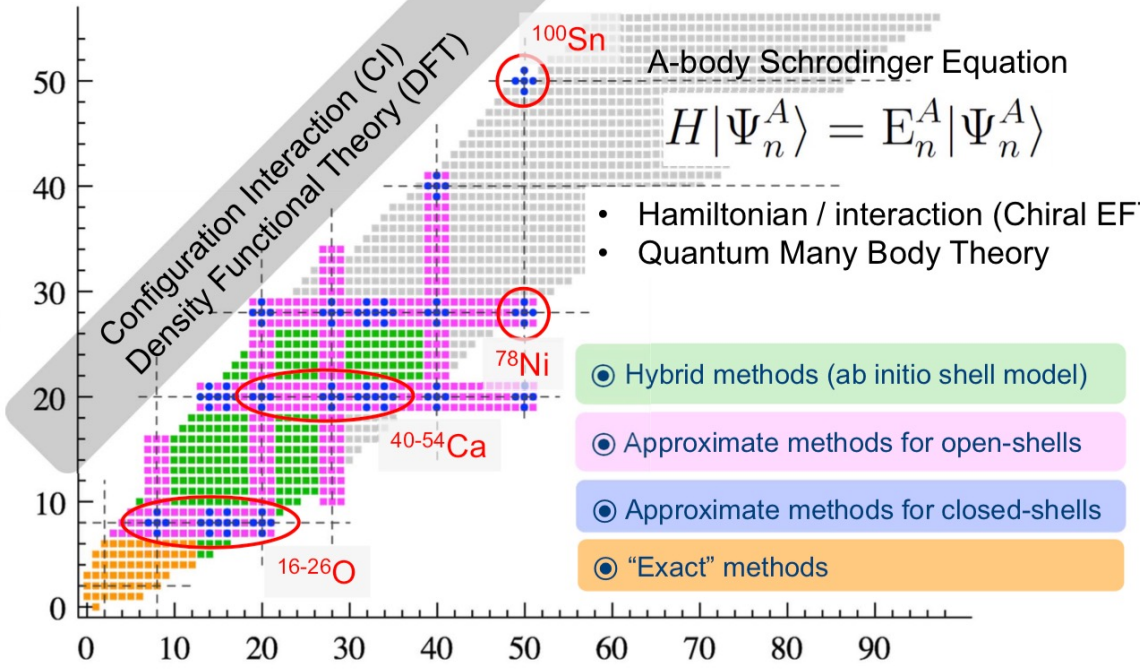
Chiral Effective Field Theory (parameters fitted to NN data)

Current *ab initio* nuclear theory

$H\,\Psi^{(A)} = E\,\Psi^{(A)}$



Application Domain of the Theoretical Approaches



A-body Schrodinger Equation

$$H|\Psi_n^A\rangle = \mathrm{E}_n^A|\Psi_n^A\rangle$$

- Hamiltonian / interaction (Chiral EFT)
- Quantum Many Body Theory

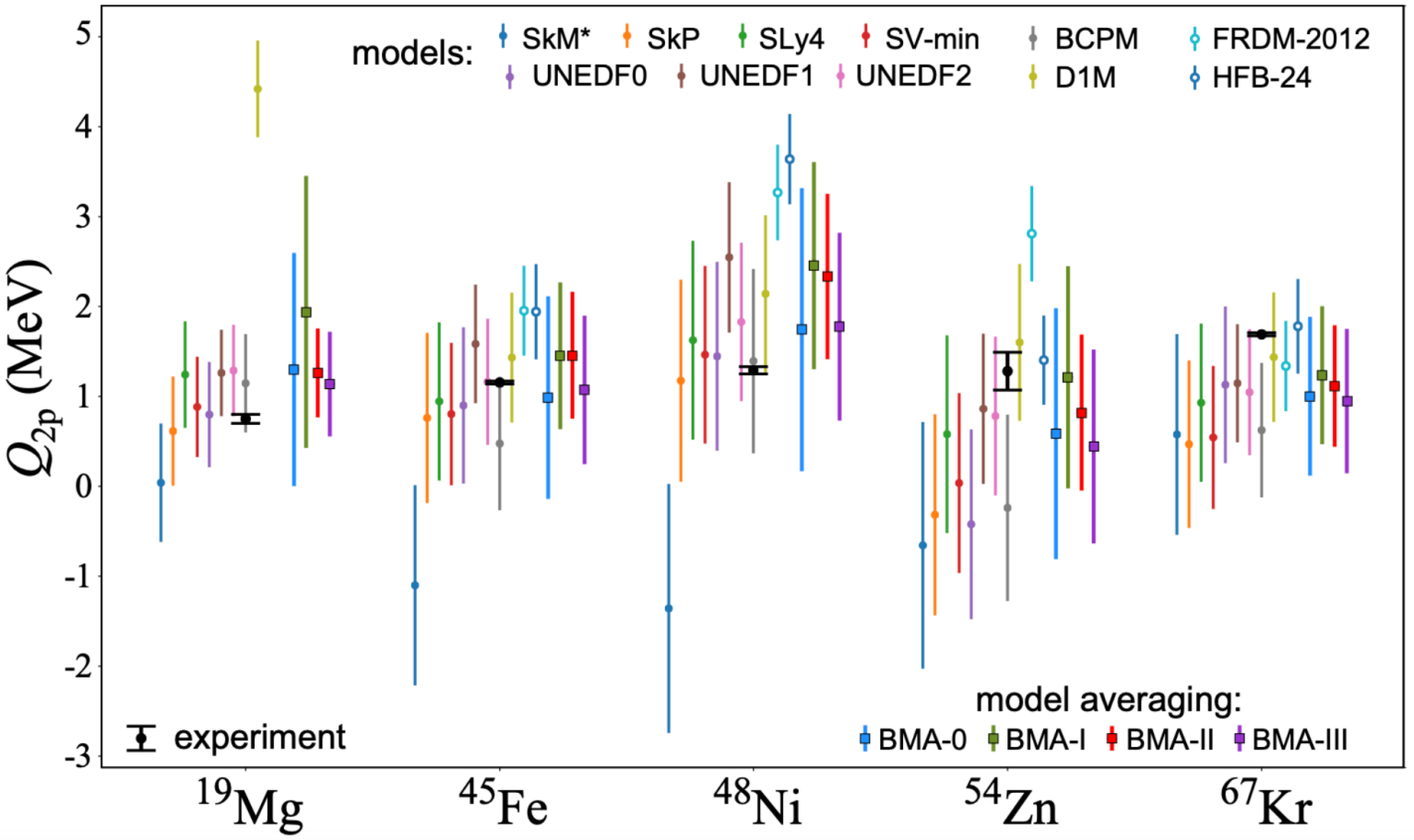
- Hybrid methods (ab initio shell model)
- Approximate methods for open-shells
- Approximate methods for closed-shells
- "Exact" methods

Machleidt & Entem, Phys. Rep. 503 (2011)
Epelbaum, Hammer & Meißner, Rev. Mod. Phys. 81 (2009)
Hagen,- Rept. Prog. Phys. 77 (2014)
Hergert,- Phys. Rep. 621 (2016)

Courtesy T. Duguet & P. Navratil

Proton drip line and beyond: Bayesian analysis of proton-emitting nuclei

L. Neufcourt et al., Phys. Rev. C 101, 014319 (2020)



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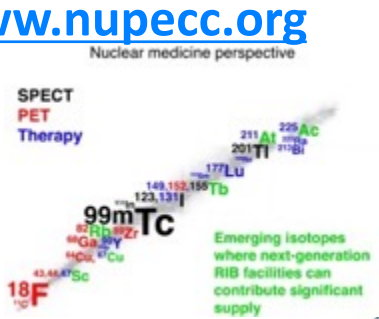
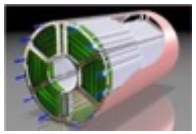
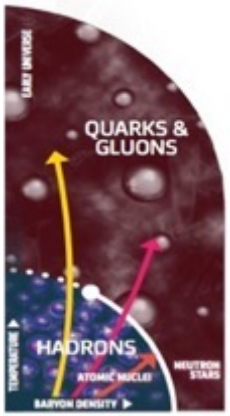
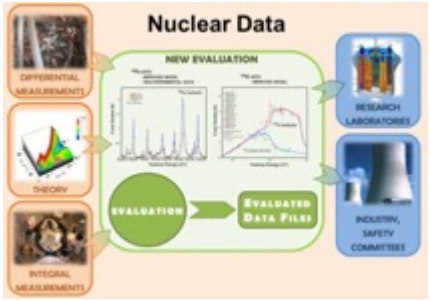
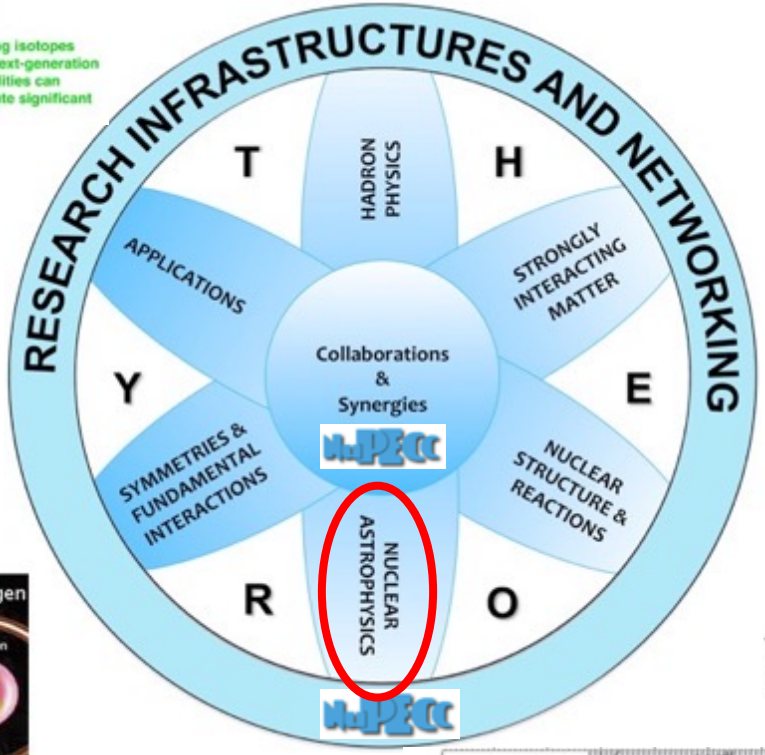
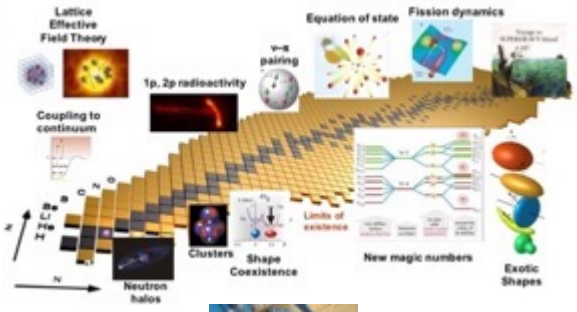


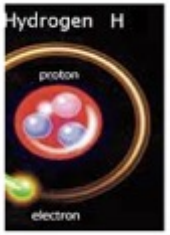


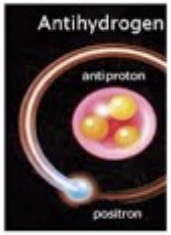


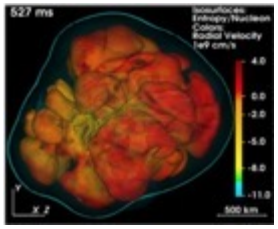


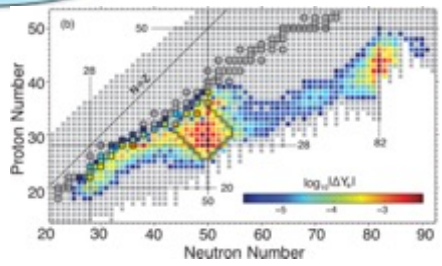










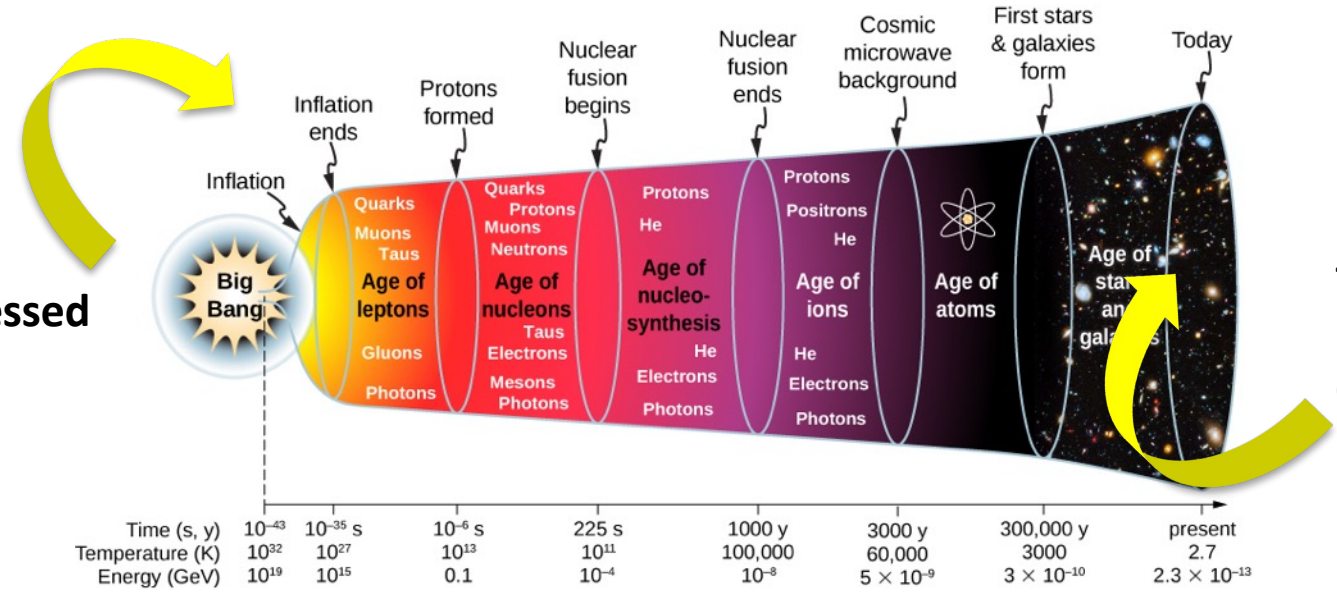


Nuclear physics and the evolution of the Universe

- What are the properties of nuclei and strong-interaction matter as encountered shortly after the Big Bang, in catastrophic cosmic events, and in compact stellar objects?
- How and where in the universe are the chemical elements produced?

QCD

QCD in hot compressed matter

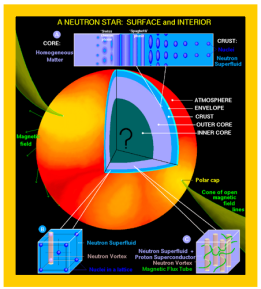


Nuclear structure
Nucleosynthesis

Reactions for astrophysics

Compressed nuclear matter

Neutron star mergers
Truly interdisciplinary research



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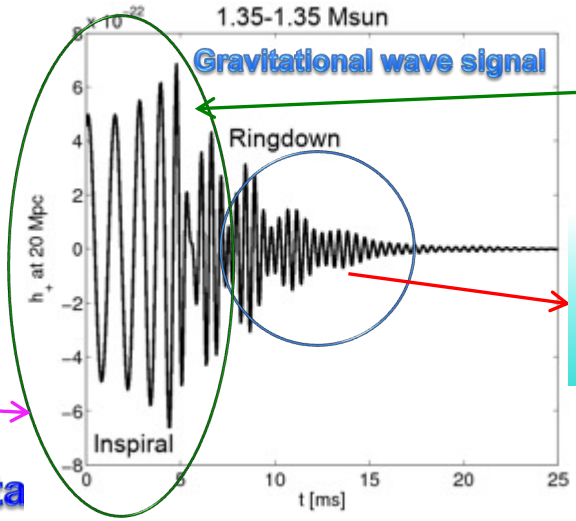


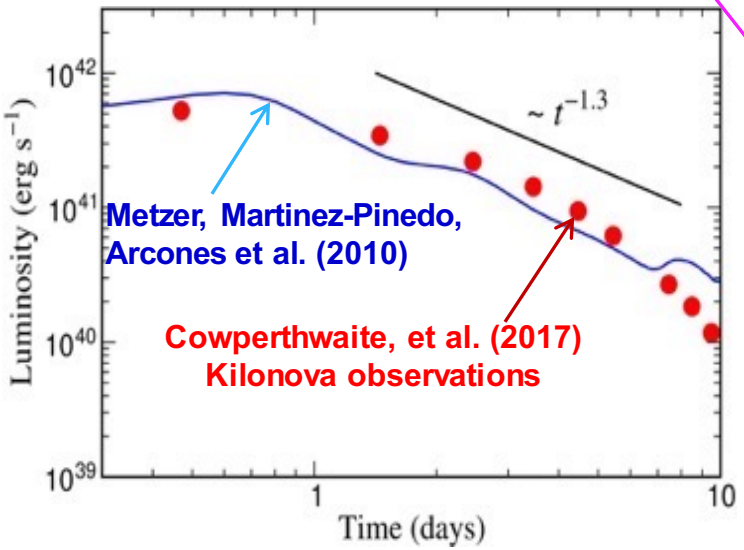
Neutron star mass

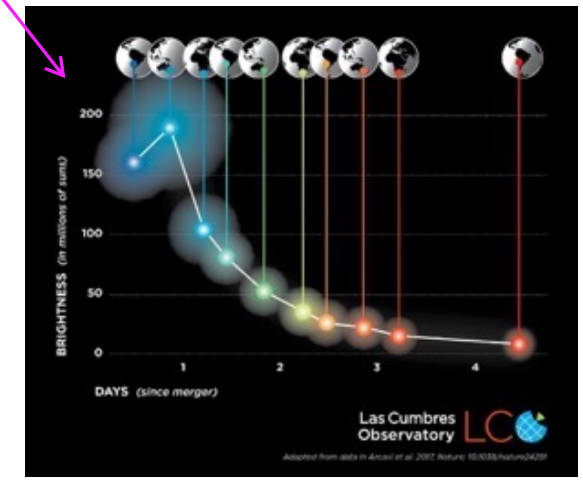
Ringdown depends on the Nuclear Equation of state

The messengers from neutron star mergers :

- **Gravitational waves**
- **Electromagnetic signals characterizing the nuclei in the ejecta**
- **neutrinos**

Gravitational wave emission seen together with electromagnetic signals

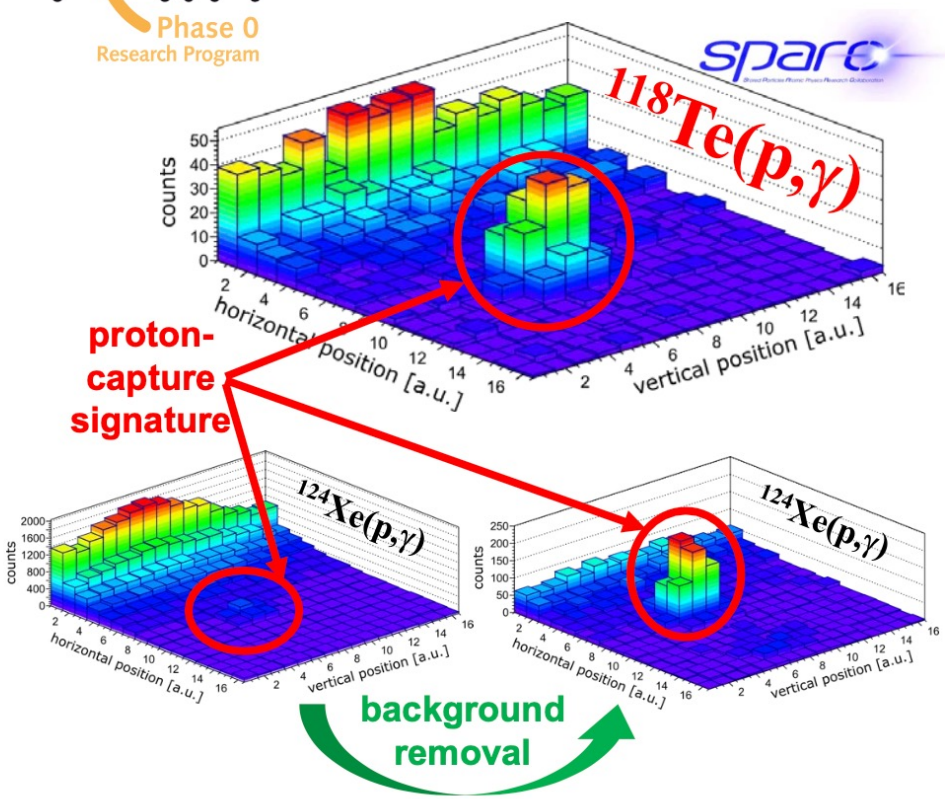




Time evolution determined by the radioactive decay of r-process nuclei (science drive of facilities with Radioactive Ion Beams)

Ground-breaking experiment opening way for nuclear astrophysics experiments at FAIR with ESR

- E127: Proton-capture rates for nuclear astrophysics:
  First reaction study on stored radio-beam at low energies
- Study of radioactive ^{118}Te (6 days half-life)
  - production, storage, accumulation and deceleration in FRS-ESR
  - proton-capture measurements realized at 7 MeV/u and 6 MeV/u
- New background-free detection method demonstrated

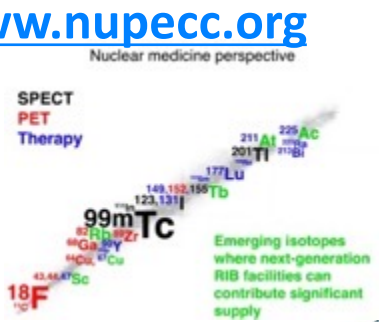


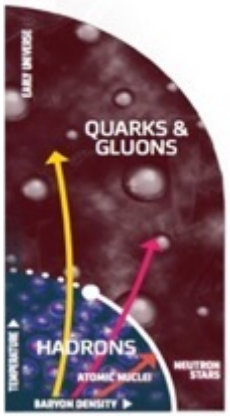
Jan Glorius et al.

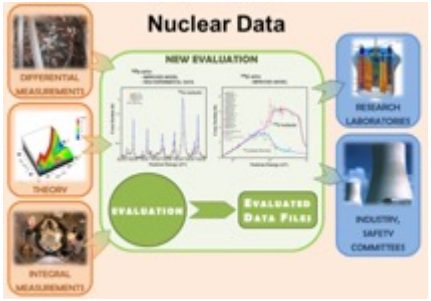
Curtesy of P. Giubellino

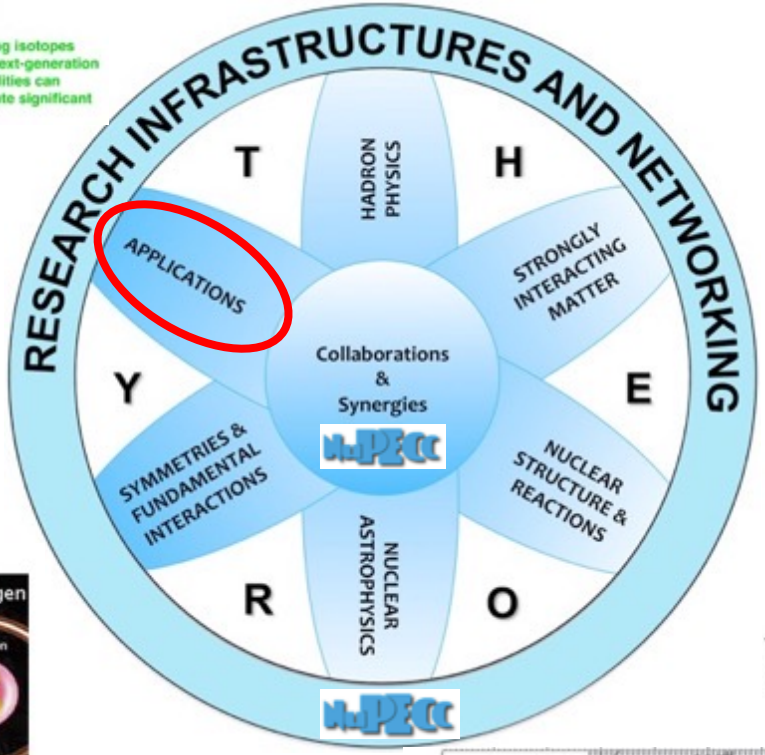
Recent Results from European Nuclear Physics Facilities

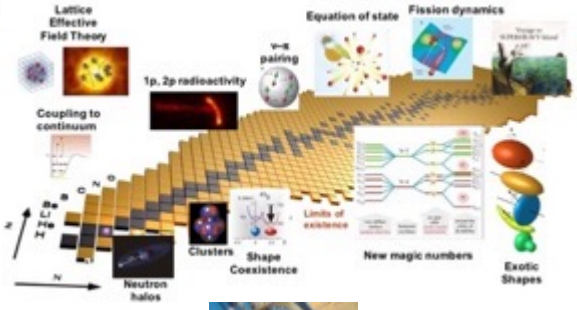
http://www.nupecc.org

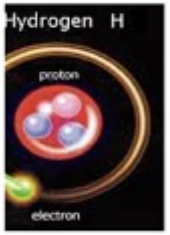


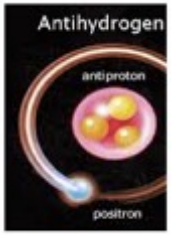


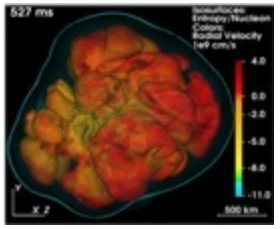


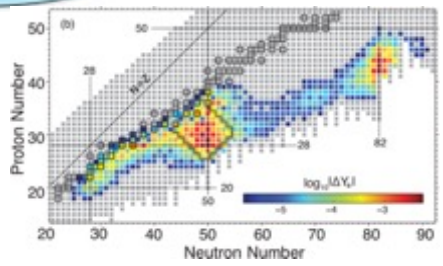




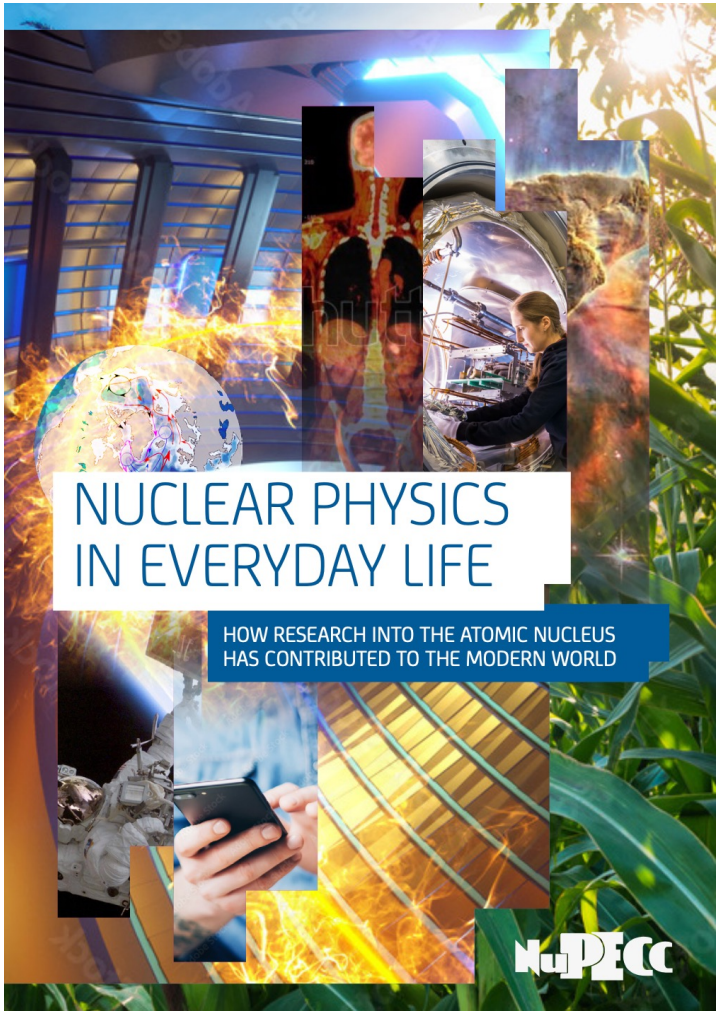








Applications of nuclear science



NuPECC report on

Nuclear Physics in Everyday Life

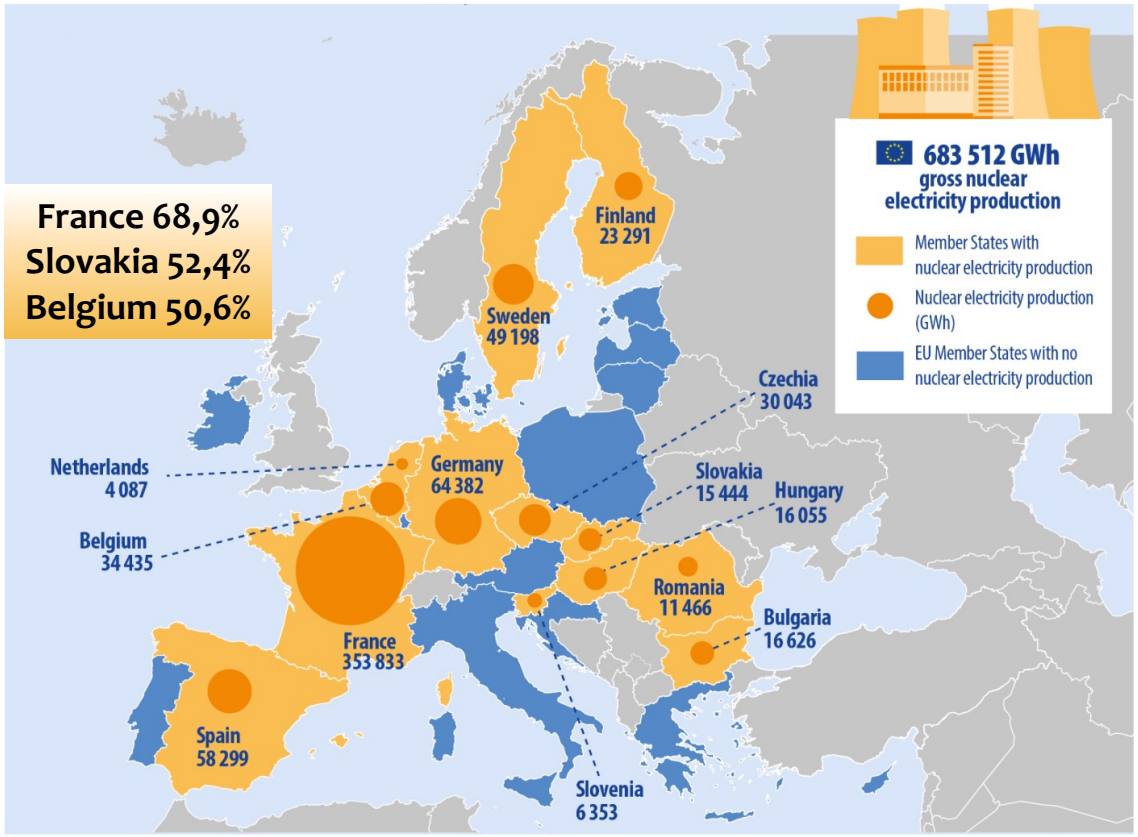
(100 pages, open access on-line and printed version available with)

https://nupecc.org/pub/np_life_print.pdf

- **Climate & Environment**
- **Energy** (electric power generation, waste management, **nuclear data**)
- **Health** (radioisotopes for therapy and diagnosis, hadrontherapy) (e.g. Theranostics, flash therapy)
- **Everyday life products**
- **Cultural heritage and Forensics**
- **Space technology & exploration**

Energy applications

Nuclear Energy in EU (2022)



France 68,9%
Slovakia 52,4%
Belgium 50,6%

In 2022, nuclear plants generated 22 % of the electricity produced in the European Union, with nuclear reactors operating in 12 Member States

In Europe (2023):
164 nuclear power reactors (107,7 GWe)
Under construction:
4 reactors in EU & UK
(5 in Russia and Ukraine)

EU Complementary Climate Delegated Act 2022

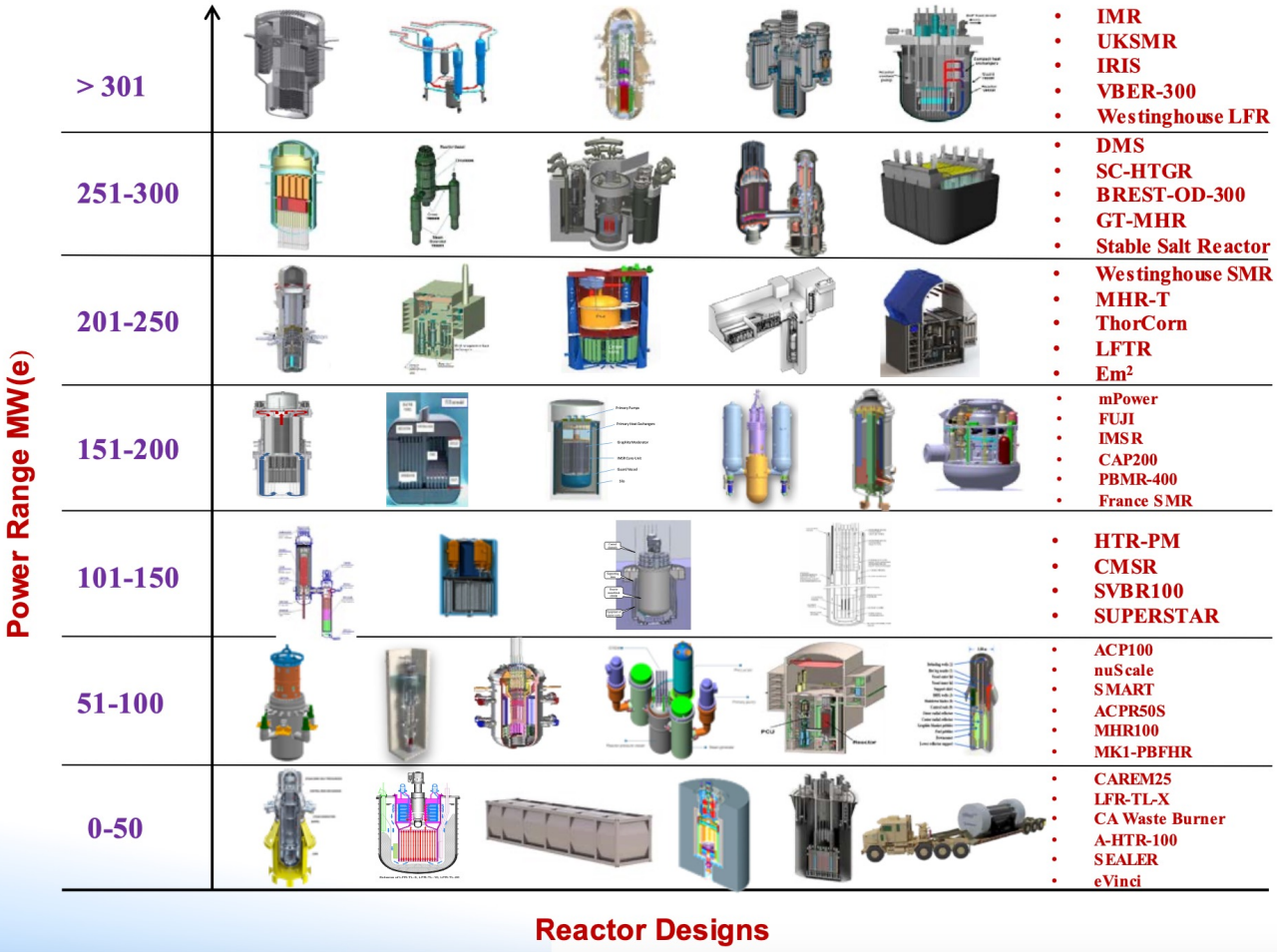
The criteria for the specific gas and nuclear activities are **in line with EU climate and environmental objectives** and will help accelerating the shift from solid or liquid fossil fuels, including coal, towards a climate-neutral future.

New reactors will be constructed in Bulgaria, France (14), Poland and UK

Sources: EUROSTAT, EC, WORLD NUCLEAR ASSOCIATION

Energy applications

Small Modular Reactors (SMR)



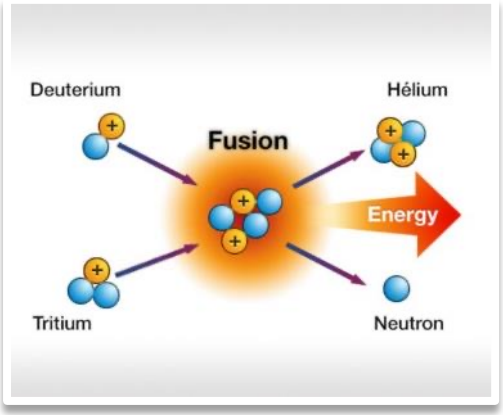
SMRs - advanced nuclear reactors, ≤300 MW(e) (1/3 of standard reactors)

Small – size
Modular – easy to transport and assemble
Reactors – fission

Sources: IAEA, NRC

Energy applications

ITER – Bringing the power of the sun to earth

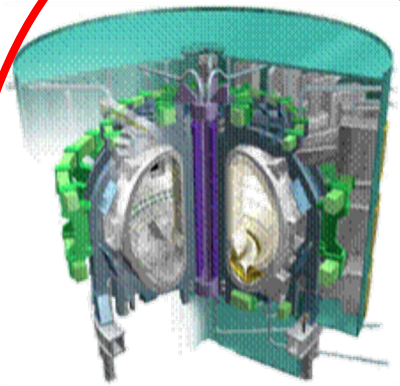


Fusion on earth needs temperatures of 100-150 million ° C

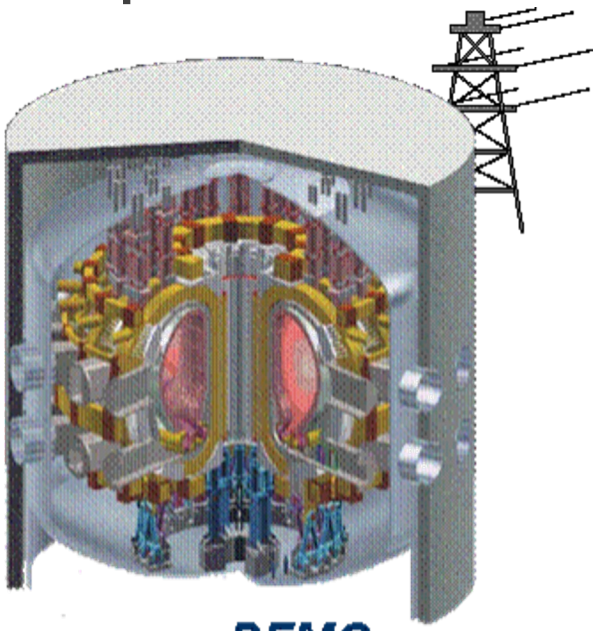
Many experiments in Europe and the rest of the world

Tore Supra
25 m³
~ 0 MW_{th}

JET
80 m³
~16 MW_{th}



ITER
800 m³
~ 500 MW_{th}

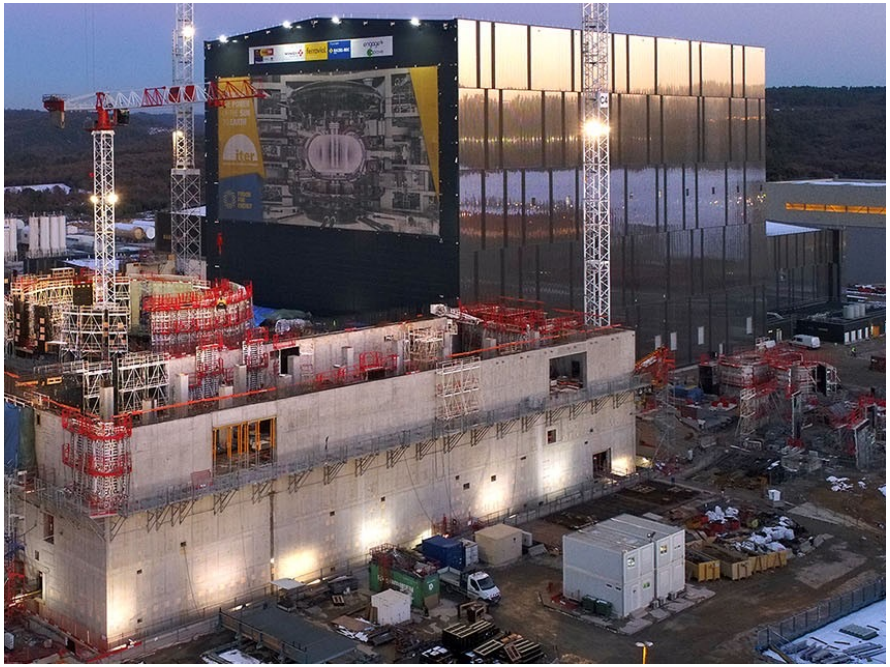


DEMO
~ 1000 - 3500 m³
~ 2000 - 4000 MW_{th}

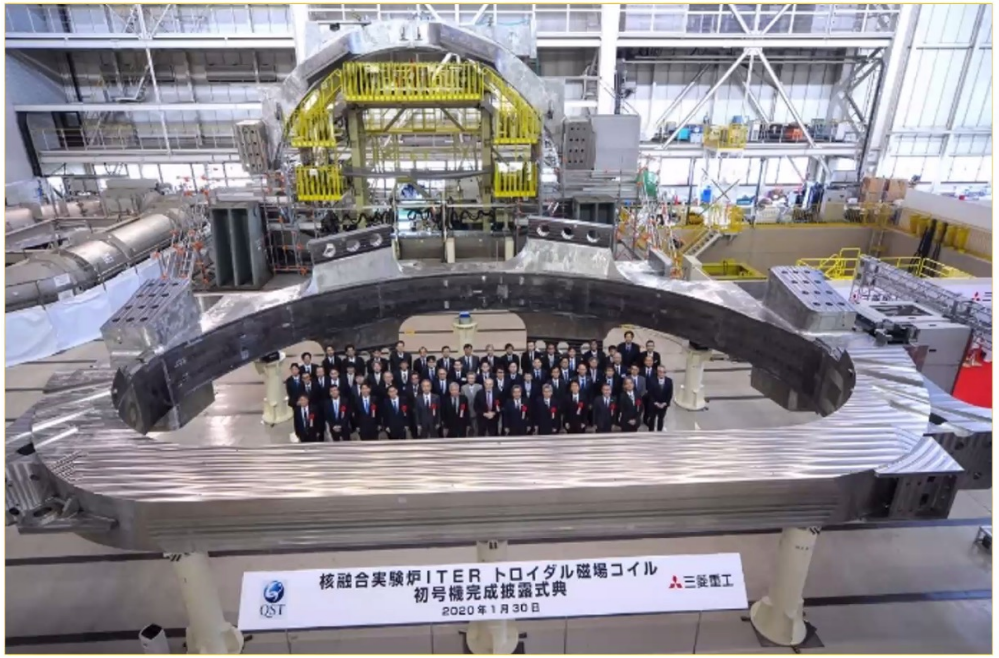
Energy applications

ITER – Bringing the power of the sun to earth

Construction site at Cadarache, France



Completed Superconducting TF Coil



First plasma ≥ 2025
Full power by 2035

Nuclear Data for fundamental physics and applications

Needs for a Comprehensive European Plan to Acquire and Curate Nuclear Data

Summary Report of the IAEA Consultants' Meeting IAEA Headquarters, Vienna, Austria
25 – 27 April 2023

Recommendations

- Establish priorities for nuclear data measurements and evaluations for applications based on existing priority lists maintained by the different stakeholders.
- Recognise the importance of curated nuclear data also for fields beyond nuclear physics and its applications, e.g., research in astrophysics and particle physics, and strive to maintain the related databases based on FAIR (findable, accessible, interoperable, reusable) principles.
- Strive to establish a sustainable source of funding of measurements and data evaluation, including well-defined career paths in nuclear data
- Maintain access to key experimental infrastructures that enable specific measurement methodologies including target preparation and supply to produce nuclear data relevant for applications.
- Reinforce cooperation with international organisations (IAEA, NEA), which should provide support in the form of coordination, training, dissemination, and outreach

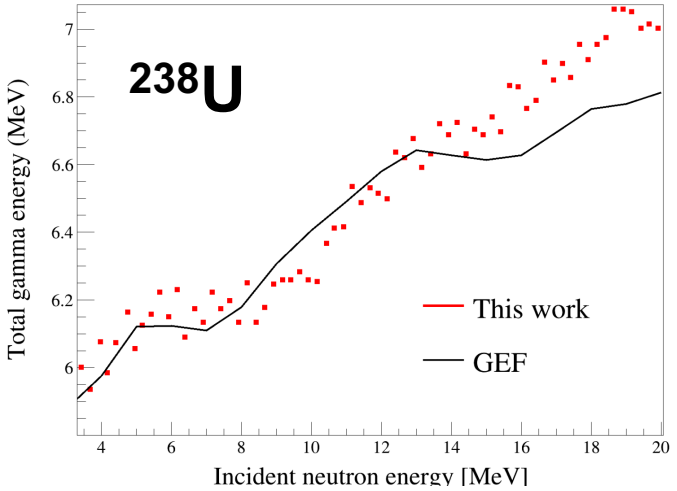
Study of the (n,xn) and (n,f) reaction for ^{238}U at NFS, GANIL/SPIRAL2

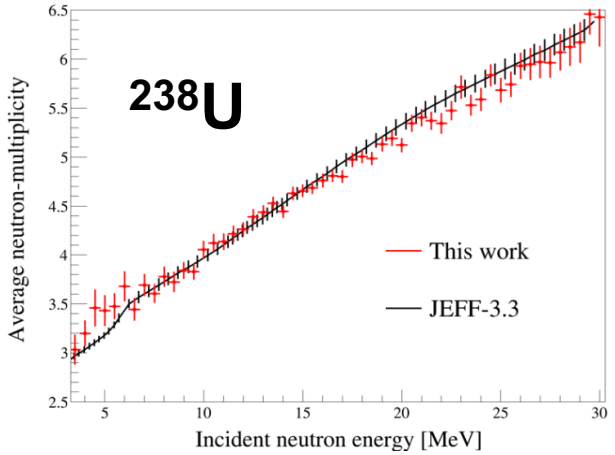
Spokesperson : G. Bélier, CEA-DAM-DIF

- (n,xn) reaction are important channels in the 5-50 MeV range
- (n,xn) cross-section measurement of actinide is very difficult:
  - radioactive sample
  - prompt neutron fission

Experimental technique :

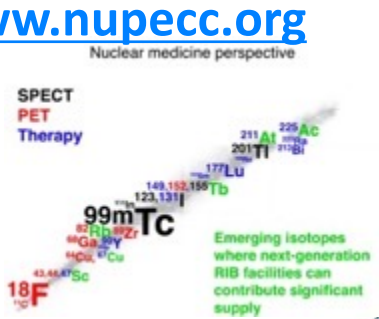
- ❑ Veto fission (fission chamber)
- ❑ 4π neutron detector SCONE
- ❑ 6 MeV<En< 20 MeV

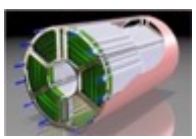


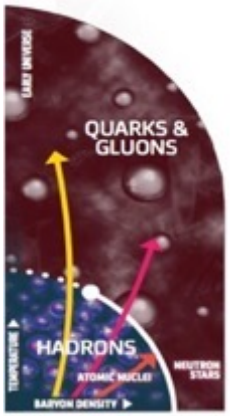


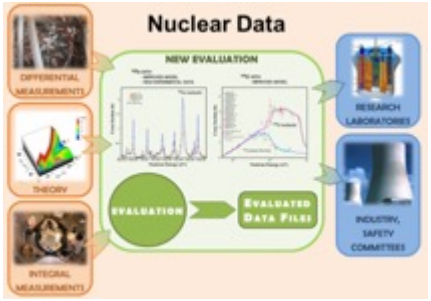
Recent Results from European Nuclear Physics Facilities

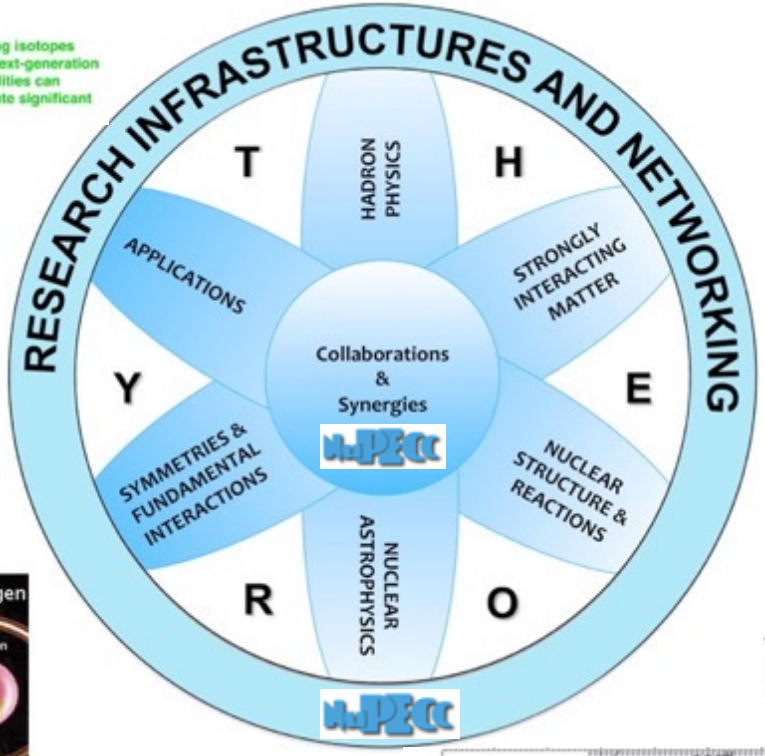
http://www.nupecc.org

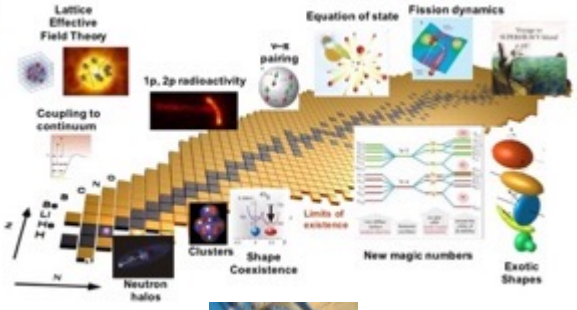


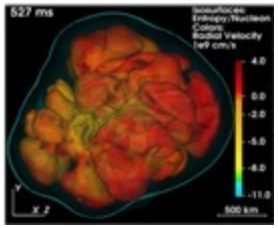


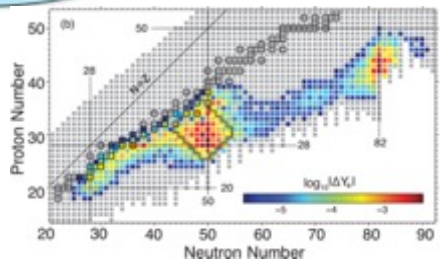










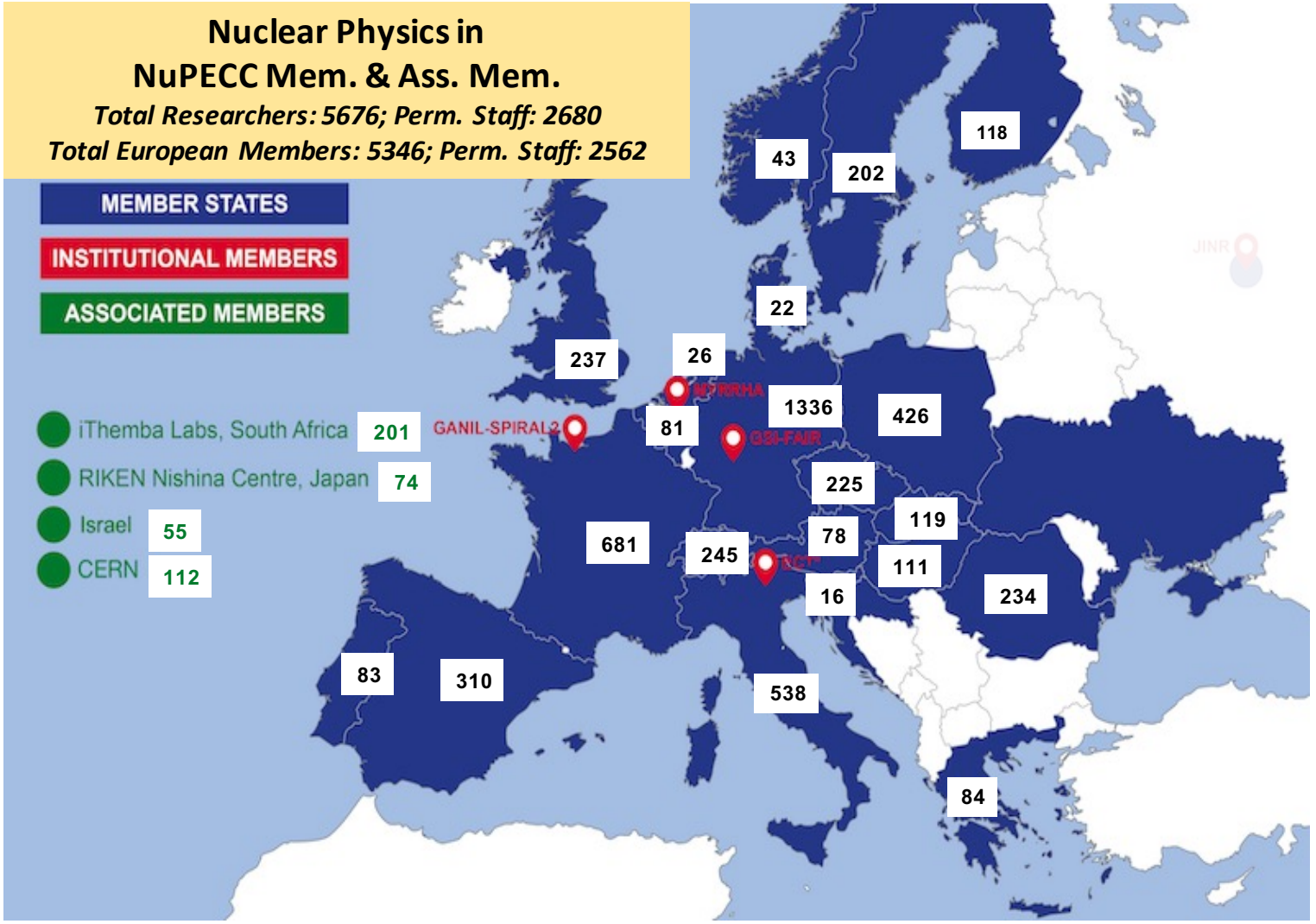


NuPECC Survey of Nuclear Physics in Europe

Nuclear Physics in NuPECC Mem. & Ass. Mem.

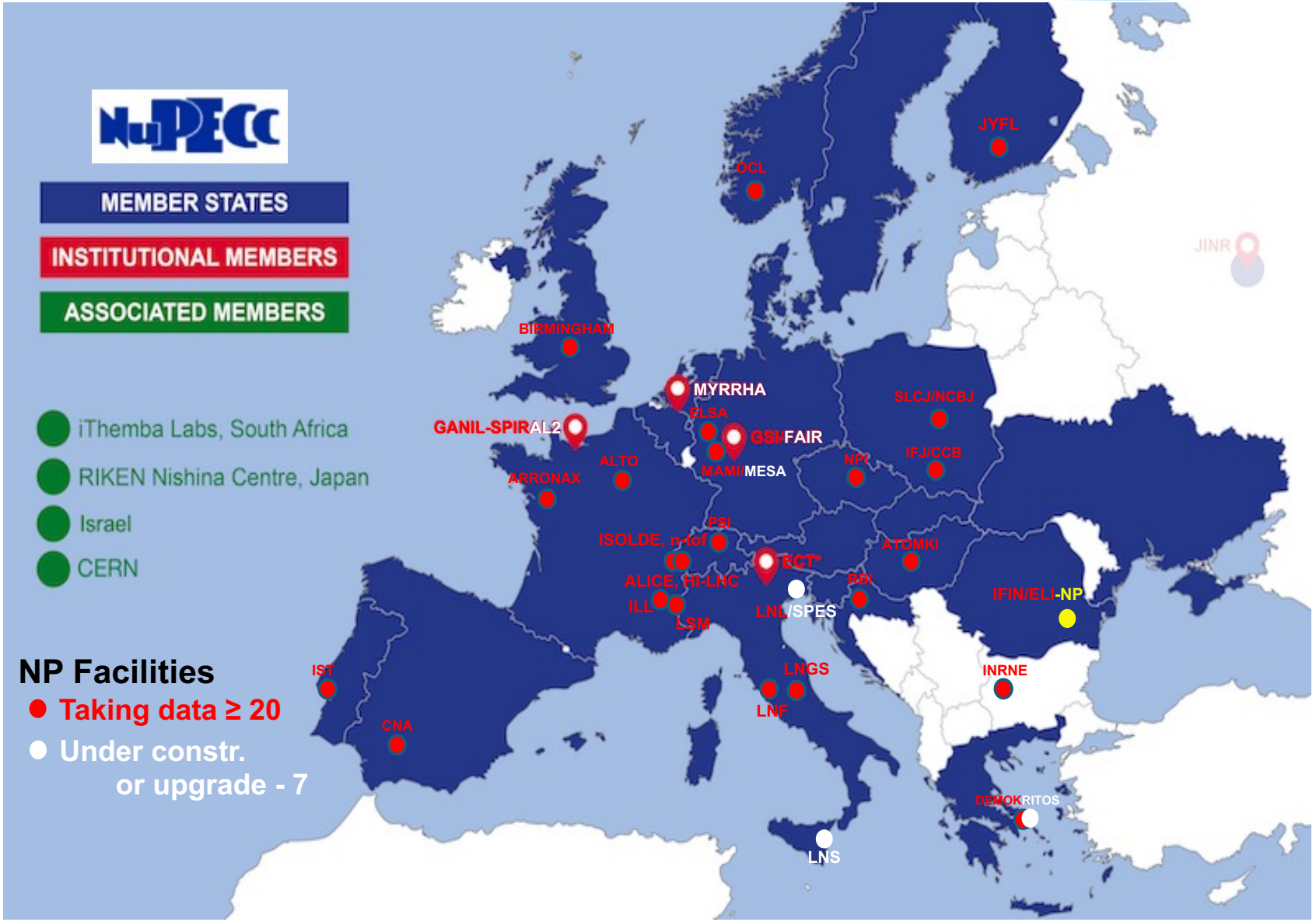
Total Researchers: 5676; Perm. Staff: 2680

Total European Members: 5346; Perm. Staff: 2562

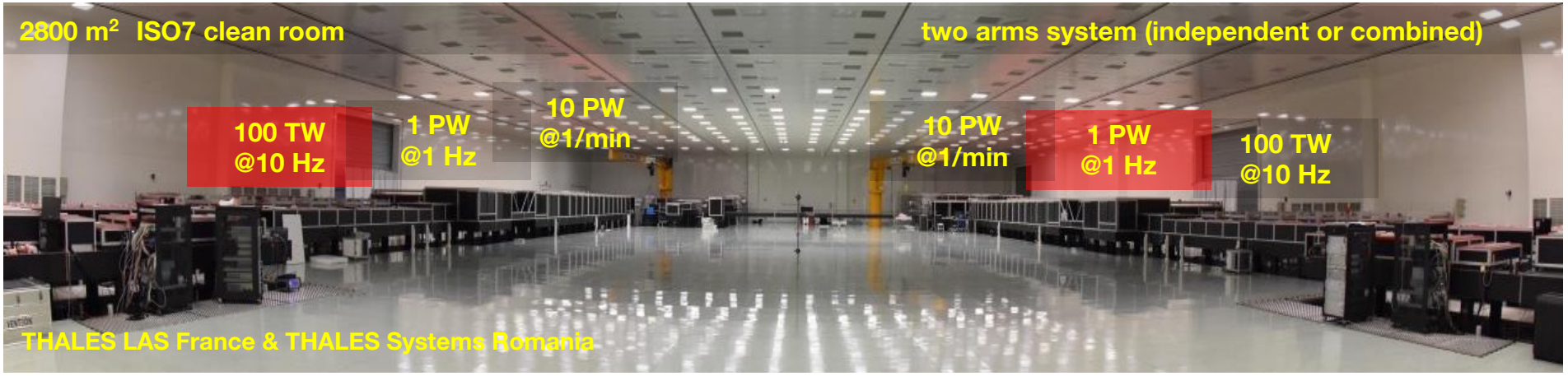


J. J. Gomez Camacho, Ulf-G. Meißner et al.

European Landscape of major NP infrastructures



Roadmap NP facilities



ELI-NP Magurele, Romania

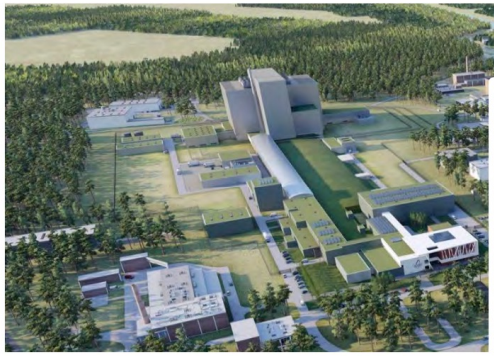
Operational since 2020

The highest power (10PW) operational laser system in the world

- **100 TW : *ongoing***
  - Four-wave mixing in vacuum, in search of dark matter candidates
  - X ray production through betatron emission
- **1 PW : *ongoing***
  - Benchmark TNSA proton acceleration
  - Benchmark LWFA electron acceleration
- **10 PW solid target**
  - Demonstrate extreme focal intensity through laser-γ conversion ("γ-flash")
  - Demonstrate over 200 MeV proton acceleration
  - Dense heavy ion beams for nuclear physics
- **10 PW gas target**
  - 10 PW laser wakefield acceleration of multi-GeV electron beams

Courtesy of N. Marginean and C. Ur

MYRRHA/MINERVA, SCK/CEN, Belgium



towards MYRRHA

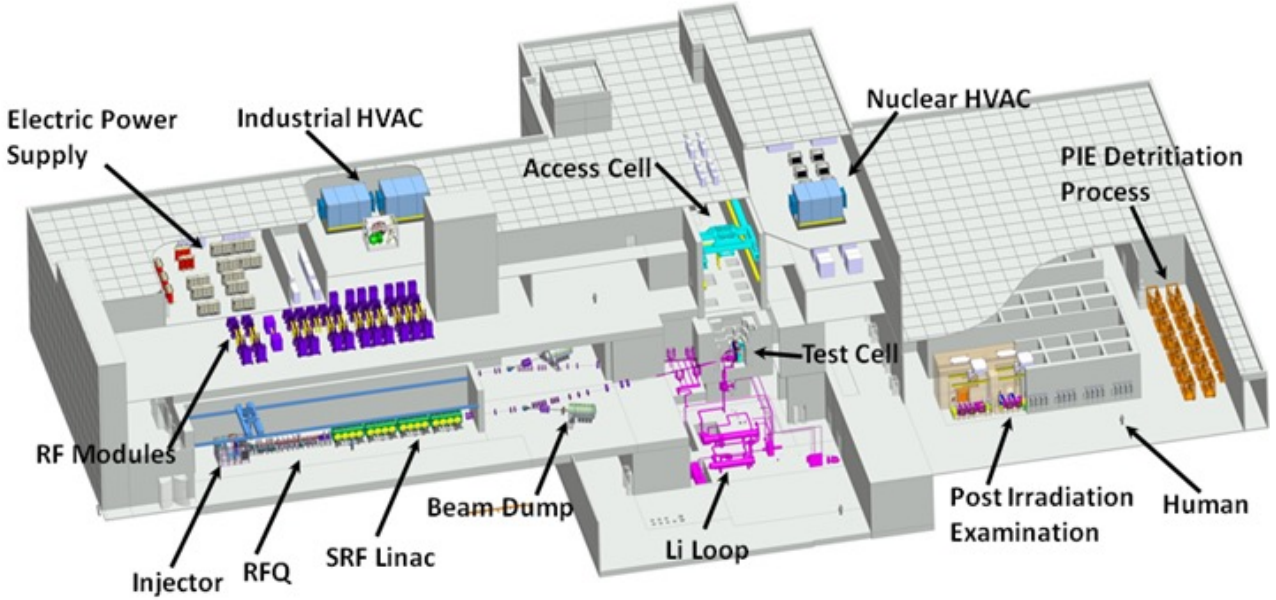
... MINERVA

ISOL@MYRRHA
Implemented in the **Proton Target Facility**

- **Accelerator Driven System (ADS) MYRRHA/MINERVA broke the ground in 2023**
- **Construction of ISOL@MYRRHA systems based on 100MeV 0.5mA proton linac started**
- **First ISOL beams by 2031**

Courtesy of L. Popescu

IFMIF-DONES, International Fusion Materials Irradiation Facility



A fusion relevant neutron source is necessary step for the successful development of fusion energy.

The International Fusion Materials Irradiation Facility – Demo Oriented NEutron Source (IFMIF-DONES) is a single-sited novel research infrastructure for testing, validation and qualification of the materials to be used in future fusion power plants like DEMO (a demonstration fusion reactor prototype)

40 MeV deutron beam at 125mA

https://ifmifdones.org

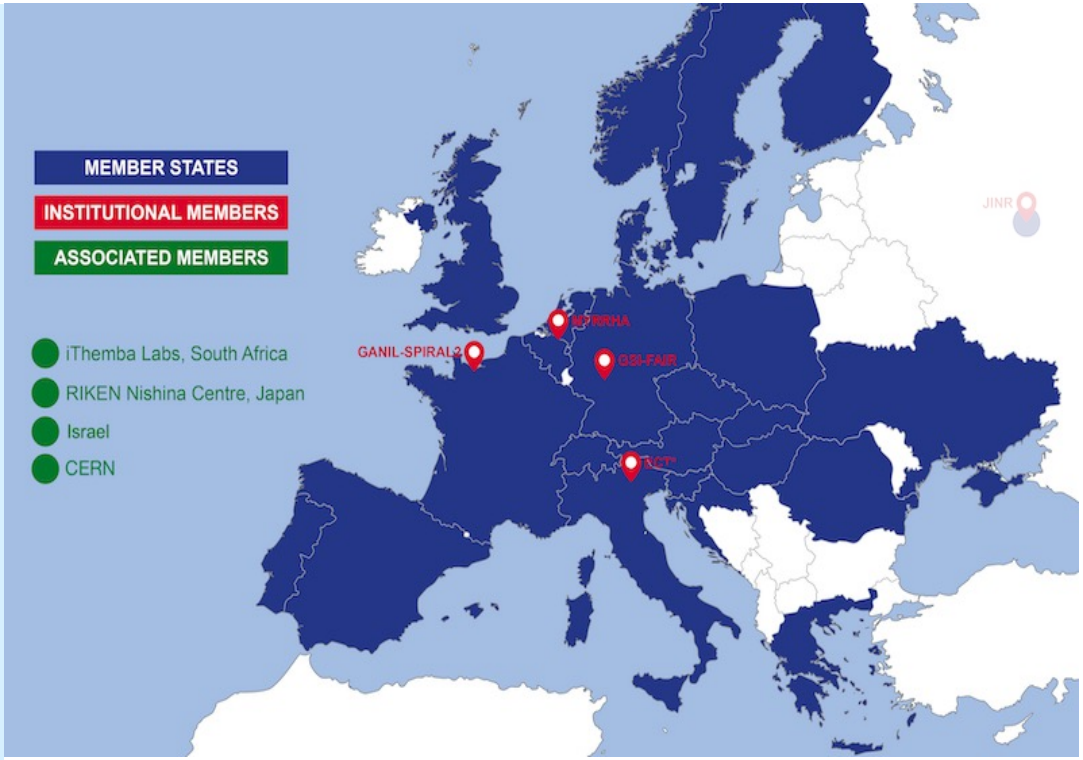
What is NuPECC ?

Nuclear Physics European Collaboration Committee (NuPECC)
Is the European Expert Board for Nuclear Physics
hosted by European Science Foundation

Representing
6000 scientists

Composition:

- 35 representatives from 23 countries (new member Ukraine), 3 ESFRI NP Infrastructures & ECT*
  JINR Dubna – suspended in March 2022
- 4 associated members
  - CERN
  - Israel
  - iThemba Labs
  - Nishina Center
- 9 observers (ALAFNA, ANPhA, APPEC, CINP, ECFA, ESF, IAEA, NPD/EPS, NSAC)



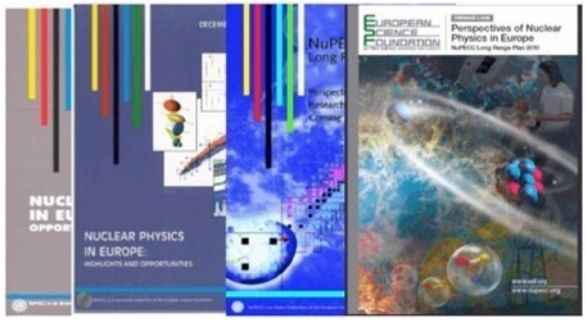
34 Years of NuPECC activities

https://nupecc.org

3 regular Committee meetings/y

Towards NuPECC Long Range Plan 2024

1991 1997 2004 2010



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

Assessment of Implementation of the NuPECC Long Range Plan 2017

February 2022

LIAISONS: G. AARTS, D. BETTONI, S. COURTIN, P. GIUBELLINO, J. GÓMEZ CAMACHO, A. GÖRGEN, R.-D. HERZBERG, D. IRELAND, B. KRUSCHE, M. LEWITOWICZ, A. MAJ, U. MEISSNER, E. NAPPI, G. NEYENS, L. POPESCU, B. SHARKOV, E. WIDMANN,

Contributors: H. Abele, N. Alahari, W. Barth, D. Bemmerer, K. Blaum, F. Bossi A. Bracco, M. Chiossi, A. Denig, M. Doser, S. Freeman, M. Gazdzicki, F. Gélis, H. Goutte, M. Grecco, M. Harakeh, M. Hori, G. Imbriani, E. Khan, K. Kirch, W. Korten, A. Laird, J. P. Lansberg, D. Lunney, F. Maas, G. Martinez-Pinedo, S. Masciocchi, A. Mengoni, O. Navillat-Cuncic, D. Rifuggiato, P. Rossi, E. Scomparin, J. Simpson, H. Schmieden, O. Schneider, N. Severijns, Th. Stöhlker, J. Stroth, H. Ströher, U. Thoma, S. Ulmer, C. A. Ur, Ch. Weinheimer, U. Wiedner, H. Wittig

NuPECC LRP 2017

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

February 2022

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

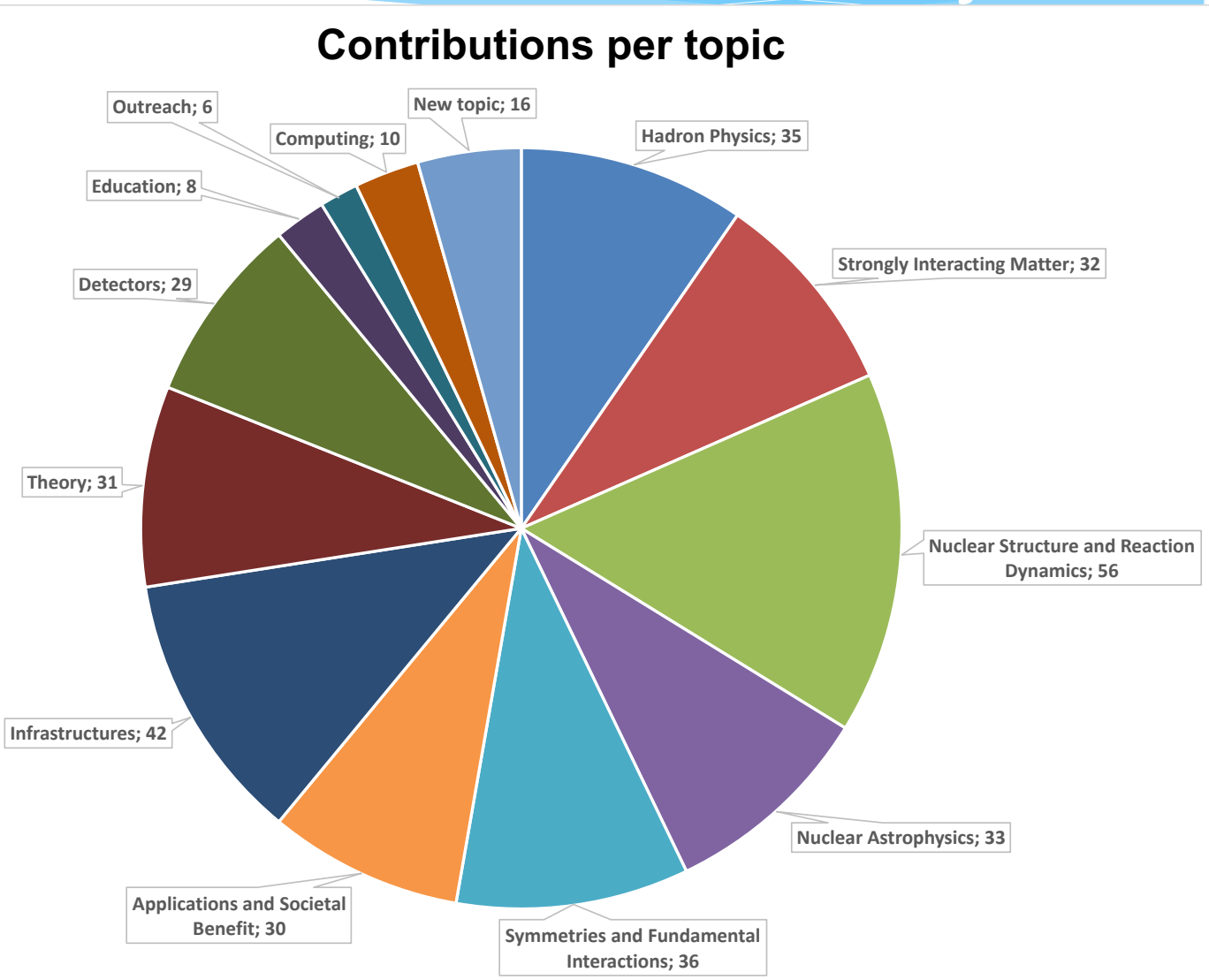
NuPECC LRP 2024

Launched in May 2022 in Madrid

NuPECC LRP 2024 – Contributions of the community

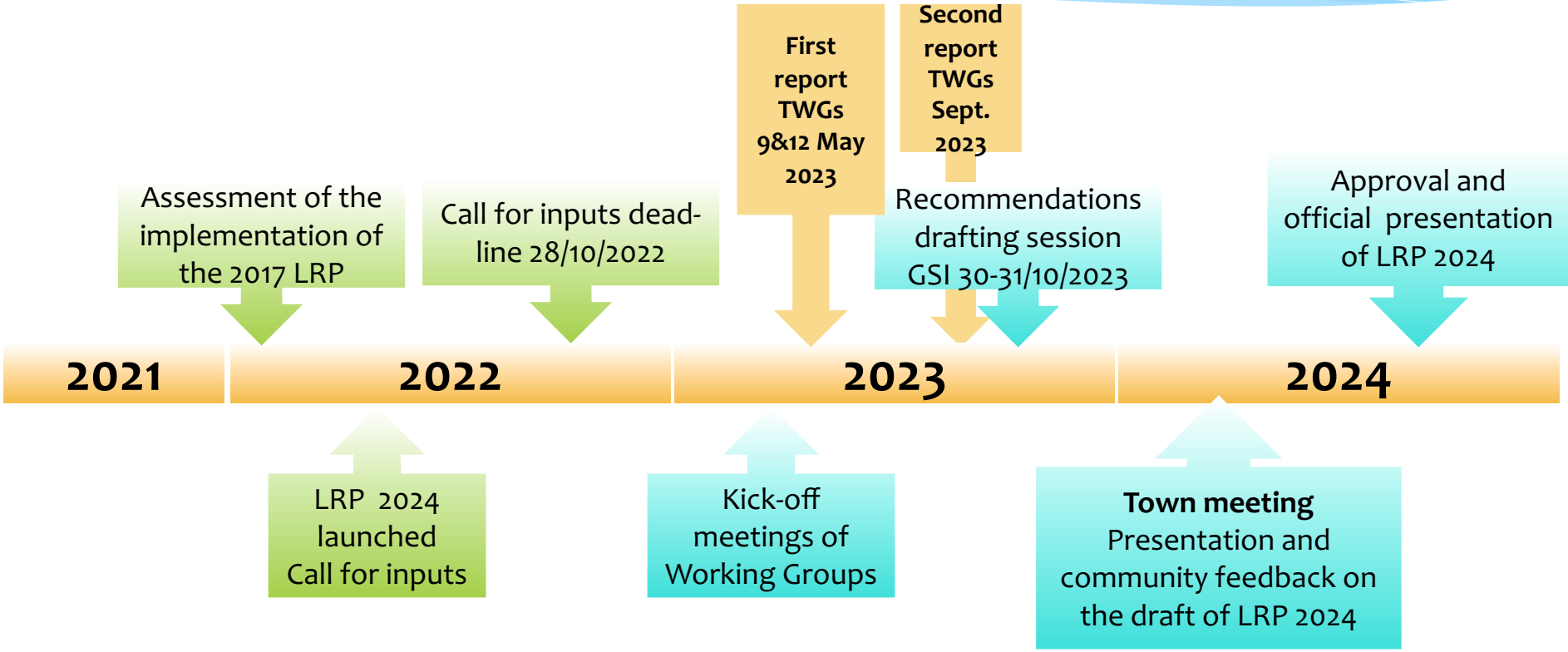
LRP Contributions:

- 159 contributions submitted
- by > 400 individual scientists, collaborations, infrastructures, and research institutions in Europe



https://nupecc.org/?display=lrp2024/call_for_input

LRP2024 Timeline



10 LRP2024 Thematic Working Groups (> 200 members)

- All TWG composition well defined
- 10/10 TWG planned/run meetings

LRP2024 Report

- Guidelines for the LRP2024 Report with a template sent on 11 April 2023
- Dead-line for drafts of TWG reports and recommendations: **15 Oct. 2023**

US Long Range Plan for nuclear science

Approved by NSAC on October 5, 2023

RECOMMENDATION 1
The highest priority of the nuclear science community is to capitalize on the extraordinary opportunities for scientific discovery made possible by the substantial and sustained investments of the United States. We must draw on the talents of all in the nation to achieve this goal.

RECOMMENDATION 2
As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

RECOMMENDATION 3
We recommend the expeditious completion of the EIC as the highest priority for facility construction.

RECOMMENDATION 4
We recommend capitalizing on the unique ways in which nuclear physics can advance discovery science and applications for society by investing in additional projects and new strategic opportunities.

https://science.osti.gov/-/media/np/nsac/pdf/202310/October-4-LRP-Report.pdf

Modern Nuclear Physics in Europe

Strategy Pillars

- **Science: Interplay between strong Theory & ambitious Experiments**
- **Applications - huge societal impact**
- **Facilities – in Europe (FAIR, SPIRAL2, ELI-NP, ISOLDE, SPES,…) and at other continents (RIBF, TRIUMF, iThemba, EIC, FRIB)**
- **Detectors - ex. ALICE3 , AGATA,…**
- **Data, Open Science, AI/ML – ex. ESCAPE H2020 program**
- **Synergies with neighbouring fields – Dark Matter, Gravitational Waves, neutrinos, EDMs, detectors, computing,… close collaboration with ECFA and APPEC (Seminars, workshops, joint EoI,…) and EURO-LABS!**

Strategy Development

- The 2017 NuPECC Long Range Plan defined an ambitious strategy for European Nuclear Physics
- **Next NuPECC LRP 2024 in a full swing!**

https://nupecc.org

Backup slides

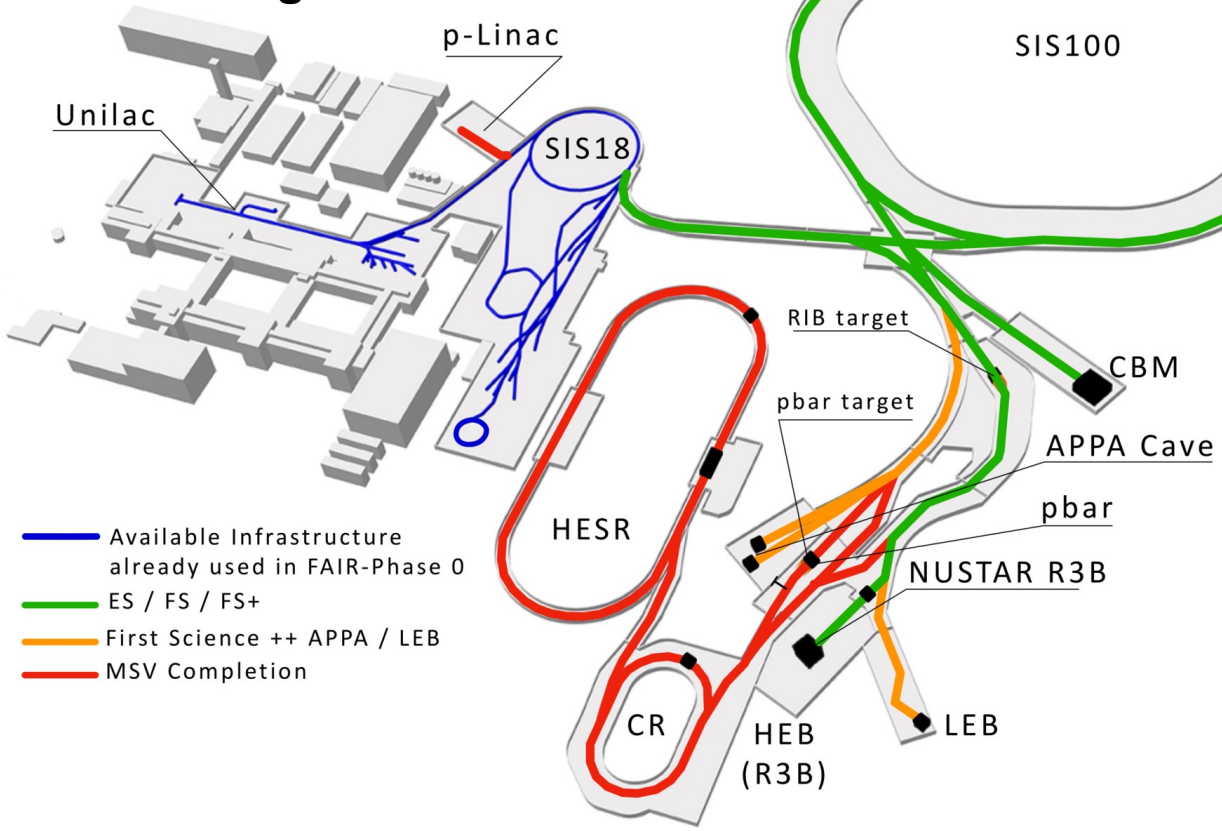
Darmstadt, Germany

FAIR by 2028

Finland France Germany India Poland Romania Russia Slovenia Sweden United Kingdom Czech Republic

> 3B€

Existing GSI



until 2028

>3.3 B€ investment

10^{12}/s; 1.5-2 GeV/u; $^{238}U^{28+}$

after 2028

Curtesy of P. Giubellino

SPIRAL2 LINAC and the new experimental rooms

Caen, France

Experimental program in full swing

EXPERIMENTAL ROOM NFS (NEUTRONS FOR SCIENCE)

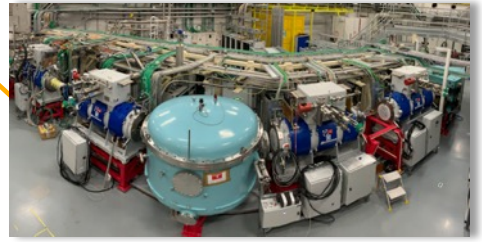
NFS

Convertor room

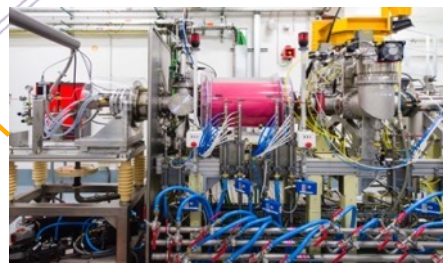
Time of Flight room

EXPERIMENTAL ROOM DESIR (Desintegration, Excitation and Storage of Radioactive Ions)

LINEAR accelerator (LINAC)



EXPERIMENTAL ROOM S3 (SUPER SEPARATOR SPECTROMETER)



ION SOURCE

NEWGAIN NEW GANIL INJECTOR

High intensity beams :
5 mA, 33 MeV protons
5 mA, 40 MeV deuterons
1 mA, <14,5 MeV/A heavy ions

TWG coordinators and SC liaisons

Theory/Exp.

TWG Number	TWG	Coordinators	Coord. e-mails	Liaisons	Liaisons e-mails
1	Hadron Physics	Karin Schönning (Uppsala)	karin.schonning@physics.uu.se	Diego Bettoni	bettoni@fe.infn.it
		Constantia Alexandrou (CY)	c.alexandrou@cyi.ac.cy alexand@ucy.ac.cy	Dave Ireland	david.ireland@glasgow.ac.uk
2	Strongly Interacting Matter at Extreme Conditions	Laura Fabbietti (TUM)	laura.fabbietti@ph.tum.de	Gert Aarts	g.aarts@swansea.ac.uk
		Urs Wiedemann (CERN)	Urs.Wiedemann@cern.ch	Raimond Snellings	R.Snellings@uu.nl
3	Nuclear Structure and Reaction Dynamics	Silvia Leoni (Univ. Milano)	silvia.leoni@mi.infn.it	Adam Maj	adam.maj@ifj.edu.pl
		Tomas Rodriguez(UCM)	tomasrro@ucm.es	Jelena Vesic	jelena.vesic@ijs.si
4	Nuclear Astrophysics	Anu Kankainen (JYFL)	anu.kankainen@jyu.fi	Daniel Bemmerer	d.bemmerer@hzdr.de
		Jordi Jose (Barcelona)	jordi.jose@upc.edu	Sandrine Courtin	sandrine.courtin@iphc.cnrs.fr
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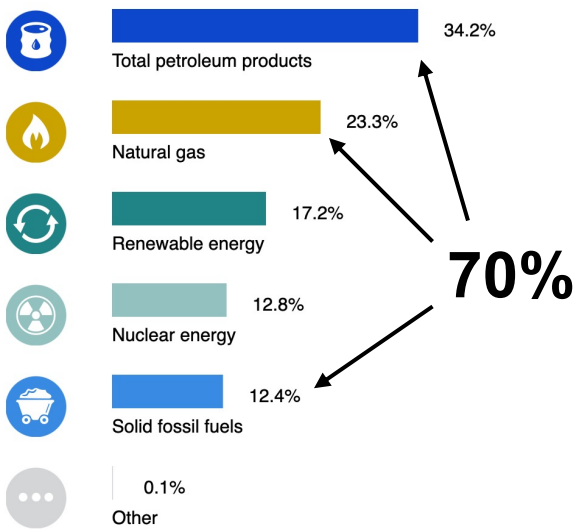
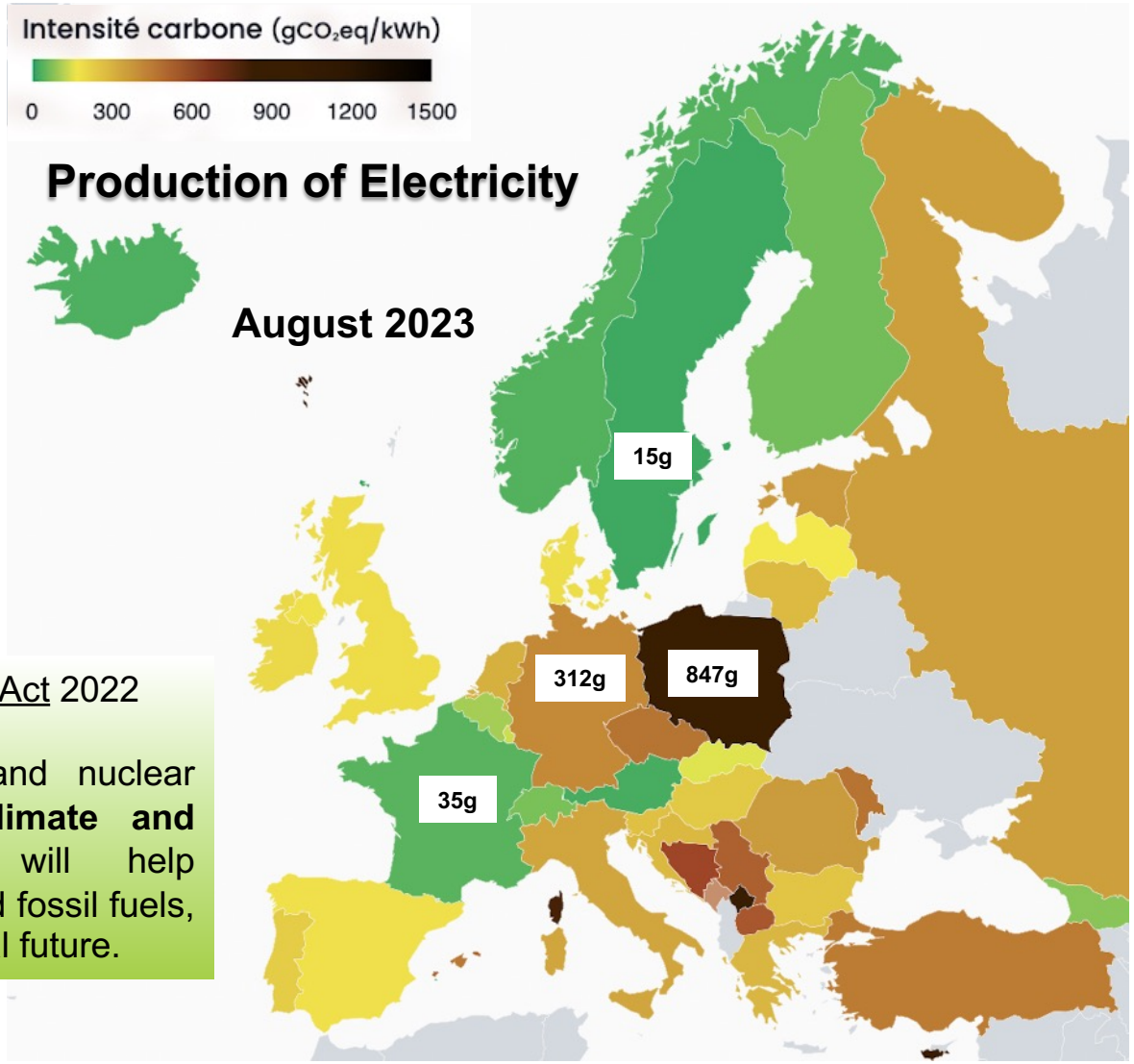
		Paolo Crivelli (ETH)	Paolo.Crivelli@cern.ch	Klaus Kirch	klaus.kirch@psi.ch
6	Infrastructures	Wolfram Korten (CEA, Saclay)	w.korten@cea.fr	Joaquin Gomez-Camacho	gomez@us.es
				Patricia Roussel-Chomaz	patricia.chomaz@ganil.fr
7	Applications and Societal Benefit	Thomas Cocolios (KU Leuven)	thomas.cocolios@kuleuven.be	Lucia Popescu	lucia.popescu@sckcen.be
		Charlot Vandevoorde (GSI)	C.Vandevoorde@gsi.de	Vladimir Wagner	wagner@ujf.cas.cz
8	Nuclear Physics Tools Detectors and experimental techniques Computing, Machine Learning and Artificial Intelligence	Silvia Dalla Torre (INFN)	Silvia.DallaTorre@cern.ch	Eugenio Nappi	Eugenio.Nappi@ba.infn.it
		Valerio Bertone (CEA Saclay)	valerio.bertone@cea.fr	Hervé Moutarde	herve.moutarde@cea.fr
		Jana Guenther (U. Wuppertal)	jguenther@uni-wuppertal.de		
9	Open Science and Data	Antoine Lemasson (GANIL)	antoine.lemasson@ganil.fr	Marek Lewitowicz	marek.lewitowicz@ganil.fr
10	Nuclear Science - People and Society Training, Careers & Diversity Education and Outreach	María García Borge (Madrid)	mj.borge@csic.es	Rolf-Dietmar Herzberg	rdh@liverpool.ac.uk
		Christian Diget (York)	christian.diget@york.ac.uk	Yvonne Leifels	Y.Leifels@gsi.de

Over 200 members of TWGs

Production of Electricity
Impact on the Environment

Energy mix for EU





EU Complementary Climate Delegated Act 2022

The criteria for the specific gas and nuclear activities are **in line with EU climate and environmental objectives** and will help accelerating the shift from solid or liquid fossil fuels, including coal, towards a climate-neutral future.

Sources: Electricity Maps