Istituto Nazionale di Fisica Nucleare
Piano Triennale
2024 | 2026

Trieste
Stazione Marittina
27 | 28 giugno 2023

Mid term plan della fisica nucleare in Italia

Marco La Cognata, LNS

On behalf of the organizing committee

Outline

Meeting rationale, format and legacy

LNL – LNS upgrades: synergies and complementarities in nuclear structure and dynamics

Nuclear astrophysics: from underground studies to indirect techniques and novel apparatuses

New frontiers in nuclear physics with high power lasers

Societal applications: FOOT, isotope harvesting, lasers

Novel detectors and setups for nuclear physics experiments

Nuclear physics as a bridge to new physics

The event rationale

In the next years the upgrade programs of INFN laboratories will be completed:

SPES at the Laboratori Nazionali di Legnaro (https://web.infn.it/spes/)

POTLNS at the Laboratori Nazionali del Sud (https://potlns.lns.infn.it/en/),

LUNA-MV accelerator of the Bellotti Ion Beam Facility at the Laboratori Nazionali del Gran Sasso (http://l.infn.it/lngs-accel).

Laboratori Nazionali di Frascati and EuPRAXIA (https://w3.lnf.infn.it and https://www.eupraxia-project.eu)

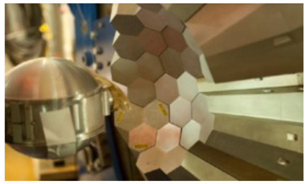
A discussion on the physics to be addressed in the mid-term perspective is timely and beneficial

CSN3 covers a broad range of physics topics

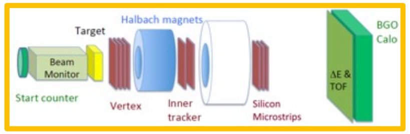
From the keV to the TeV scale

LUNA

GAMMA



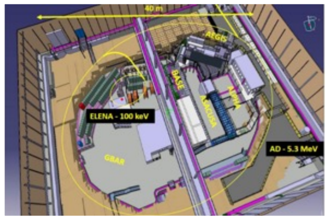
FOOT



JLAB

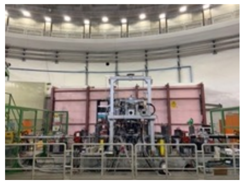
ALICE

Energy **keV** **MeV** **GeV** **TeV**



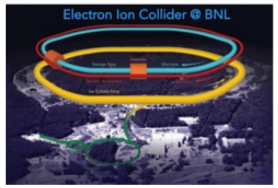
LEA

NUMEN, ASFIN2,NUCLEX, CHIRONE, FORTE



SIDDHARTA

JEDI



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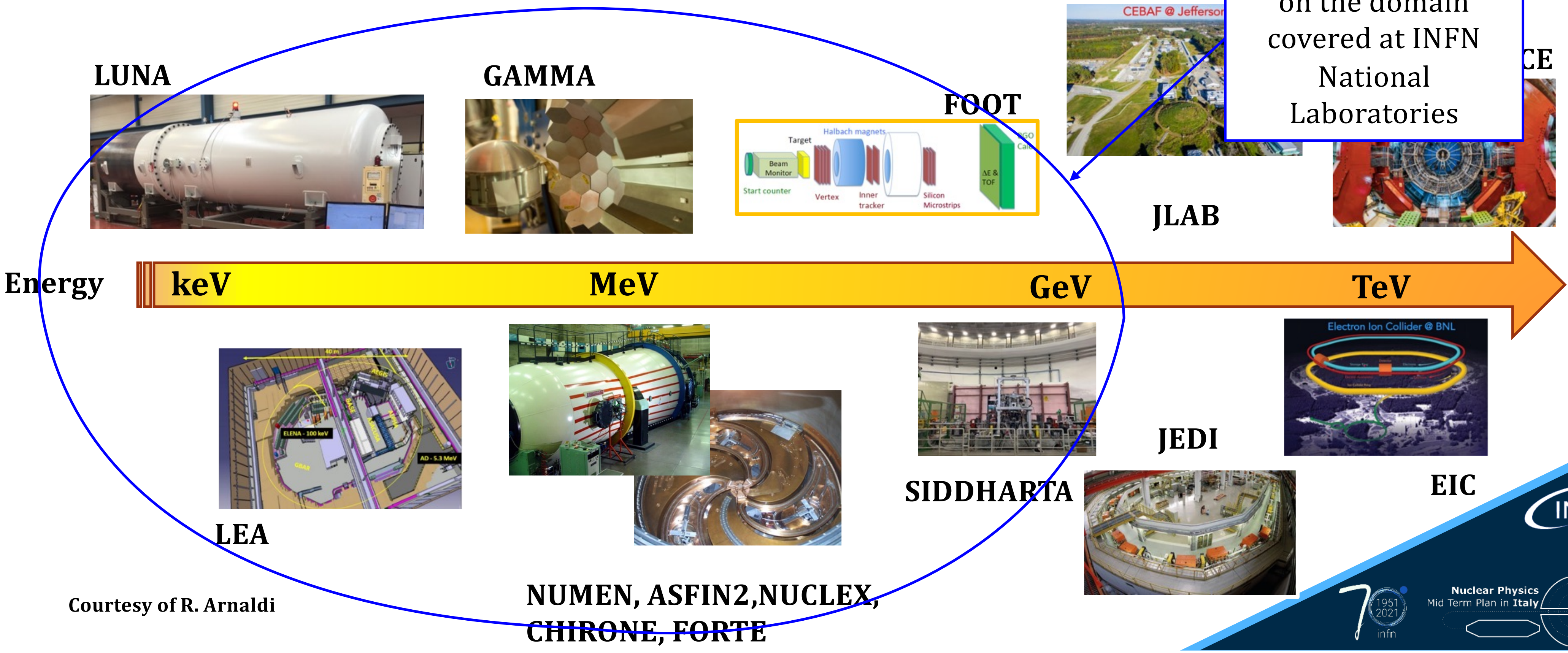
Courtesy of R. Arnaldi

CSN3 covers a broad range of physics topics

From the keV to the TeV scale

We will mostly focus on the domain covered at INFN National Laboratories



Courtesy of R. Arnaldi

ORGANIZING COMMITTEE

Giovanna Benzoni	Carlo Gustavino
Diego Bettoni	Matthias Junker
Fabio Bossi	Marco La Cognata
Maria Colonna	Ivano Lombardo
Antonino Di Leva	Rosario Nania
Enrico Fioretto	Ezio Previtali
Alba Formicola	Stefano Romano
Lorenzo Fortunato	Paolo Russotto
Santo Gammino	Francesca Soramel
Fabiana Gramegna	Jose Javier Valiente-Dobón

eetings started in 2021

Event webpage:

https://web.infn.it/nucphys-plan-italy/

The workshops

In the preparatory meetings, CSN3 has promoted a discussion forum on the future of nuclear physics research in Italy with particular emphasis on:

- *The role of younger generations of scientists*
- *Developing synergies between infrastructures*
- *Opening dialogue with the theory groups*

Specific working groups have discussed ideas and topics to be developed in the mid term future with the goal of **defining experiments** at the upgraded facilities, promoting ad-hoc **developments for new setups** and **establishing a timeline** for the projects' implementation

Worldwide researchers interested in future research program have joined the working groups and elaborated questions and proposals

The working groups have reported on their activities in four final events, dedicated to each Laboratory

Session 1 – LNS (4-5 April 2022)
Session 2 – LNL (11-12 April 2022)
Session 3 – LNGS (11 October 2022)
Session 4 – LNF (1-2 December 2022)

The working groups

The contributions and participation were organized in specific working groups coordinated by **conveners**, with the task of discussing the items in the preceding months and prepare **summary reports** during the final events in the laboratories.

INFN LNS

LNS SESSION

4 - 5 April 2022

Scientific Program and Conveners

- Nuclear Dynamics (S. Pirrone)
- Nuclear Structure (C. Agodi)
- Nuclear Astrophysics (R. Pizzone)
- Applications (S. Tudisco)

INFN LNL

LNL SESSION

11 - 12 April 2022

Scientific Program and Conveners

- Nuclear Astrophysics (R. Depalo)
- Nuclear Structure (D. Mengoni)
- Nuclear Reactions and Dynamics (T. Marchi)
- Applications (G. Pupillo)

INFN LNGS

LNGS SESSION

11 October 2022

Scientific Program and Conveners

- Fundamental symmetries (C. Curceanu)
- Direct measurement for nuclear astrophysics (G. Imbriani)
- Applied nuclear physics (L. Gialanella)

INFN LNF

LNF SESSION

1 - 2 December 2022

Scientific Program and Conveners

- Future possibilities for nuclear physics at LNF
- Charged particle detectors (G. Pasquali & F. Galtarossa)
- Neutron detectors (C. Massimi, A. Gottardo)
- Detectors for gamma/X-ray radiation (A. Scordo & W. Raniero)
- Detectors for medical applications (R. Catalano, P. Cardarelli & M. Lunardon)
- Targets for nuclear physics measurements (M. Cavallaro & S. Corradeti)
- New facilities at LNL and LNS (A. Di Pietro, A. Gottardo)

Setting up a roadmap for future detectors in the field of nuclear physics.

Some numbers

LNS (4-5 April 2022)

160 WG members

270 participants in the workshop

30% from foreign institutions

LNL (11-12 April 2022)

180 WG members

280 participants in the workshop

30% from foreign institutions

LNGS (11 October 2022)

80 WG members

90 participants in the workshop

10% from foreign institutions

LNGS (1-1 December 2022)

170 WG members

220 participants in the workshop

10% from foreign institutions

The outcome

The legacy of the series of workshops is:

The collection of material (physical ideas, new detectors, new ways to use the detectors under development) hosted by the event website

More long-term implications

→ the physical ideas developed in the context of the midterm plan will be also included in the **NUPECC** long-range plan

The publication of review works on

EPJ Plu

Eur. Phys. J. Plus (2023) 138:526
https://doi.org/10.1140/epjp/s13360-023-04108-9

THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

Check for updates

Nuclear physics midterm plan in Italy: introduction to the series

G. Benzoni[1], D. Bettoni[2], F. Bossi[3], M. Colonna[4], A. Di Leva[5,6], E. Fioretto[7], A. Formicola[8], L. Fortunato[9], S. Gammino[4], F. Gramegna[7], C. Gustavino[8], M. Junker[10], M. La Cognata[4], I. Lombardo[11,12], R. Nania[13,a], S. Pisano[3,14], E. Previtali[10], S. Romano[4,12,b], P. Russotto[4], F. Soramel[9,15], J. J. Valiente-Dobón[7]

1. Introduction tc
2. LNL manuscrip
3. LNS manuscrip

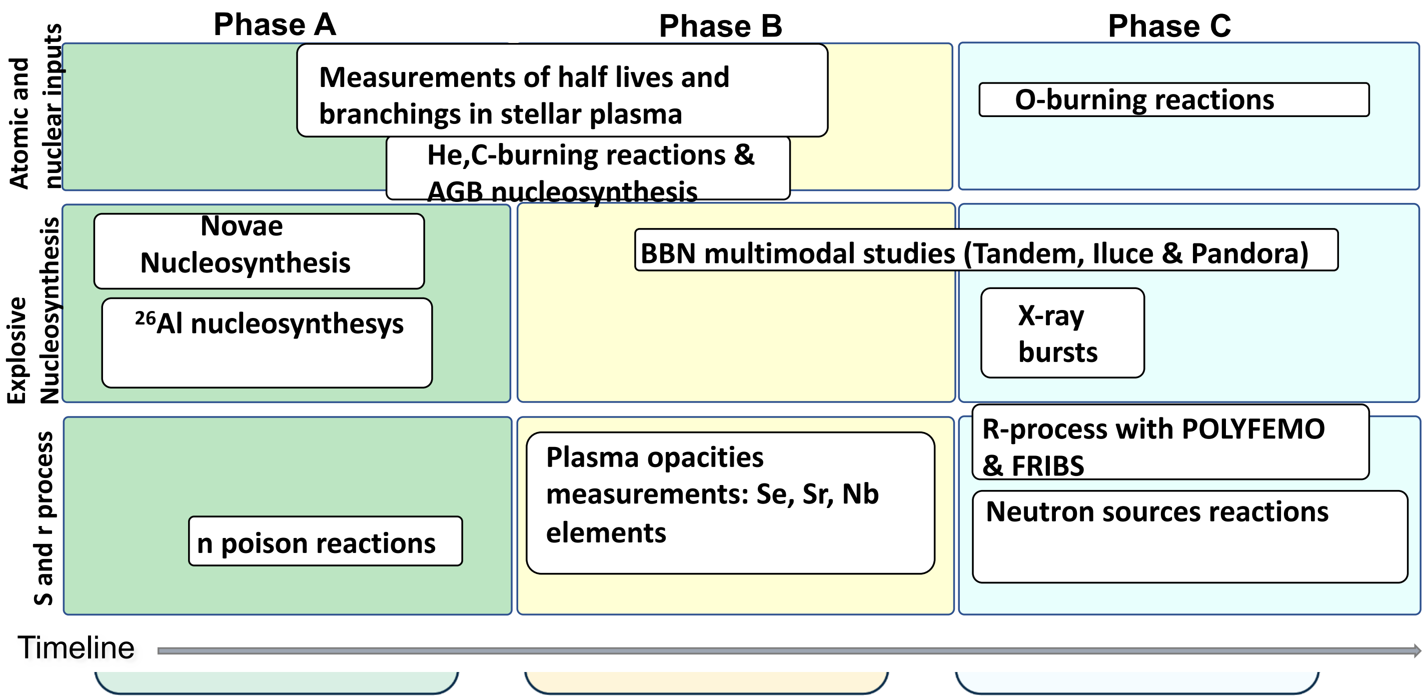
on

nuclear physics studies also ready?

INFN

Nuclear Physics
Mid Term Plan in Italy

Establishing a timeline for the projects' implementation



Phase A if feasible already at the start of the operations

Phase B in case of small upgrade/additions to the experiments are needed

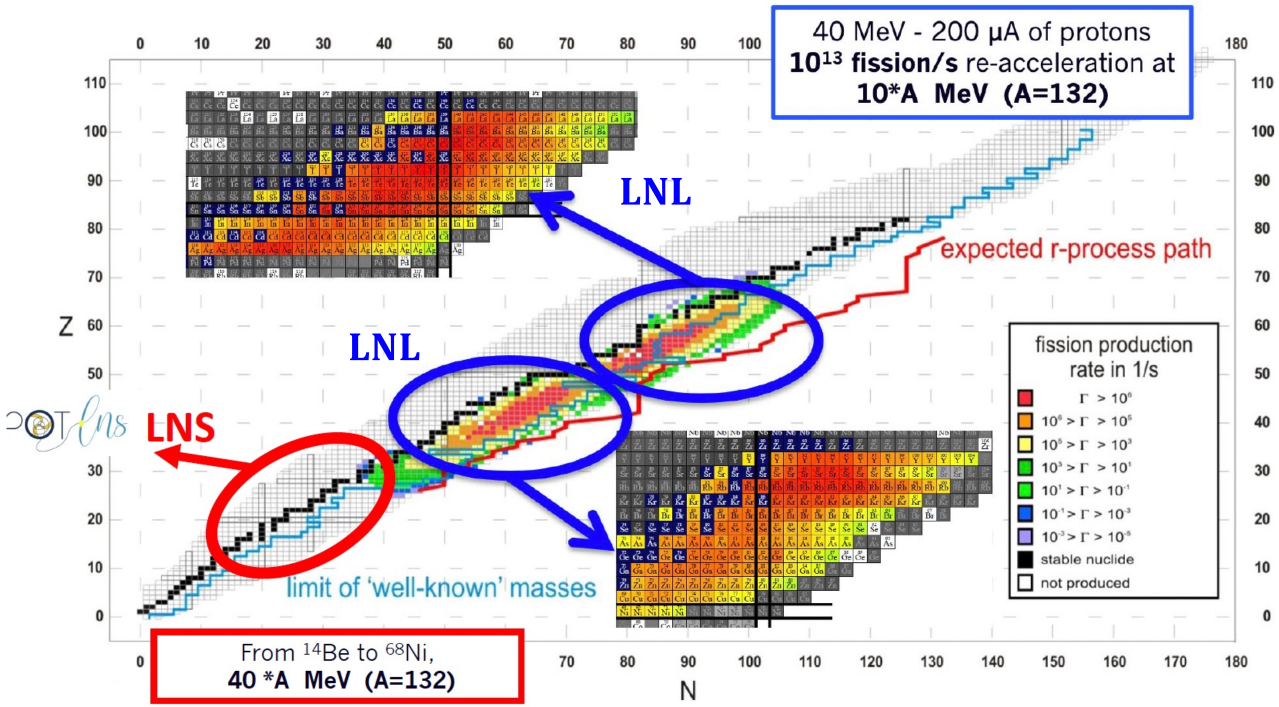
Phase C when the full machines performances are required as well as important experiments update.

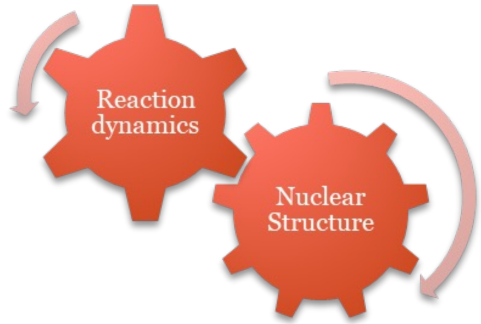
Nuclear Structure and Dynamics

INFN CSN3

LNL-LNS complementarity

LNL
SPES





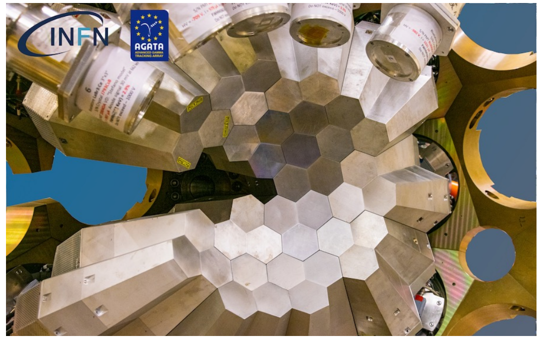
The interaction between nuclei and their structures are strictly connected, and the observed phenomena strongly depend on the energy and on the probe that is used

→ Different accelerators

→ Different detectors

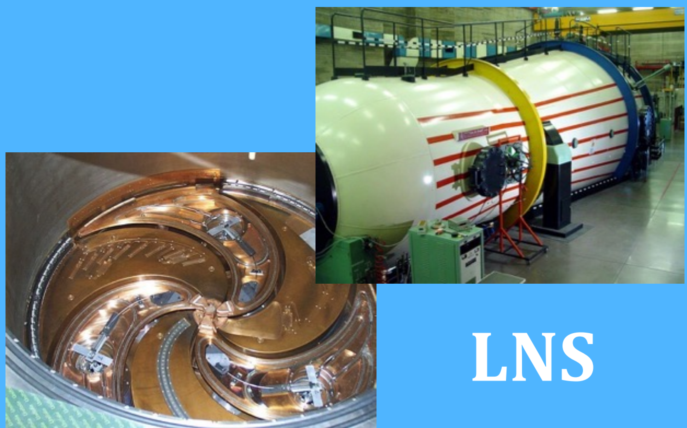
LNS and LNL synergies and complementarities

LNL

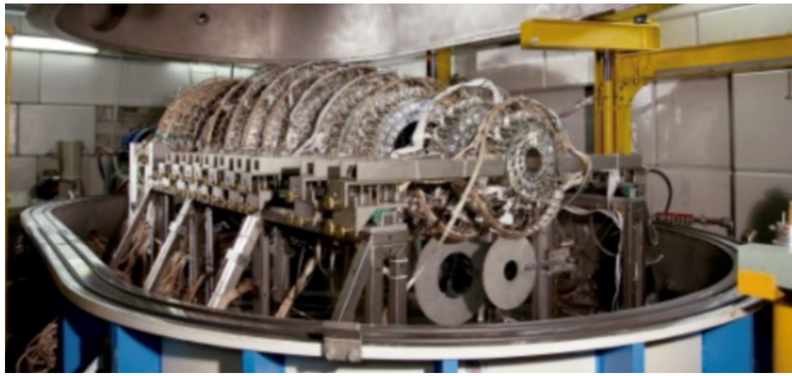


Gamma detection

Investigation of the collective and shell-model properties of the nuclei



LNS



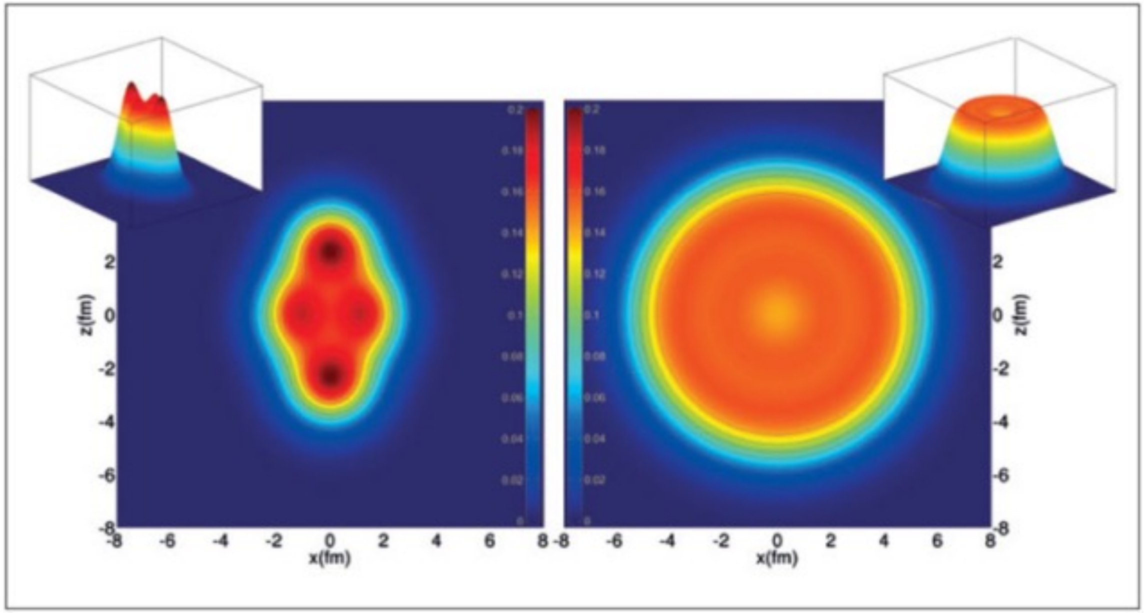
particle detection

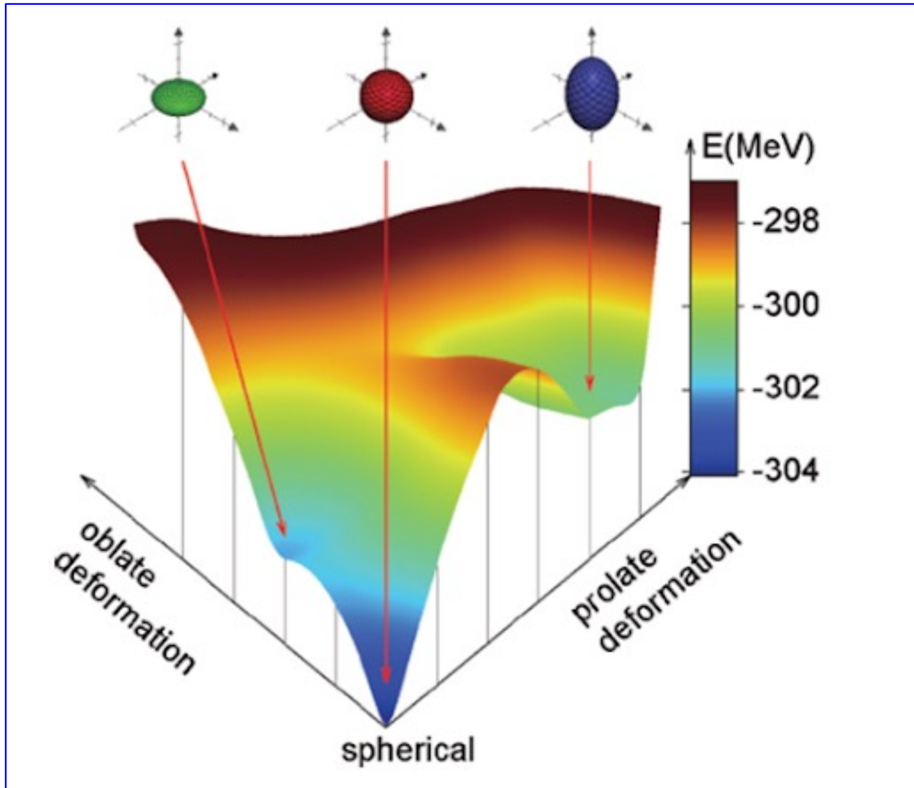
High granularity detectors to study nuclear structure at a smaller scale

LNL: studying the nucleus collective features

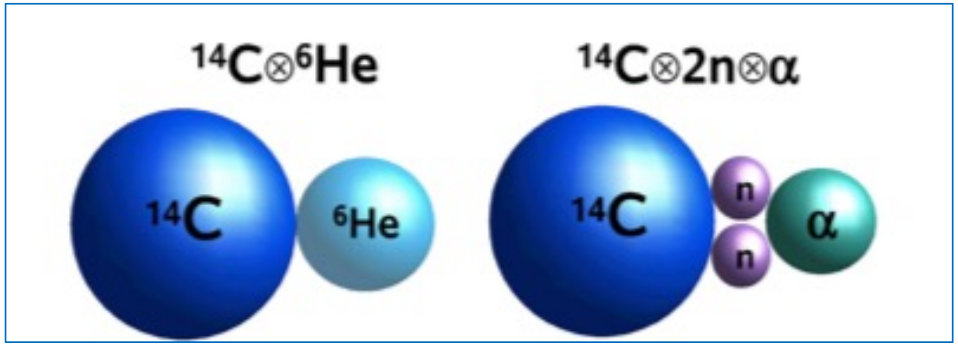
Questions that could answered:
- What is the shape of nuclei? Why is it important?
- What is the distribution of nucleons inside the nucleus?

SPES → extension to exotic nuclei





LNS: testing nuclear building blocks

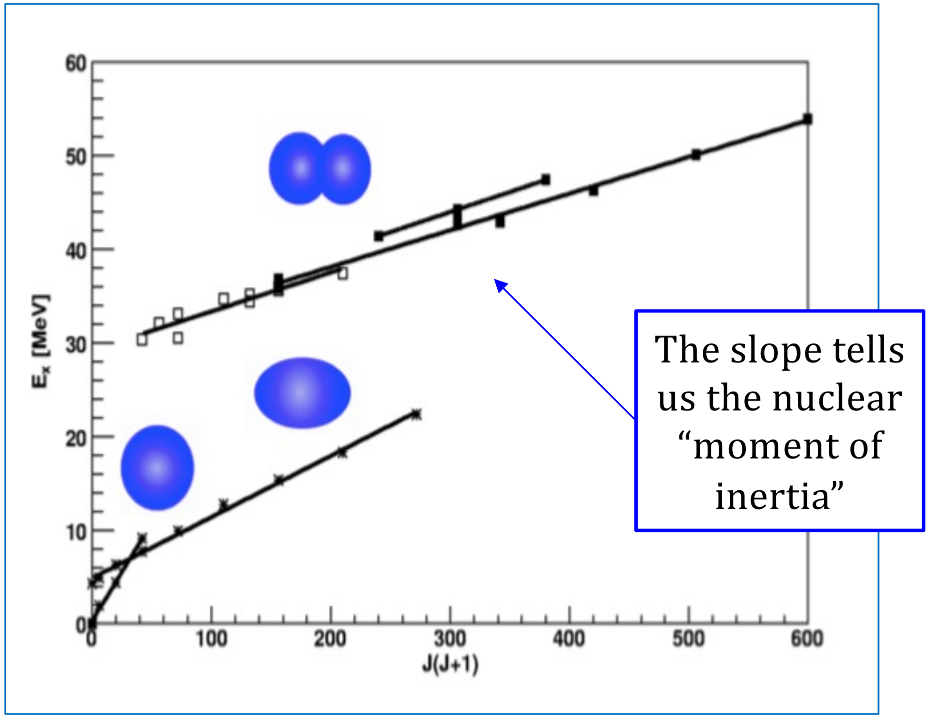


Cyclotron energies → fragmentation

From the disintegration of nuclei it is possible to study the building blocks

Under some conditions, protons and neutrons cluster together and form substructures inside nuclei

Nuclei may can be described as "molecules" with neutrons which may act as "bonds" among "clusters"

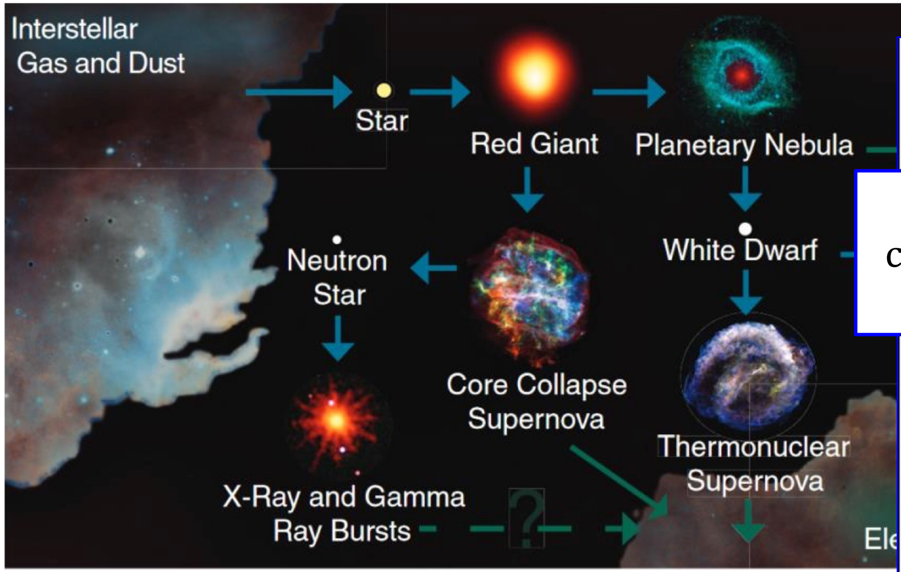


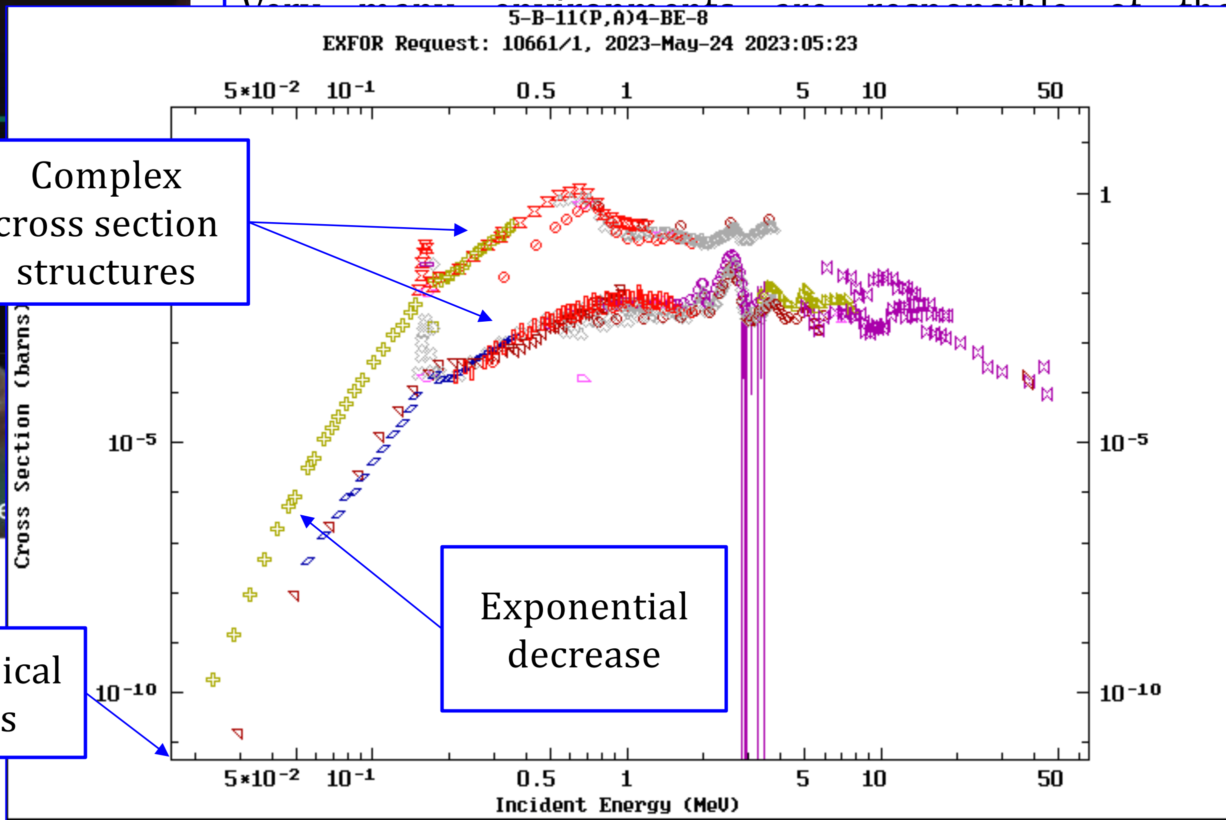
Experimental observation of molecular rotational-bands

Tandem-accelerated exotic nuclei

→ **World record intensities** for studying exotic clustering phenomena

Nuclear astrophysics: from underground…





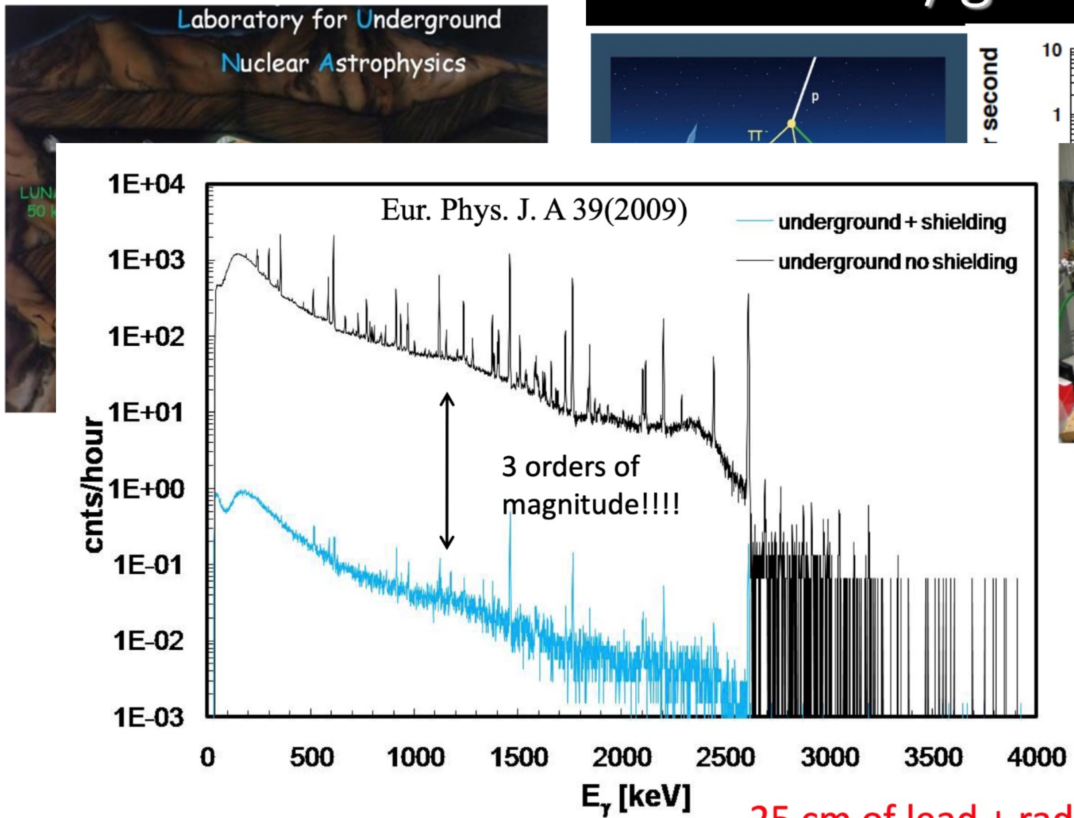
For a nuclear physicist, stars are **COLD**

10^9 K → 86 keV

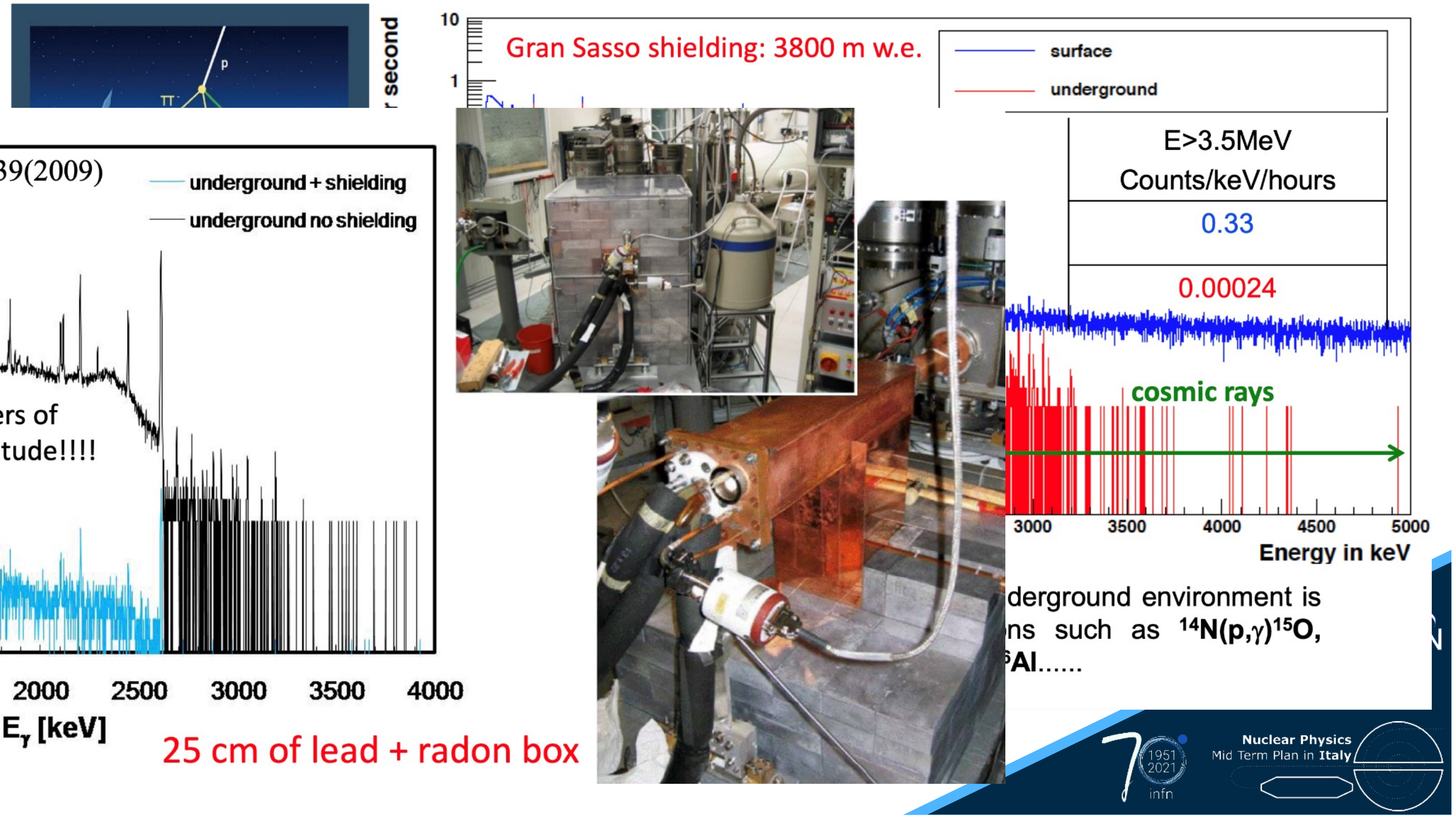
In the sun core: 15 million degrees
Astrophysical energies → energies of interest can be as low as few keV → pb scale cross sections

Nuclear astrophysics: from underground…

Bellotti facility @ LNGS

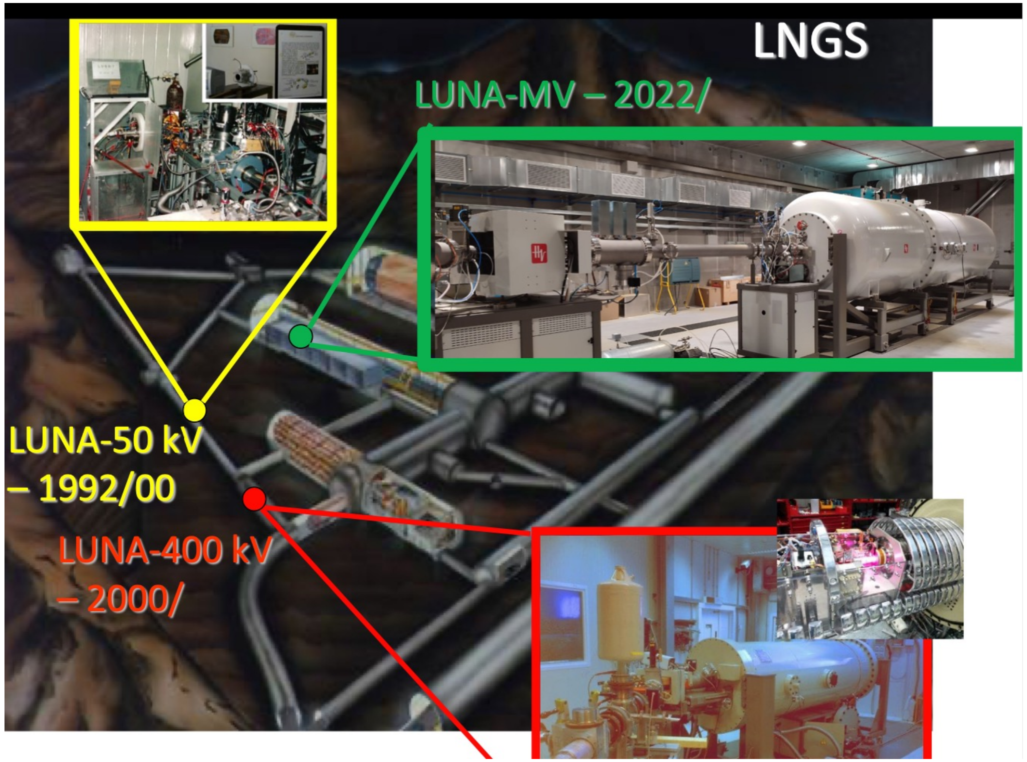


Why going underground: γ-background



25 cm of lead + radon box

Nuclear astrophysics: from underground…



Commissioning measurement: $^{14}N(p,\gamma)^{15}O$.
High scientific interest for revised data covering a wide energy range (400 keV- 3.5 MeV). Scientific results of high impact, e.g. for the independent evaluation of the age of the Universe

$^{12}C+^{12}C$ fusion: estimating the neutron formation rate

$^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$: neutron sources for heavy-ion nucleosyntheis

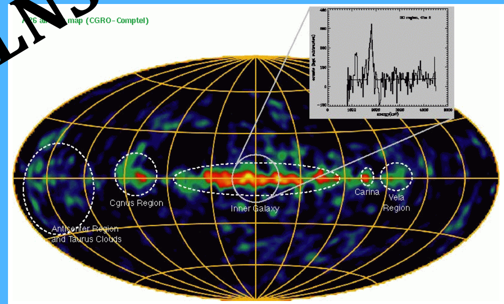
$^{12}C(\alpha,\gamma)^{16}O$: understanding the nucleosynthesis of massive stars

However at astrophysical energies and RIBs we need to go at lower energies / lower cross sections and find alternatives.

… to indirect methods…

- ✓ Radioactive ion source for long-lived isotopes on the Tandem (SN Nucleosynthesis) with **indirect methods** (such as the Trojan Horse Method)
- ✓ Noble gas source for the Tandem (massive stars)
- ✓ **Fraise** to deliver beams for astrophysical applications (Polyfemo, novae and supernovae nucleosynthesis)

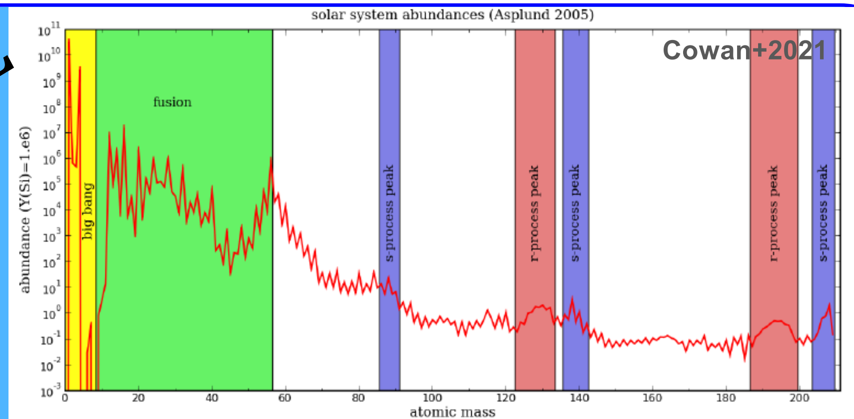
LNS



XTU Tandem + Alpi/Piave + SPES will provide a unique opportunity to explore the different reaction mechanisms leading to isotope synthesis, especially for nuclei heavier then iron

→ **r-process: link with multi-messenger astronomy**

LNL

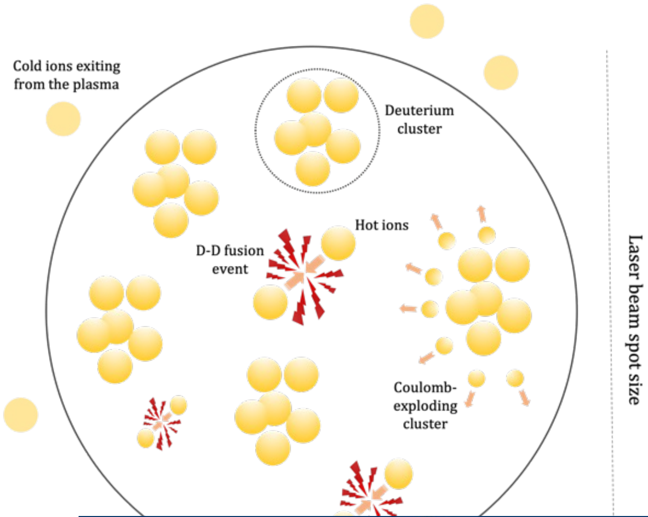


… to novel tools and methods

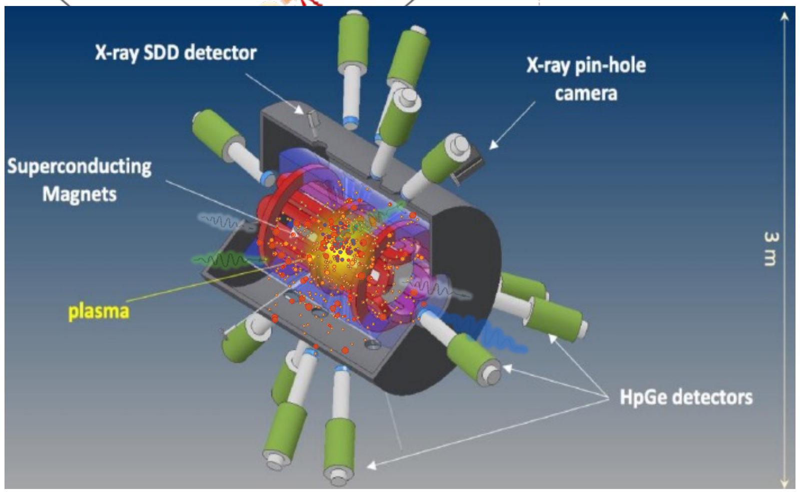
Laser induced measurements in plasmas

@ FLAME and EuPRAXIA (LNF), I-LUCE (LNS)

→ **Study of fusion processes and decays β in ionized environments**



…and at the **Pandora facility (LNS) +** measurements of K-Novae opacities



→ Novel approaches to understand the big bang nucleosynthesis and the mechanism behind neutron star mergers

High-power lasers: from FLAME ...

- ***FLAME @ LNF***

Max energy: 7J

Max energy on target: ~ 5J

Min bunch duration: 23 fs

Wavelength: 800 nm

Bandwidth: 60/80 nm

Spot-size @ focus: 10 µm

Max power: ~ 300 TW

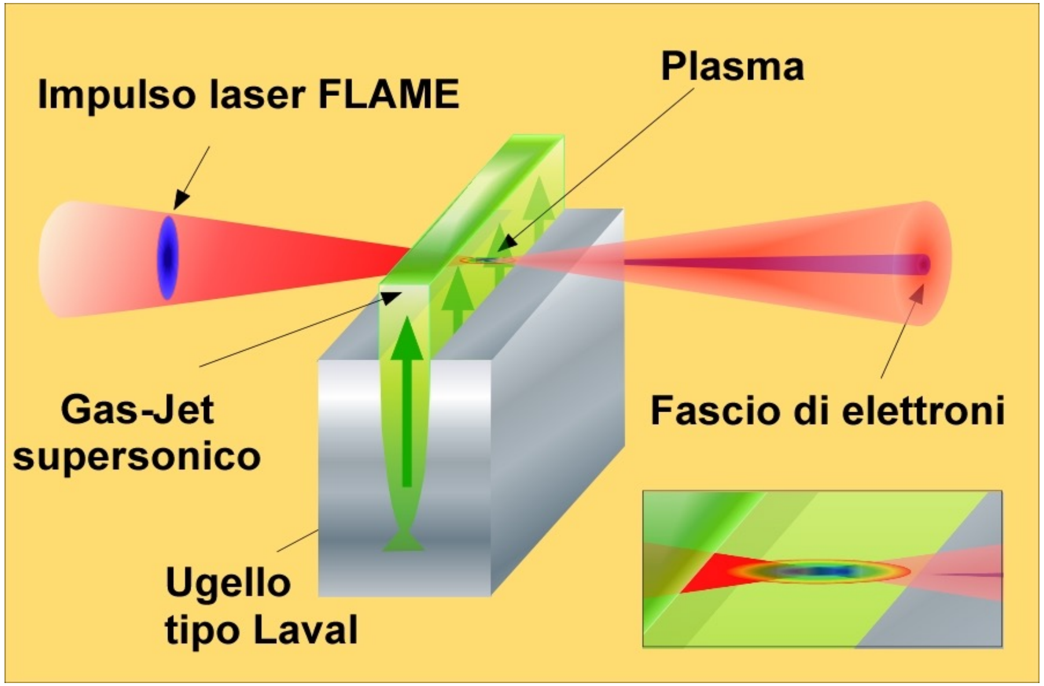
Contrast ratio: 10^{10}

- *FLAME + SPARC*

SPARC → high brightness LINAC and a high power laser

a. Compton scattering

b. Electron acceleration by external injection



Laser wakefield accelerators (LWFA) are a novel type of accelerators capable to produce accelerating field up to 100 GV/m. This feature gives the possibility to have very compact accelerators able to accelerate electrons to GeV energies in few **centimetres**.

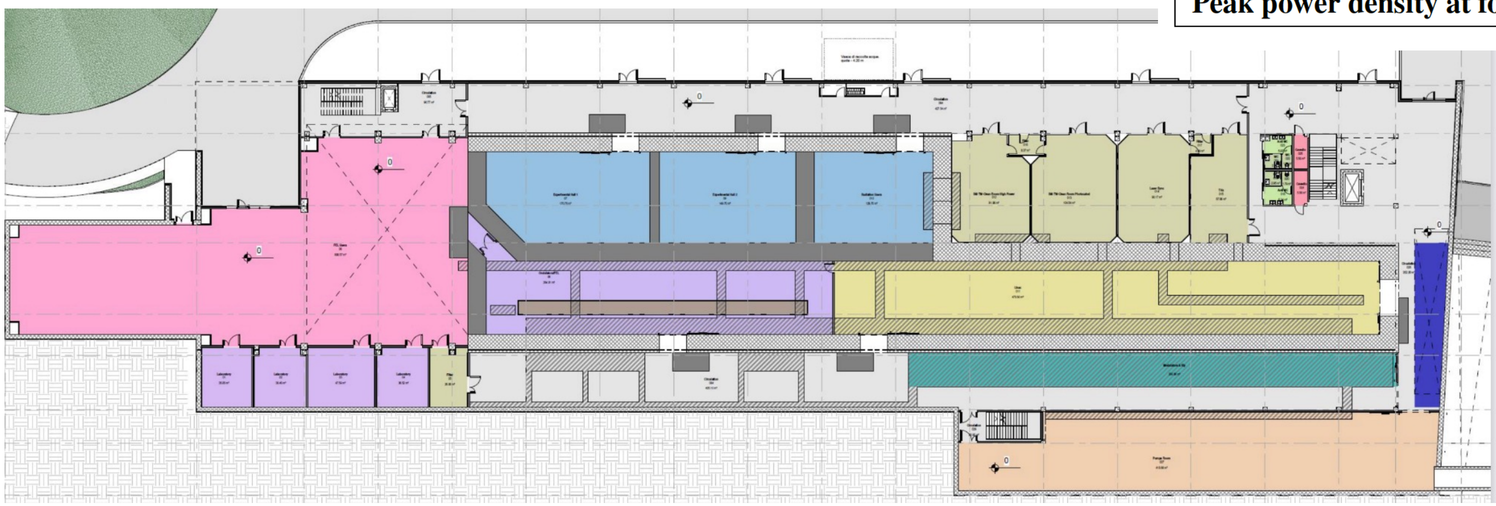
...to EUPRAXIA

1st Phase: 500TW laser will be installed

2nd Phase: second 500TW (or upgrade to 1PW)

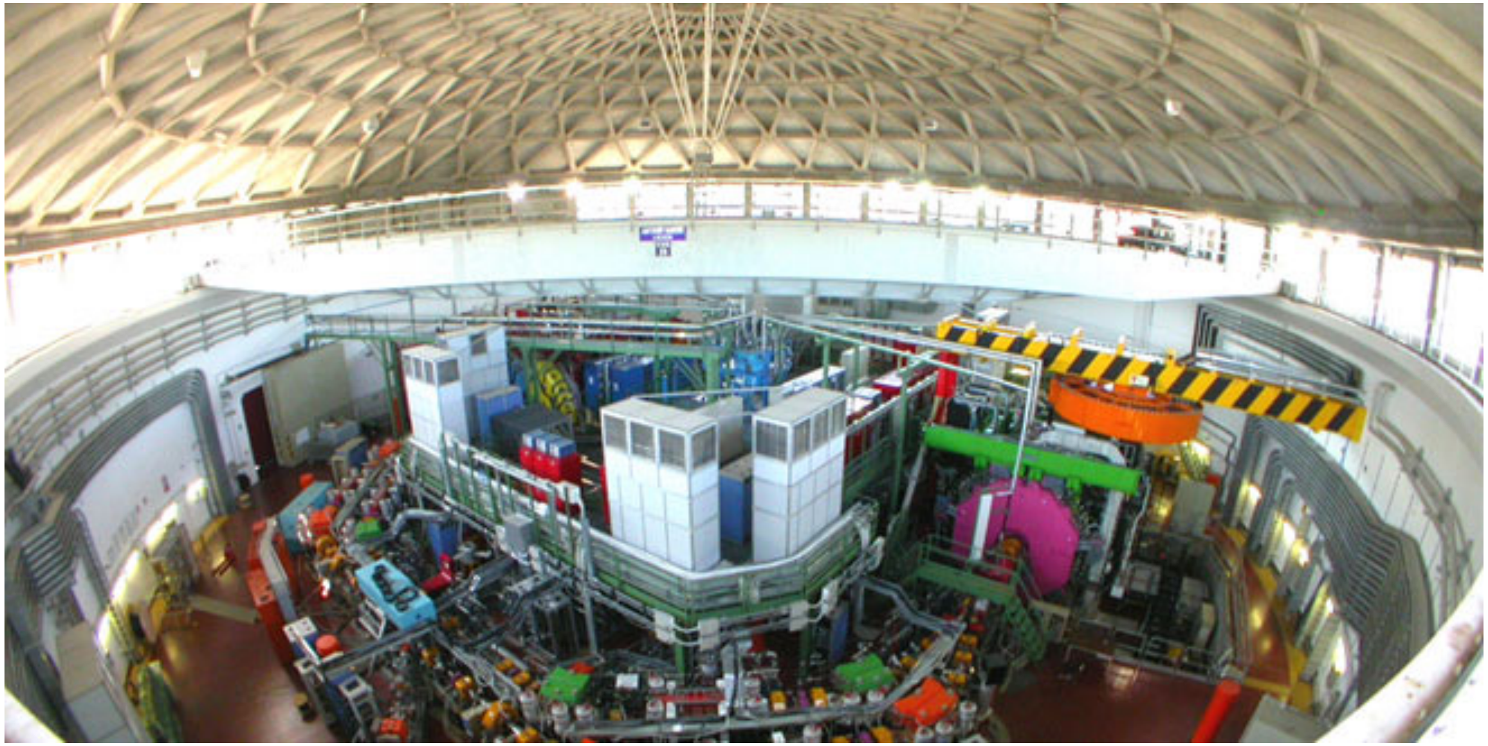
Two 500TW laser could satisfy the 24h/7day operation request in parallel on different experiments.

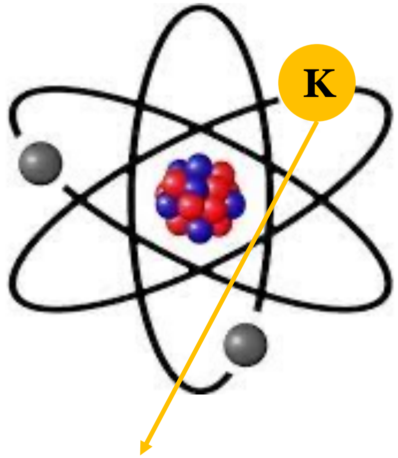
	Units	value
Central wavelength	nm	800
Bandwidth	nm	60 - 80
Repetition rate	Hz	1 - 5
Max energy before compression	J	20
Max energy on target	J	13
Min pulse length	fs	25
Max power	TW	500
Contrast ratio		10^{10}
Laser spot size at focus (optics dependent)	μm	2 - 50
Peak power density at focus (optics dependent)	W/cm^2	10^{22} - 10^{19}



Other future activities at LNF

Continuation of the study of kaonic atoms with the SIDDHARTA experiment

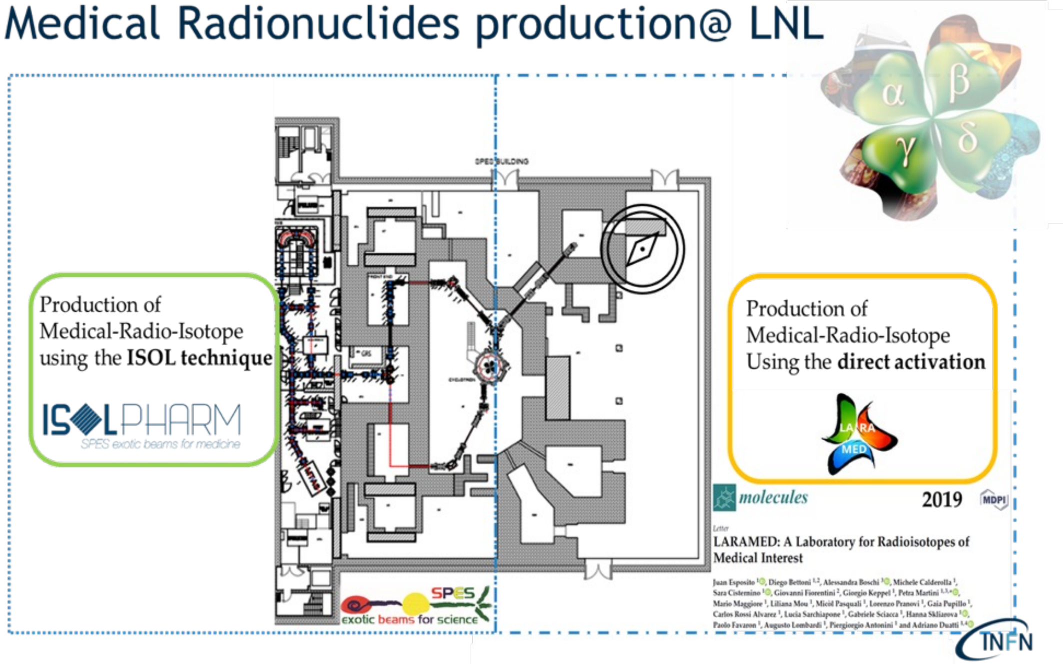




The kaon, one of the particles produced by DAΦNE, replaces an atomic electron → probing nuclear properties

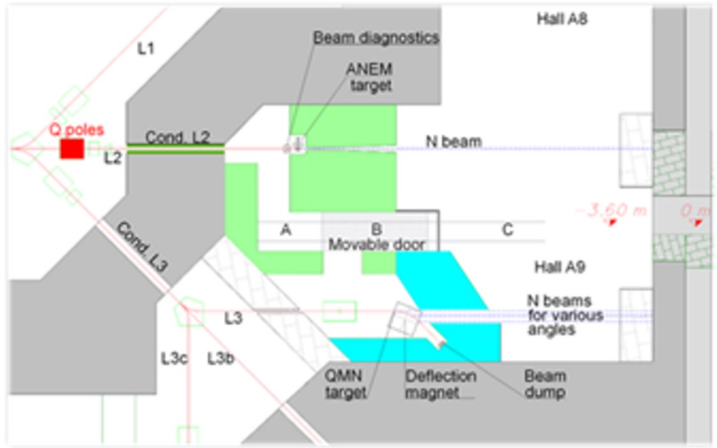
Societal Applications at LNL

Medical Radionuclides production@ LNL

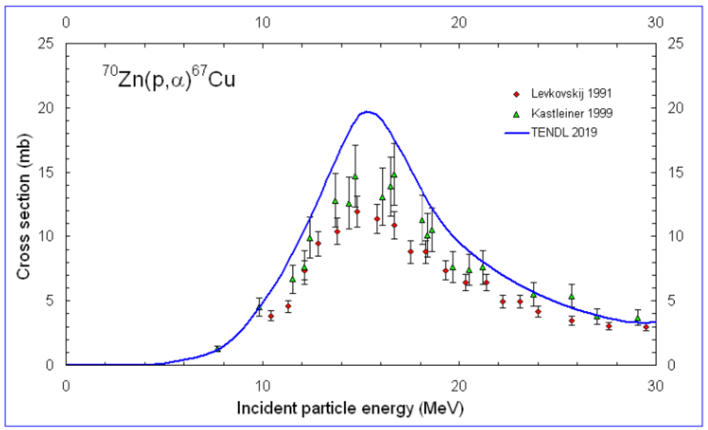


Nuclear cross sections measurements and modelling for direct radionuclide production

Material analysis & test of radiation damage

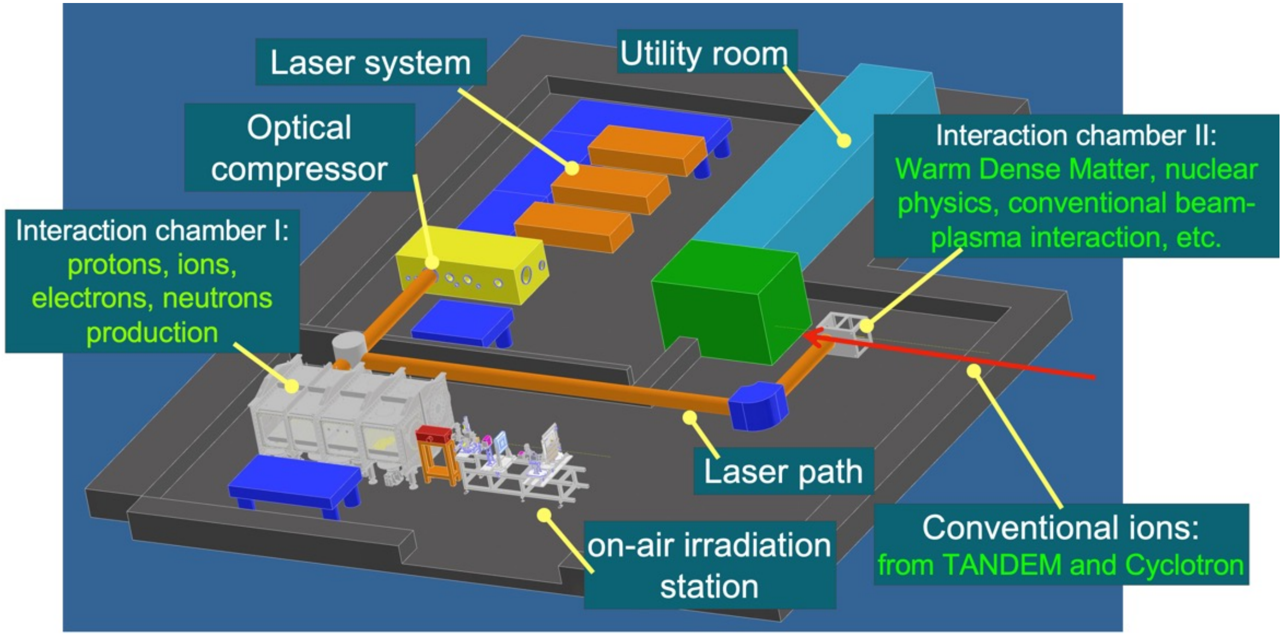


Neutron facility @ SPES

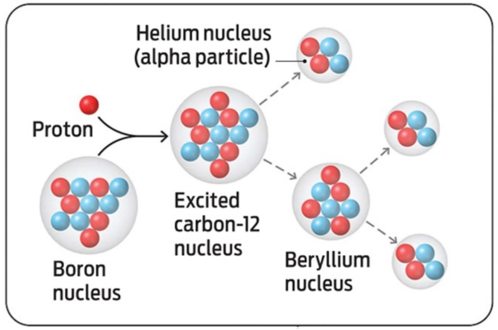


Need of more accurate data

Societal Applications at LNS



Clean energy production:
Proton-boron fusion reaction in plasma is of interest to many different research groups as a potential candidate for future generation of fusion ignition scheme



I-LUCE INFN Laser indUCEd radiation production

- Ion and electron acceleration (connection with FLAME-EXUPRAXIA)
- Neutron generation
- Boron Neutron Capture Therapy
- Applications with high-energy electrons in radiobiology and medical applications for flash radiotherapy studies

- Nuclear reactions in Plasma
- Stopping power in Plasma
- Nuclear decays
- Inertial fusion
- Radioisotopes production

Societal Applications @ CIRCE

CIRCE @ Caserta → 3 MV Pelletron

Diagnostics and modifications of materials with ion beams

For example:
- Characterization of radiation damage
- Investigation of semiconductors

Accelerator Mass Spectrometry (AMS) for the measurement of rare-isotope abundances

Astrophysics: meteorite analysis or rare reaction products

Environment: pollutant such as actinides from nuclear reactor decommissioning

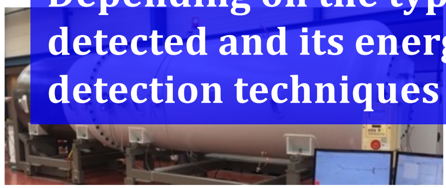
Cultural heritage: ultrasensitive determination of ^{14}C isotope ratios for archaeometry

Roadmap for next-generation detectors for nuclear physics

Depending on the type of particle to be detected and its energy, different detection techniques will be required

CSN3 is covering a broad range of energies and physical cases, calling for a broad variety of detectors

LUNA



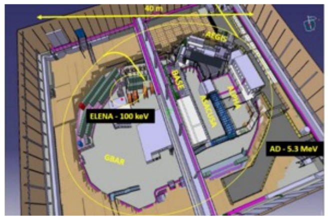
GAMMA

FOOT

JLAB

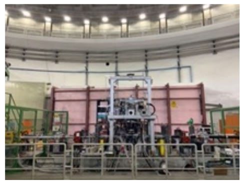
ALICE

Energy — keV — MeV — GeV — TeV



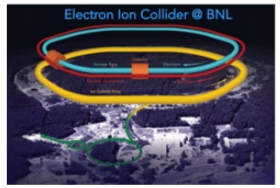
LEA

NUMEN, ASFIN2,NUCLEX, CHIRONE, FORTE



SIDDHARTA

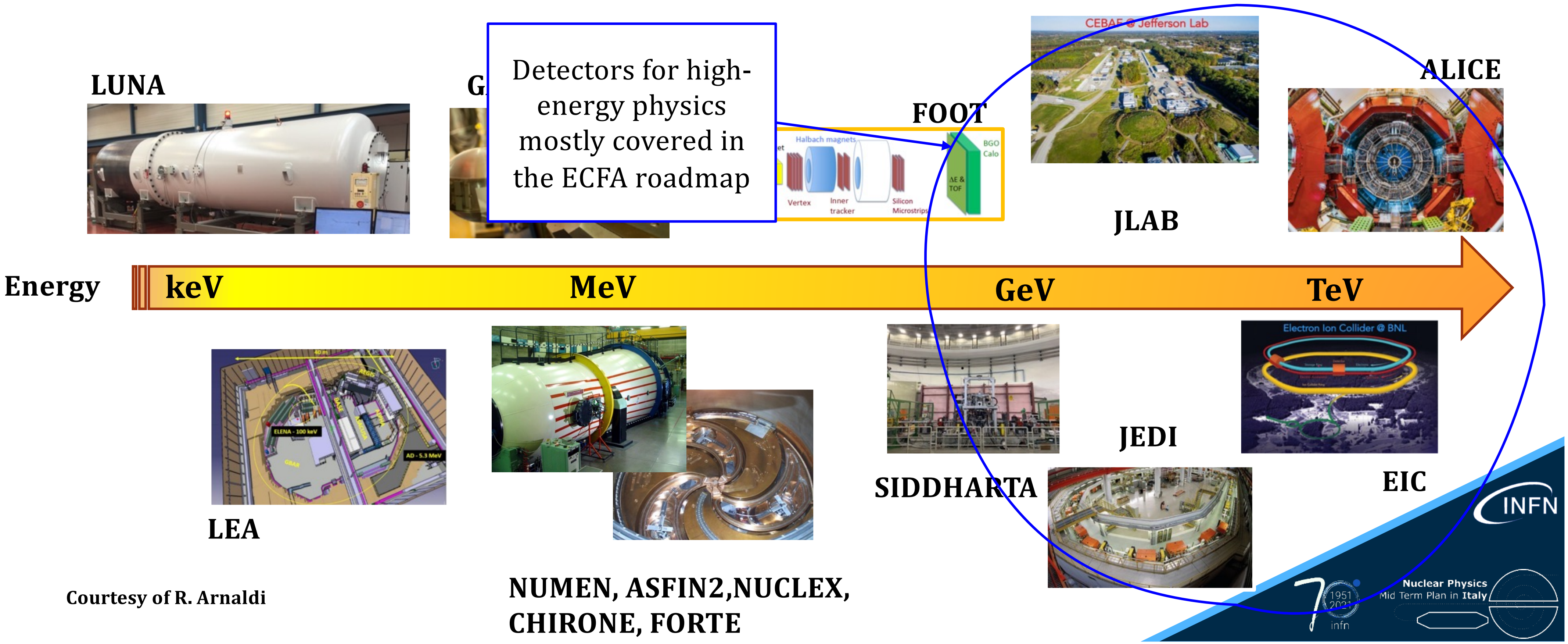
JEDI



EIC

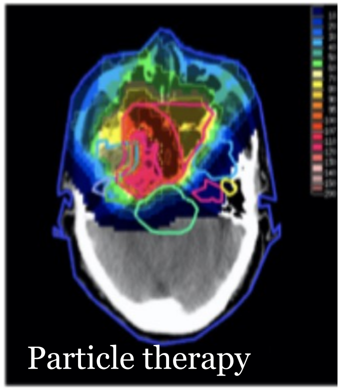
Courtesy of R. Arnaldi

Roadmap for next-generation detectors for nuclear physics



Courtesy of R. Arnaldi

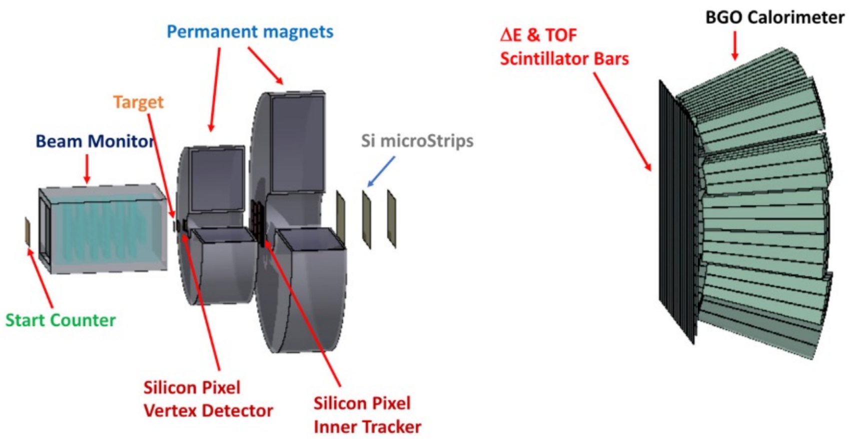
FOOT



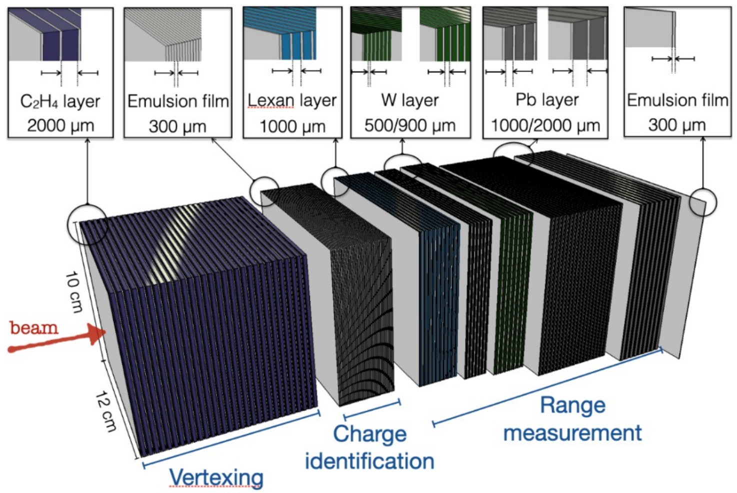
The FOOT (FragmentatiOn Of Target) experiment is an international project designed to carry out the fragmentation cross section measurements relevant for Charged Particle Therapy(CPT), a technique based on the use of charged particle beams for the **treatment of deep-seated tumors**, and for radioprotection in **space applications**

FOOT is based on two complementary setups:

a magnetic spectrometer (Z>=3)



an emulsion spectrometer (Z<=3)



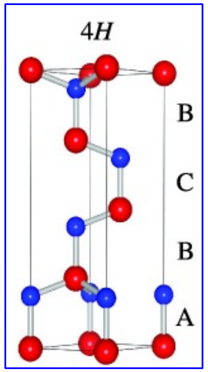
Solid-state devices: silicon carbide

General Properties of SiC

- **high thermal conductivity**
- **low thermal expansion**
- **high strength (hardness)**
- **chemical inertness**

→ **Exceptional thermal shock resistant qualities**

Lattice structure

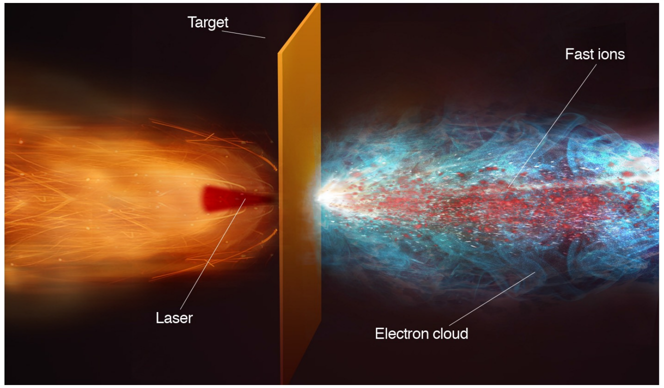


SiC wide-band-gap semiconductor

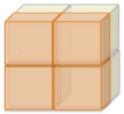
Energy gap => E_{SiC}=3.28 eV > E_{Si}=1.12 eV
Saturated electron velocity => $v_{SiC} > v_{Si}$

→ ⇒ Visible blind
⇒ Lower Leakage current

Nuclear Reactions in Laser Plasmas



R&D



SiC Telescope

Applications on ELECTRONIS and DEVICES

- High power
- High frequency
- High temperature
- Radiation hard detectors

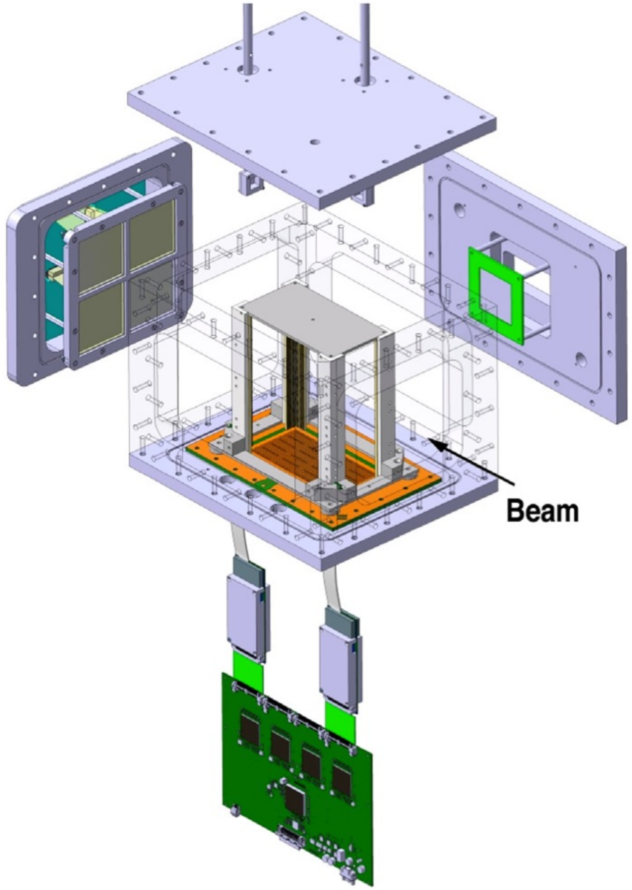
S. Tudisco et al. SENSORS Vol. 18 (2018) 2289
F. Negoita et al. Rom. Rep. in Phys. Vol. 68 (2016) S37-S144

Gas detectors: active targets

Time Projection Chambers (TPC) operated in **Active Target** mode offer new experimental opportunities, mainly in connection with Radioactive Ion Beams, where **high efficiency and thick targets are needed to compensate the weak beam intensity**.

They offer the possibility to
1. track the incoming beam up to the interaction vertex
2. reconstruct the variable interaction energy
3. reconstruct the outgoing tracks with a resolution Δθ ~ 1°
4. reach efficiencies close to 100%
5. perform particle identification

Versatile apparatus: data taking at LNS, LNL…

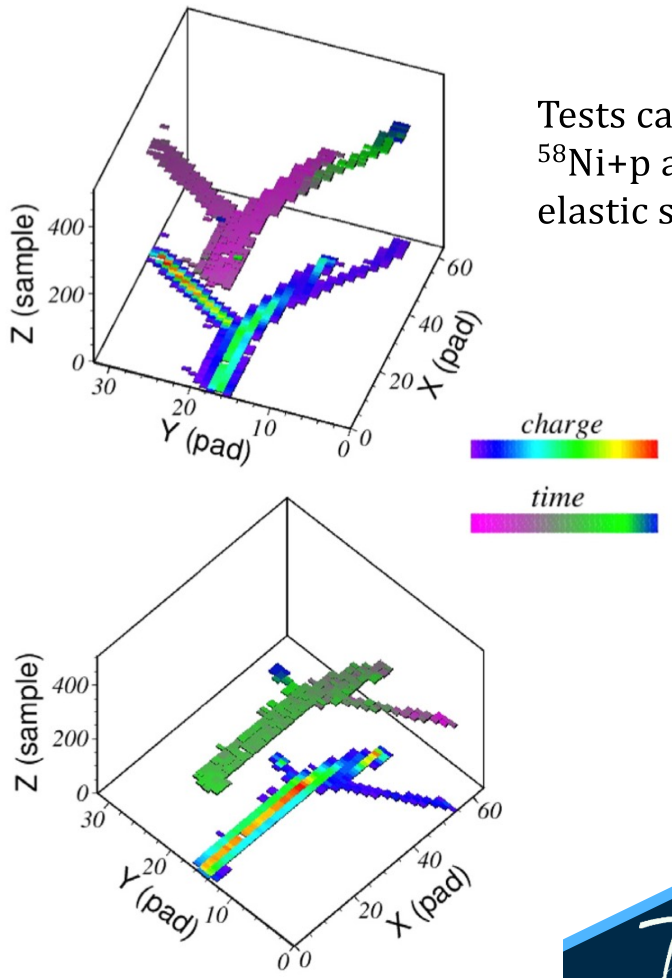


The ACTAR TPC demonstrator

Gas detectors: active targets

Time Projection Chambers (TPC) operated in **Active Target** mode offer new experimental opportunities, mainly in connection with Radioactive Ion Beams, where **high efficiency and thick targets are needed to compensate the weak beam intensity**.

They offer the possibility to
1. track the incoming beam up to the interaction vertex
2. reconstruct the variable interaction energy
3. reconstruct the outgoing tracks with a resolution $\Delta\theta \sim 1°$
4. reach efficiencies close to 100%
5. perform particle identification



Tests carried out using ^{58}Ni+p and $^{24}Mg+\alpha$ elastic scattering

Targets for nuclear physics experiments

Target are an essential ingredients for nuclear physics experiments, representing a necessary ingredient in all projects.

Special targets are necessary to couple with high intensity beams, for producing exotic nuclei, for minimizing background

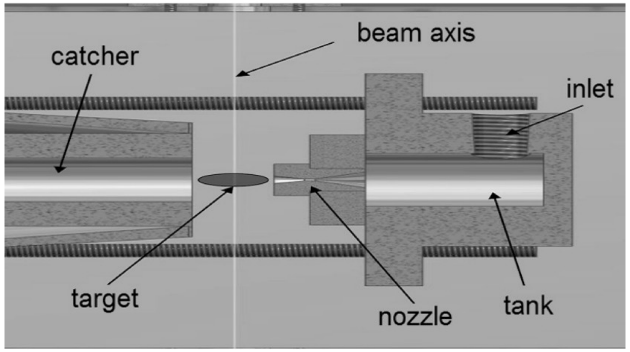
Targets for high intensity beams @ LNS cyclotron - NUMEN

High Oriented Pyrolytic Graphite (HOPG) + cryocooler reaching 40K

Primary target for producing exotic nuclei @ SPES – LNL

The target represents the heart of SPES in which the proton beam is converted in radioactive ions by means of nuclear reactions, for nuclear physics studies or medical isotopes research

Windowless gas target @ LUNA – LNGS

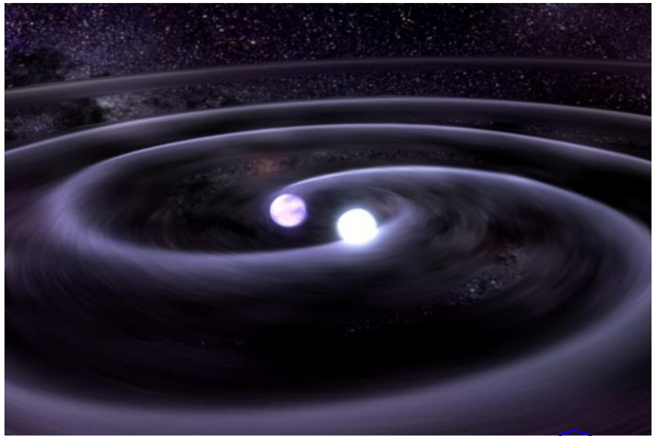


In the case of gas targets, windows may introduce unwanted energy loss and parasitic reactions. A Supersonic Gas Jet Target would combine high density and purity

Complementarities with other fields

CSN3 and star models / gravitational waves

1 Studying the nuclear equation of state: nuclear matter looks like a fluid under some conditions. New RI beams @FRAISE , heavy ions stable beams @TANDEM and @CYCLOTRON and new instrumentation



2 Production of elements heavier than iron: neutron star mergers could produce half of the heavy elements using neutron-rich beams @SPES

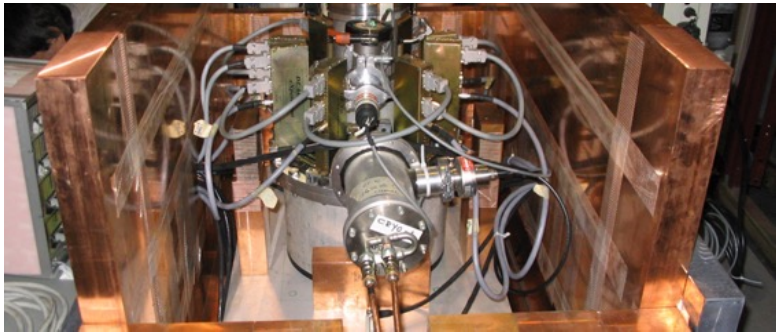
3 Observation of kilonovae: optical spectra bears the fingerprint of the elemental production, but accurate plasma physics input is necessary @PANDORA

Neutron star merger

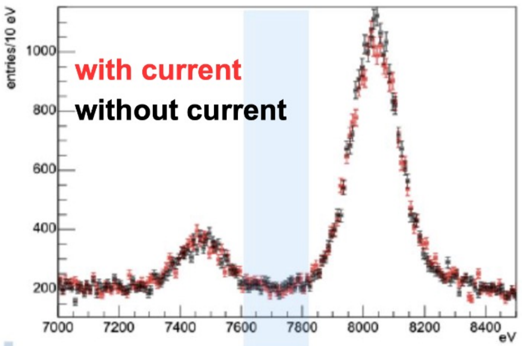
- Kilonova: Powered by radioactive nuclei decays
- Gravitational waves: Observed using LIGO/VIRGO

Complementarities with other fields

CSN3 and the physics beyond the standard model

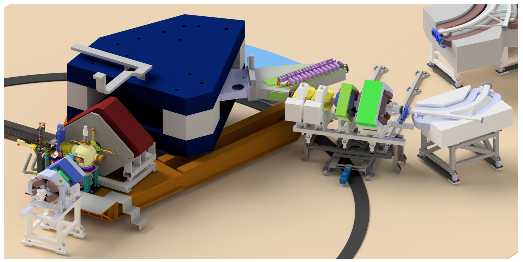


VIP setup @ LNGS
→ Violation of the Pauli principle
→ Test of quantum gravity models



$t^{wc} = 27110263$ s $= 314$ days
$t^{woc} = 26916404$ s $= 311$ days

Heavy-ion DCE as surrogate process of 0νββ

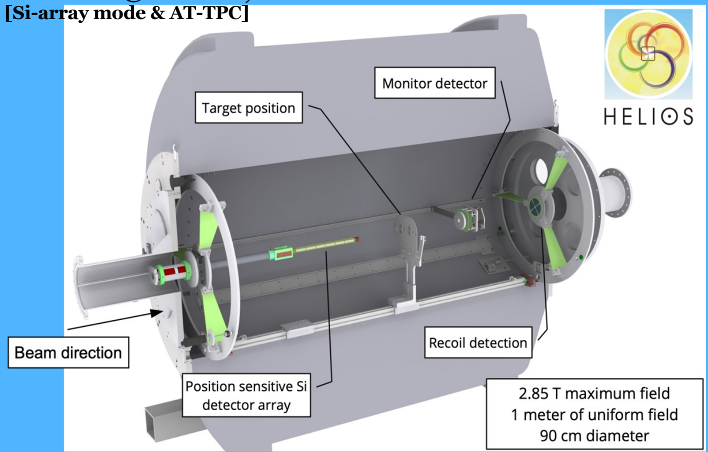


CS and MAGNEX magnetic spectrometer crucial for the experimental challanges
→ high-intensity CS beams are necessary

Using nuclear physics to explore the matter-antimatter asymmetry

Legacy: long-term developments

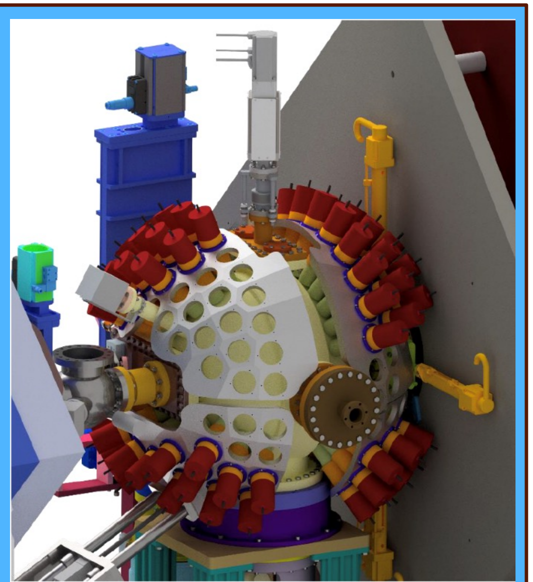
HELIOS@ATLAS, USA
[Si-array mode & AT-TPC]

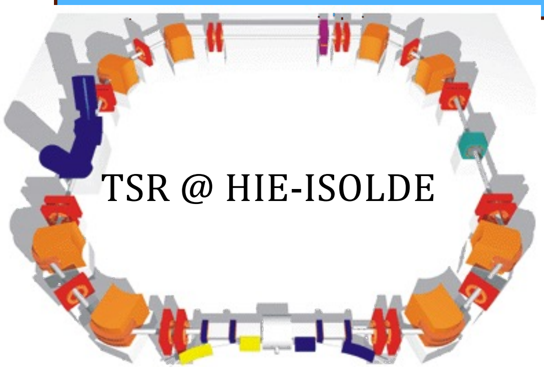


Solenoid spectrometers dedicated to radioactive ion beam experiments **(SPES, FRAISE)**

G-NUMEN

Array of ≈ 110 LaBr3(Ce) crystal scintillator detectors for pushing the NUMEN sensitivity

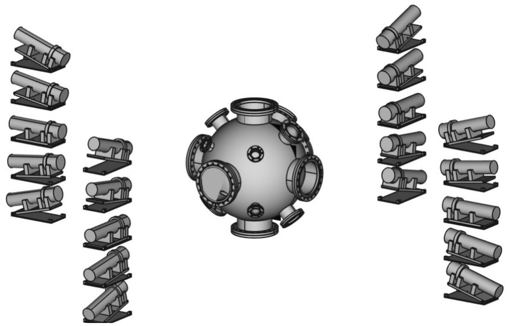




Storage Rings
- Higher resolution
- Higher luminosity
- Mass measurements

→ SPES

Versatile Array for Laser-induced Astrophysics Research
VALAR



- cryo-cooled supersonic nozzle
- neutron ToF detectors (plastic/liquid scintillators)

Summary

The upgrade programs of INFN national laboratories have led **CSN3 to promote a discussion forum** on the future of nuclear physics research in Italy

Four events have been organized at the INFN national laboratories during 2022, and the results of the discussion (**new physics cases, new detectors and synergies among the laboratories**) are being published on a dedicated EPJ Plus Focus Point

A roadmap for future detectors and facilities has been established, **focusing on the special needs of CSN3 experiments**

More than 500 researchers from all around the world have been involved in the forum, with particular emphasis on younger scientists

All the experiments belonging to INFN CSN3 have contributed to the discussions, enhancing cooperation and synergies within the CSN3 and with CSN4-CSN5

Thanks for your attention

Rosario Nania, Jose Javier Valiente Dobon, Alba Formicola, Silvia Pisano, Marco La Cognata

More details and reference at the event webpage:
https://web.infn.it/nucphys-plan-italy/