Quo Vadis
Nuclear Physics in Europe?

Marek Lewitowicz

- What is NuPECC?
- 2017 Long Range Plan in Nuclear Physics
  - Nuclear Structure and Physics with Radioactive Ion Beams (RIB)
  - RIB facilities

What is NuPECC ?

The European Expert Board for Nuclear Physics associated to European Science Foundation

Almost 30 years old

Representing
about 6000 scientists

Members: 31 representatives
from 20 countries + JINR Dubna
5 observers

Main mission: elaborate
a strategy at the European scale
for Nuclear Physics

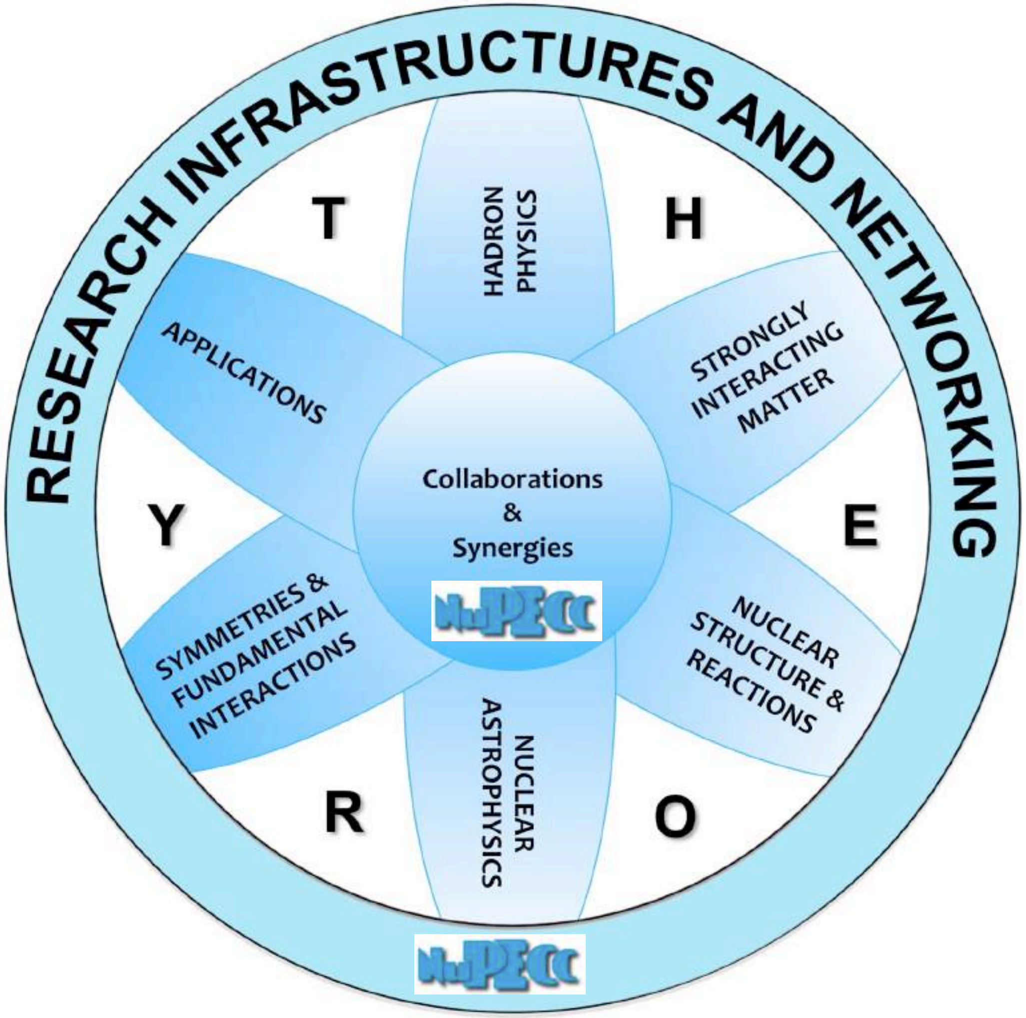
NuPECC Objective

The objective of NuPECC is to:

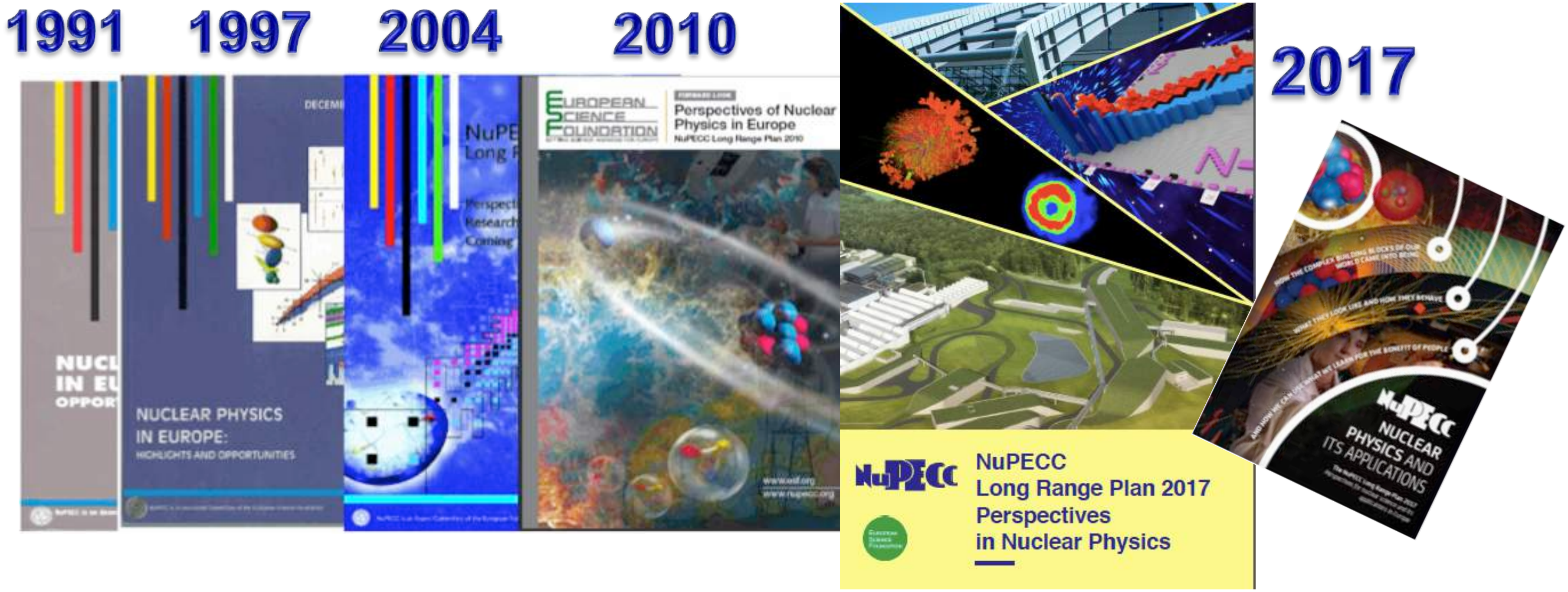
- **develop the strategy for European Collaboration in nuclear science by supporting collaborative ventures between research groups within Europe -> Long Range Plan**

- **promote nuclear physics and its trans-disciplinary use in applications for societal benefit.**

NuPECC ToR



Long Range Plan of NuPECC

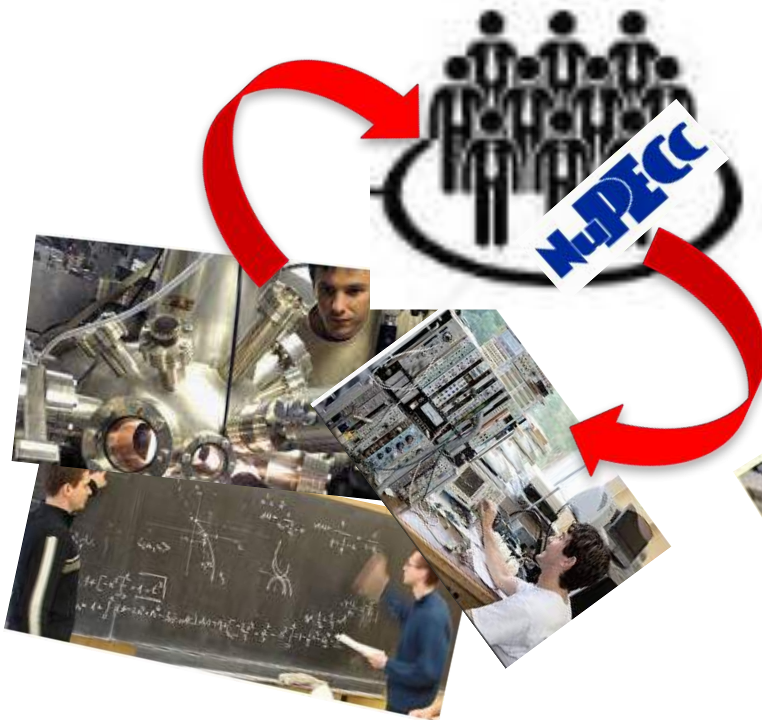


- **The LPR identifies opportunities and priorities for the nuclear science in Europe**
- **The LRP provides the European Commission and national funding agencies with a framework for coordinated advances in nuclear science in Europe**

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

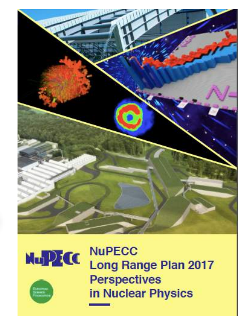
Who did produce this strategic document ?

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



Community working in the field :
200 experts in experiments and theory
7 working groups

Town meeting
in Darmstadt
January 2017

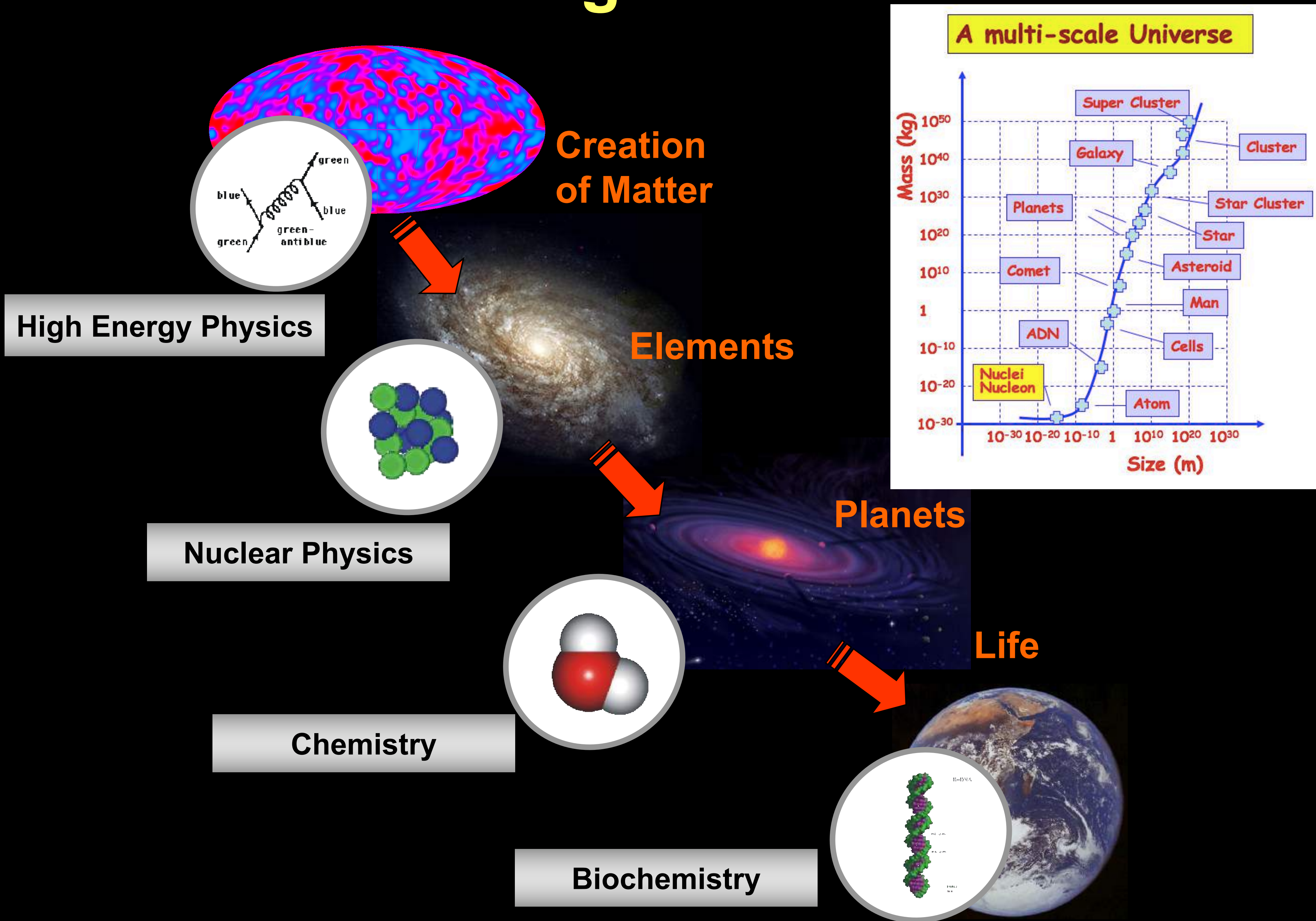


Report
June 2017

2016
beginning

end 2017

The origin of life

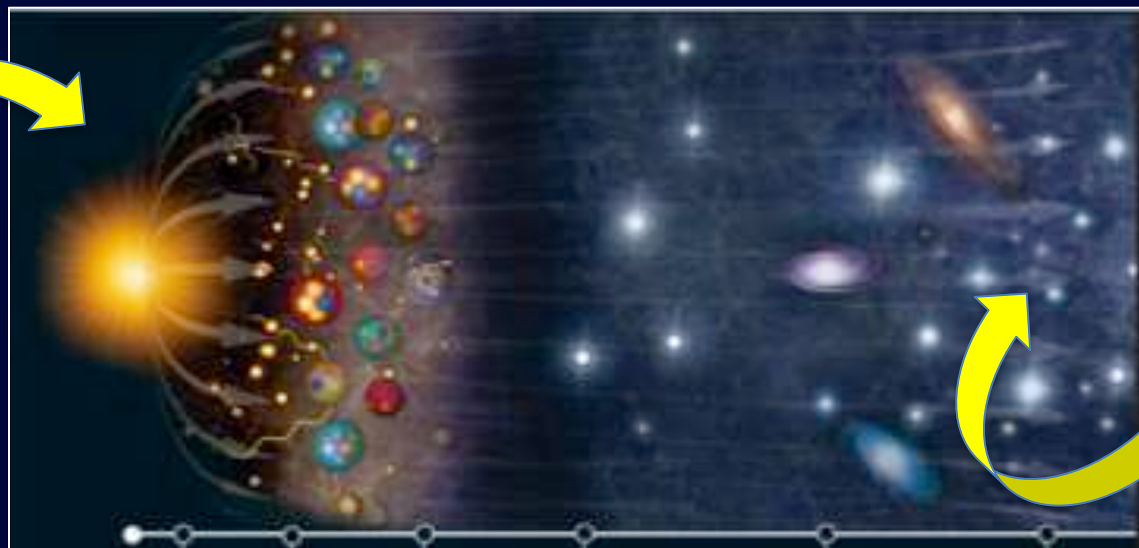


Nuclear physics and the evolution of the Universe

Nuclear Physics with its different research domains addresses several key issues for the understanding of the different stages of the evolution of the universe

QCD

QCD
in hot
compressed
matter



10^{-32} sec | 10^{-6} sec | 100 sec | 100 Millions years | 500 Millions years | 4 Billions years

Nuclear structure
Nucleosynthesis

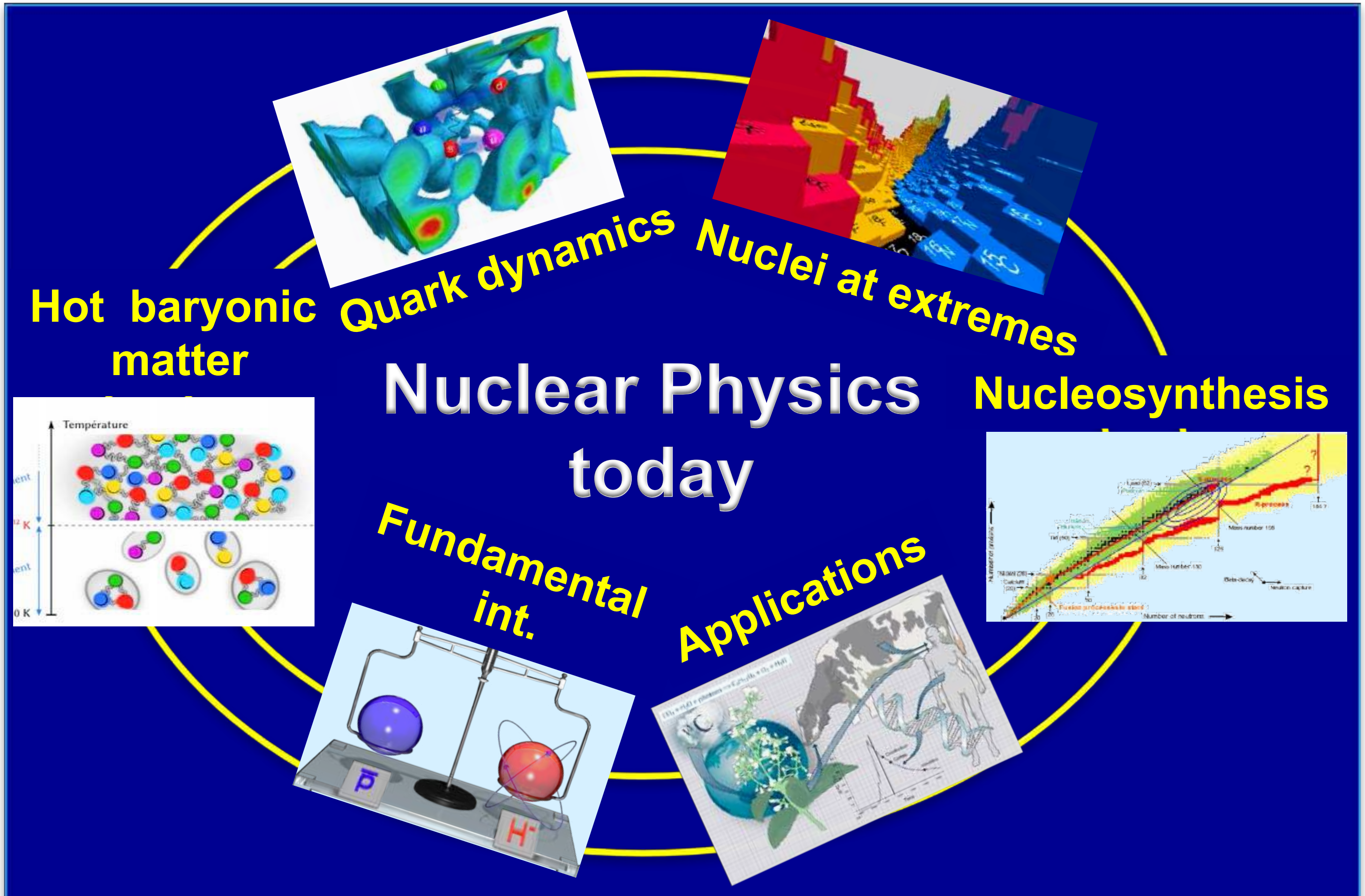
Reactions
for astrophysics

Compressed
nuclear matter

To tackle the different problems one needs a distributed approach and efforts :
different accelerator types and energies

Nuclear Physics Today

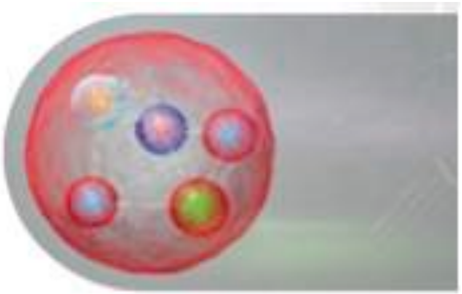
Study of nuclear matter in all its forms exploring their possible applications



Nuclear physics is a very broad field !

Each area needs particular tools and technologies

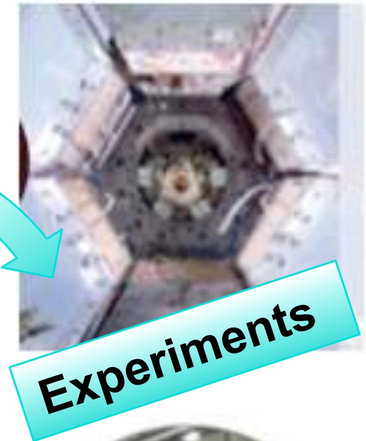
The Physics of Hadrons



Hadron physics involves studying the intricate patterns of the hadron structures that emerge, the spectra mapping their energies and their interaction

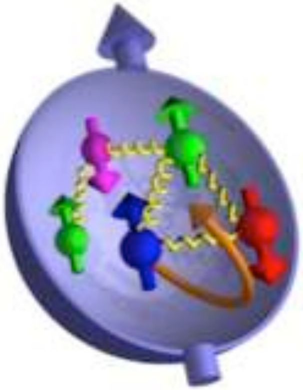
- **How is mass generated in Quantum Chromo Dynamics (QCD) and what are the static and dynamical properties of hadrons?**
- **How does the strong force emerge from the underlying quark-gluon structure of nucleons?**

Identify the connection between quark dynamics and quantum numbers (spin and orbital angular momentum)



QCD : theory of strong force

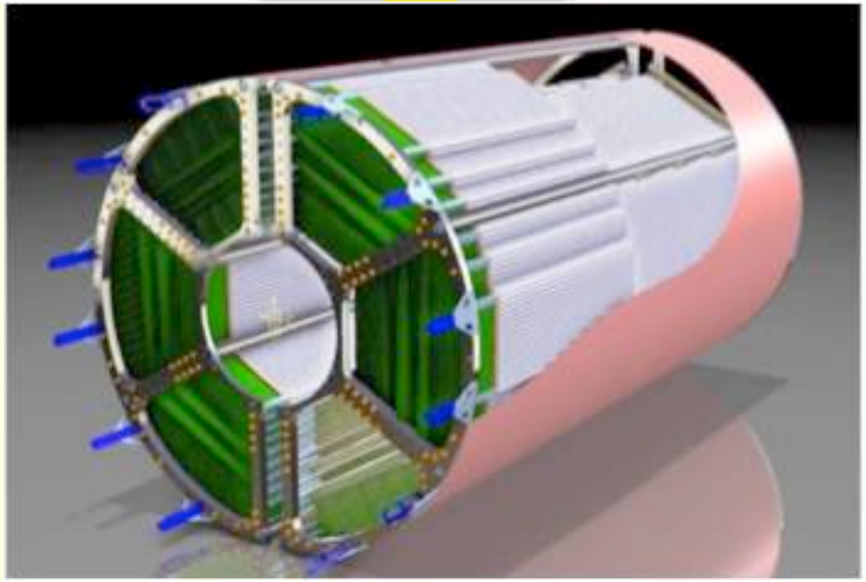
The Physics of Hadrons



The proton

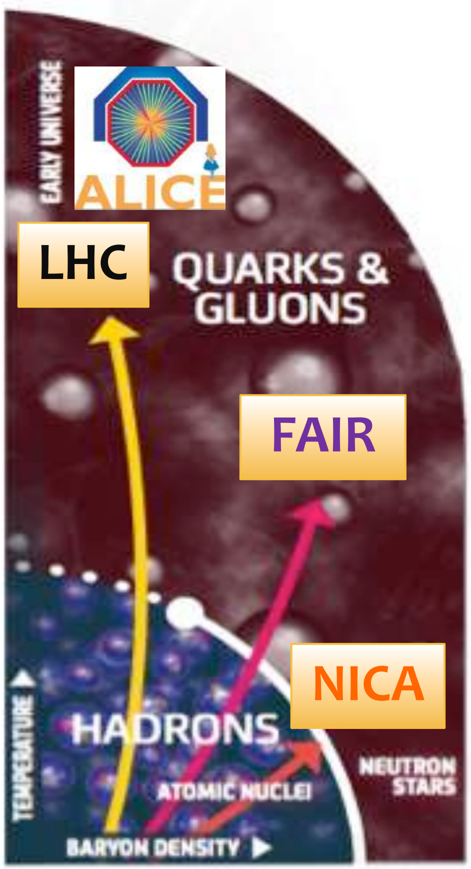
Studies have uncovered discrepancies in measurements of the proton radius made with different techniques.

New experiment planned to tackle this issue (one at Mainz-MESA) : new physics?

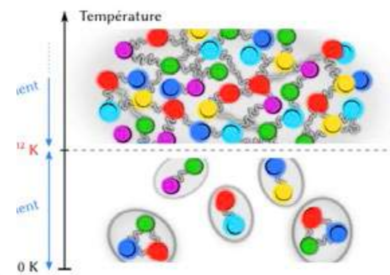


High resolution experiments with antiprotons (PANDA) at FAIR will address many issues to test in detail theory of Quantum Chromo Dynamics (QCD)

Hadronic Matter at the very extremes

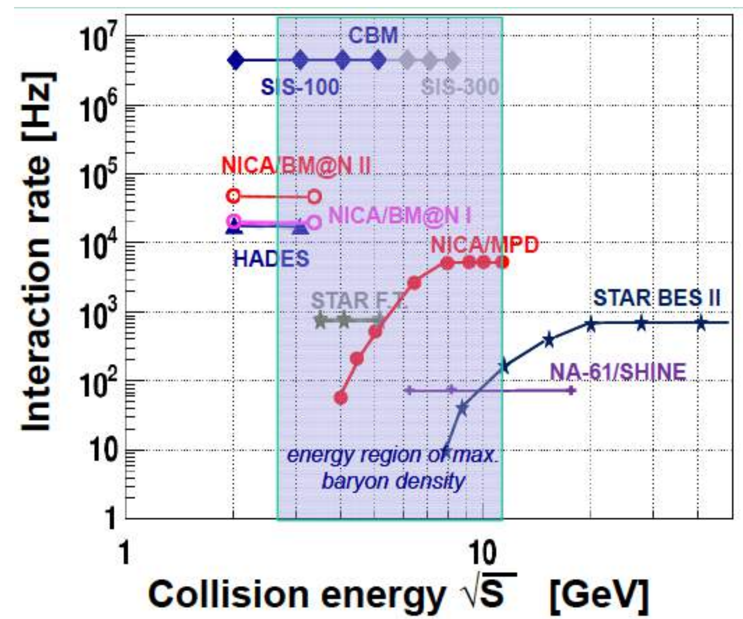


Matter at very high temperature and density Quark Gluon Plasma (QGP) reveals the high energy processes that drove the evolution of the universe after its birth.



signals from de-confinement and chiral symmetry restoration

Its very exotic nature is found in massively compressed stellar corpses : neutron stars



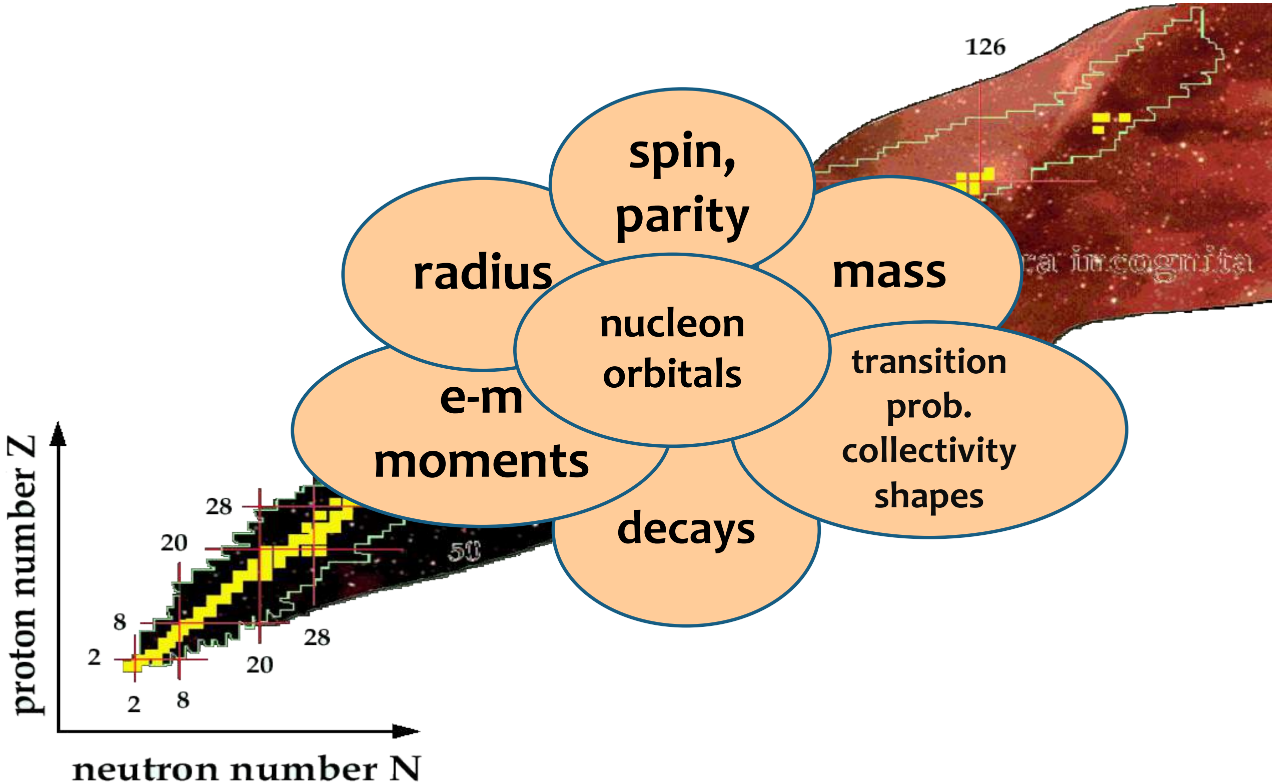
QGP turned into hadrons few μs after Big Bang. It is not seen in astronomical observations and thus is recreated in the Heavy Ion labs within volumes of nuclear size

Nuclear Structure and Reactions

Questions

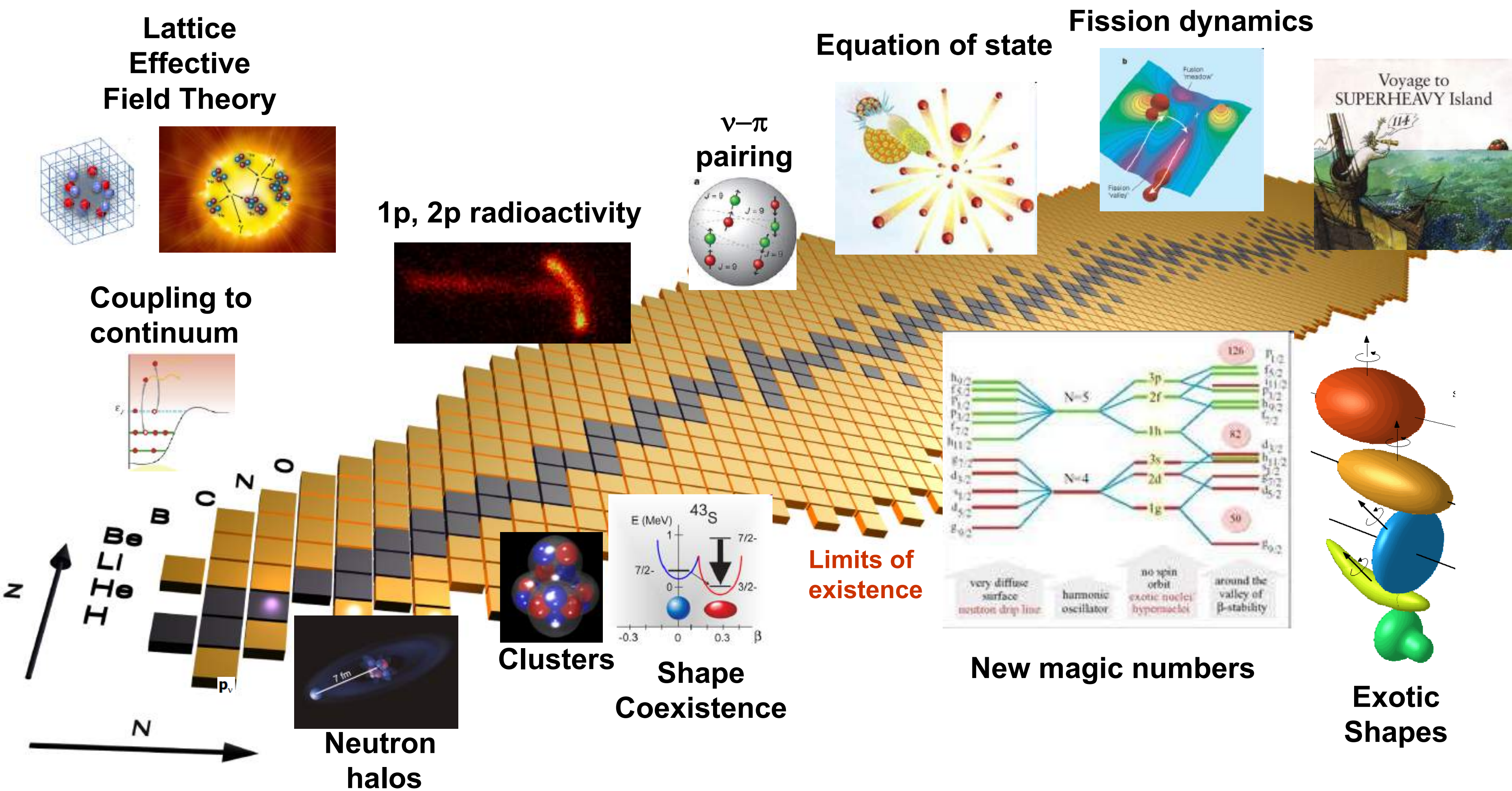
- Where are the limits of stability and what is the heaviest element?
- How does nuclear structure evolve (also with T and L) and what shapes can nuclei adopt ?
- How complex are nuclear excitations?
- How do correlations appear in dilute neutron matter ?
- What is the density and isospin dependence of the nuclear equation of state ? (for neutron stars)

Protons and neutrons via the nuclear force can create as many as 7000 nuclear species (250 stable, about 2000 synthesised). At limit of stability there is an extreme proportion of p or n in a nucleus.



Tools : Heavy ion beams far from stability produced with different reaction types, gamma beams and radioactif decay

Structure of complex nuclei



<u>Search and UNDERSTAND</u> regular and simple patterns in the structure of complex nuclei by <u>characterizing</u> them under <u>EXTREME conditions (E,J,T)</u>:*

amplify different aspects of the interaction

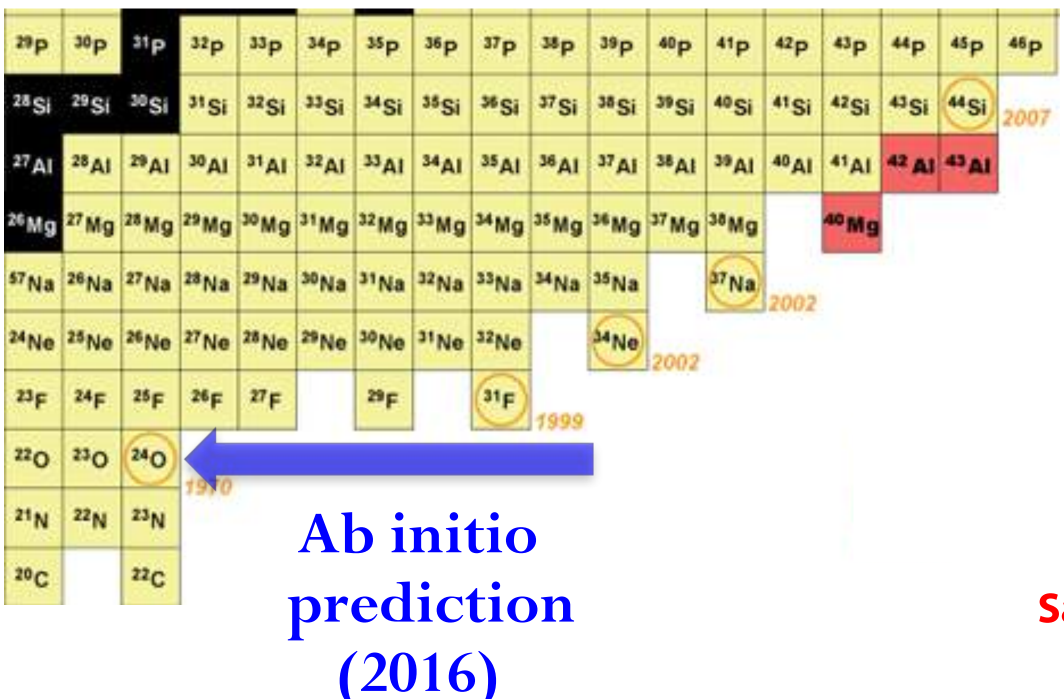
Major Issue: Where Are the Limits of Existence?

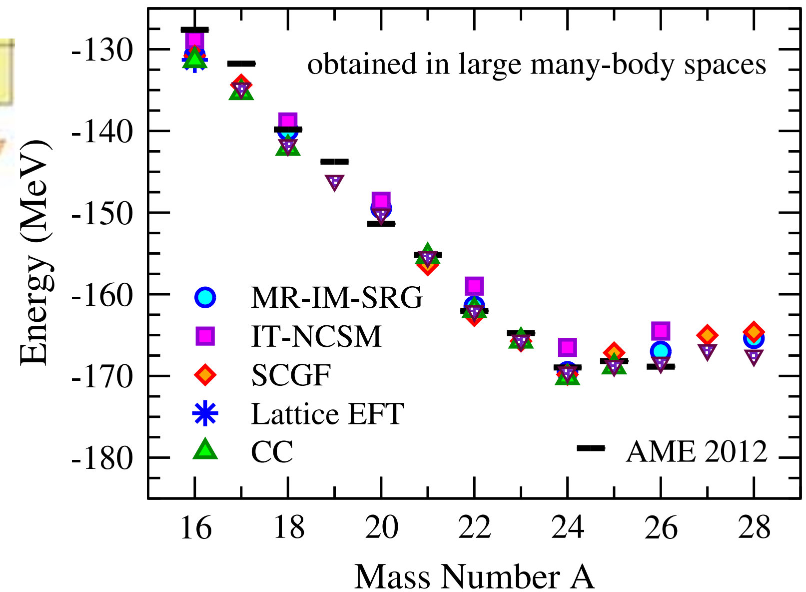
Where (and what) is the nuclear dripline?

Limits defined as last isotope with positive neutron separation energy

- Nucleons “drip” out of nucleus

Neutron dripline experimentally established to Z=8



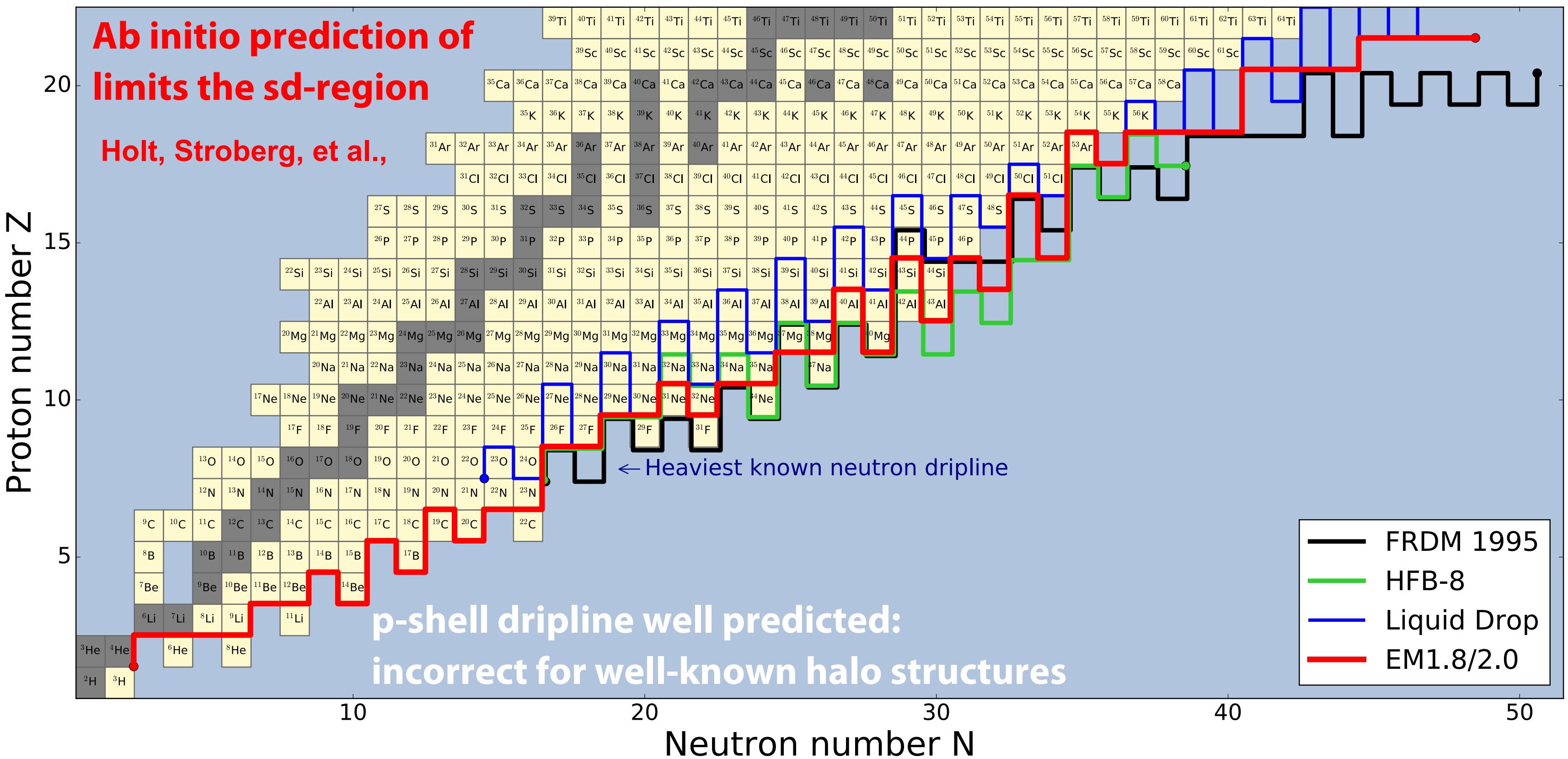


Same result from same input NN+3N forces

Already well beyond where fit to data!

Courtesy of J. Holt

Ab Initio Dripline Prediction



General agreement with FRDM/HFB predictions (not available for p-shell)

Very strong experimental programs at and competition from RIKEN, FRIB, FAIR, RAON !

Courtesy of J. Holt

Evolution of Nuclear Shell Structure Far From Stability

Shell evolution novel phenomenon in exotic nuclei

Unexpected magic numbers appear

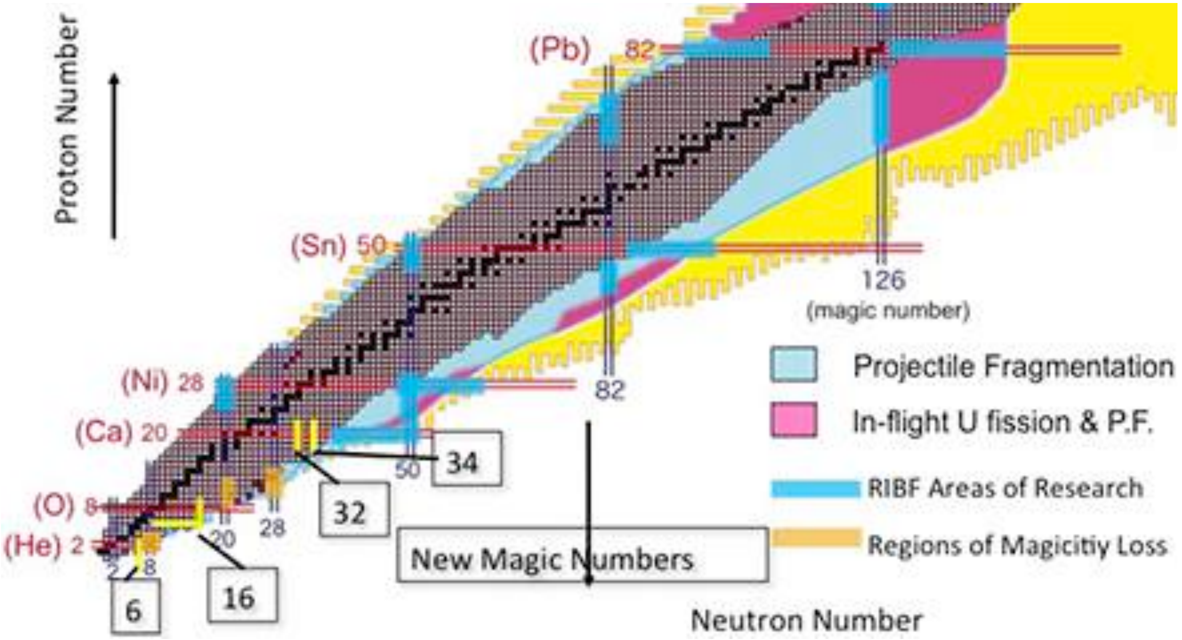
Expected ones disappear

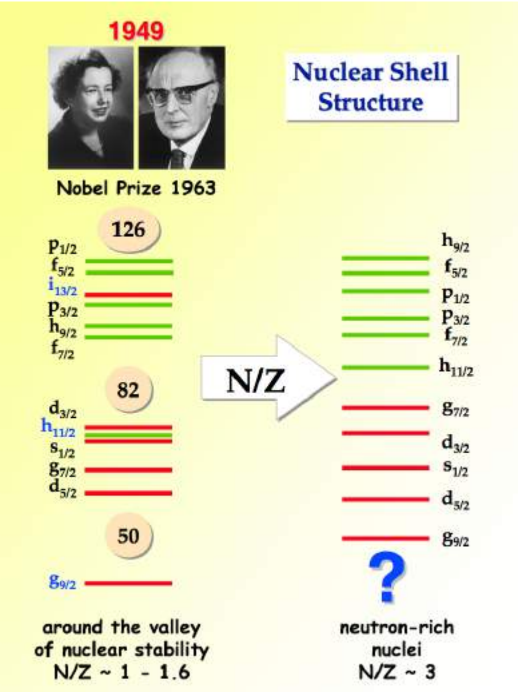
Can we understand/predict this trend?

Signatures of Magic Numbers

- **Sudden decrease in separation energies (masses)**
- **Elevated first excited state (spectroscopy)**
- **Tightly bound (decreased radii)**

Must observe all signatures – many experiments needed!

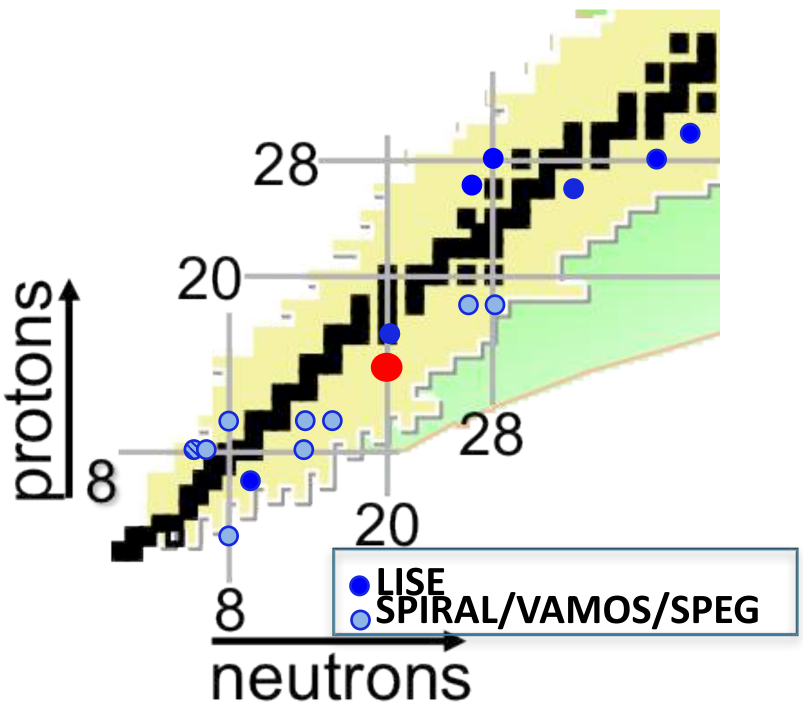




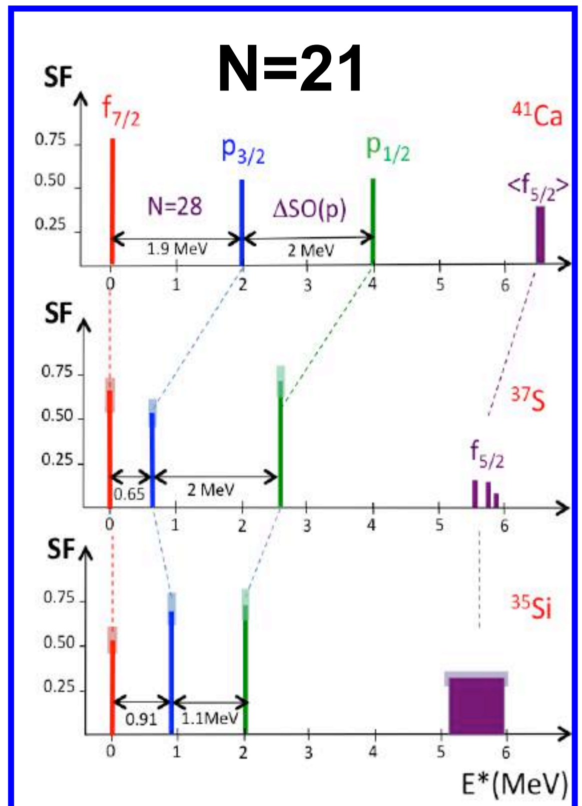
Courtesy of J. Holt

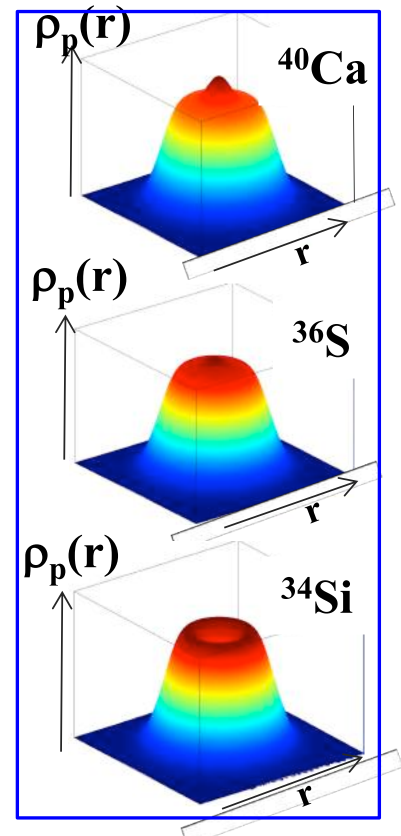
Transfer reactions & bubble nuclei

- **Probe single particle energies, shape coexistence or pairing modes via** **^{34}Si(d,p),** (d,t), (d,^{3}He), (p,d), (p,t), (p,^{3}He) … reactions.
- **Variety of beams at 10-20MeV/A**
- **Instrumentation: magnetic spectrometers, Si and gamma arrays**



Spin - orbit interaction in the ^{34}Si bubble nucleus





G. Burgunder et al. PRL (2014)

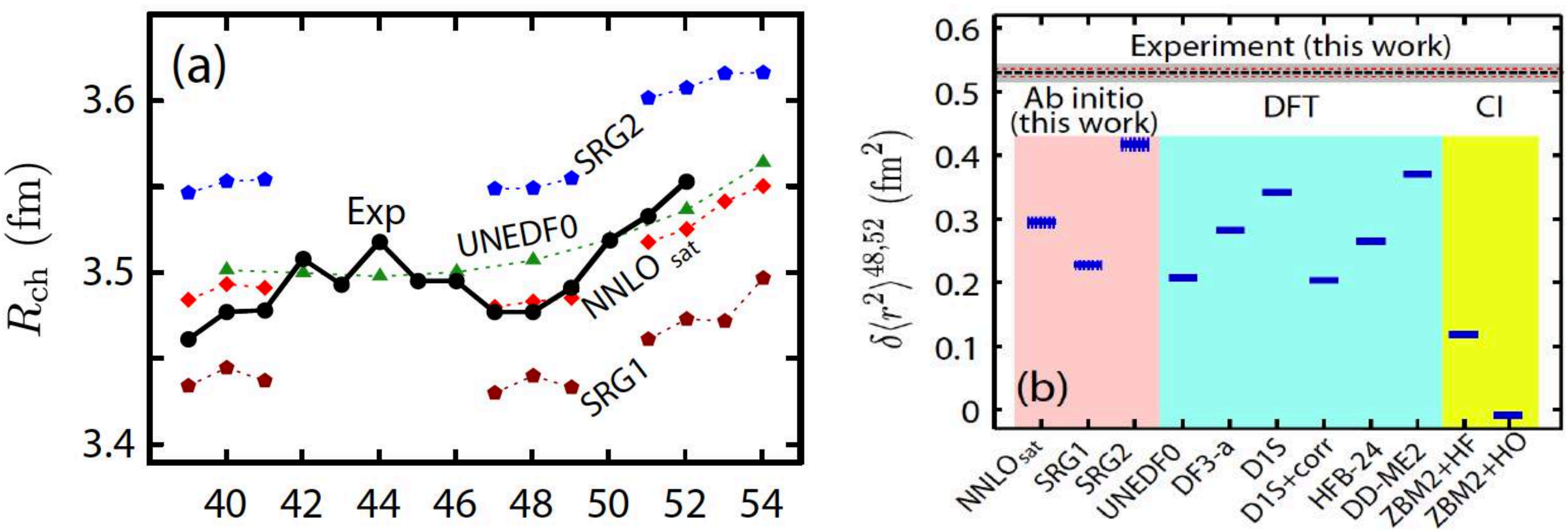
Magic Numbers in the Calcium Isotopes: Charge Radii

Charge radii of $^{49,51,52}Ca$, obtained from laser spectroscopy experiments at ISOLDE, CERN

Unexpected large charge radius questions the magicity of ^{52}Ca

Theoretical models all underestimate the charge radius

Ab-initio calculations reproduce the trend of charge radii

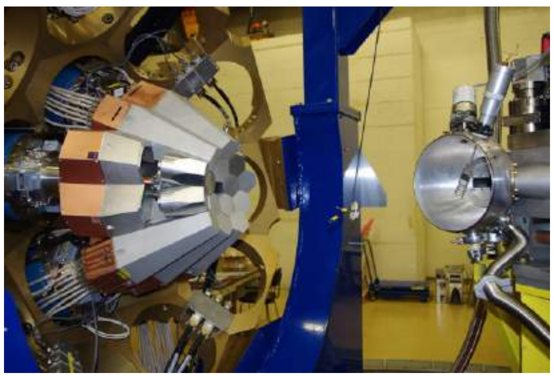


R. F. Garcia Ruiz *et al*, Nature Physics (2016)

AGATA Tracking array for gamma spectroscopy

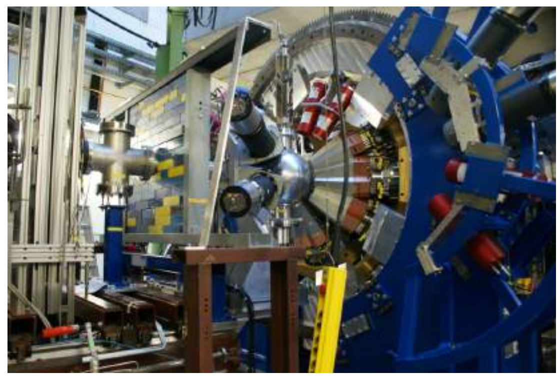
High-sensitivity for nuclear structure of exotic nuclei – used in several EU laboratories

2010 → 2011 LNL, Italy
5TC (15 detectors)



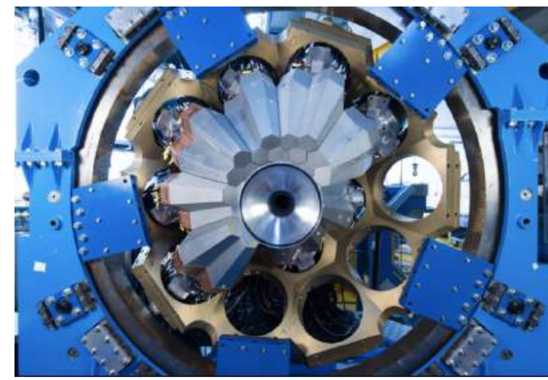
AGATA Demo.+PRISMA
Total Eff $_{Nominal}$. ~2.6%

2012 → GSI, Germany
6TC+3 DC (22 detectors)



AGATA @ FRS
Total Eff. (β=0.5) ~ 10%

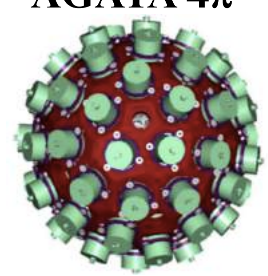
2014 → GANIL, France
15TC (45 detectors)



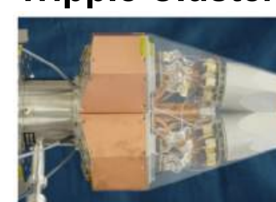
AGATA @G1
Total Eff ~ 8% to 14%

AGATA array: A powerful traveling instrument - its construction has to proceed in the next years up to 4π coverage (60 triple clusters = 160 detectors) !

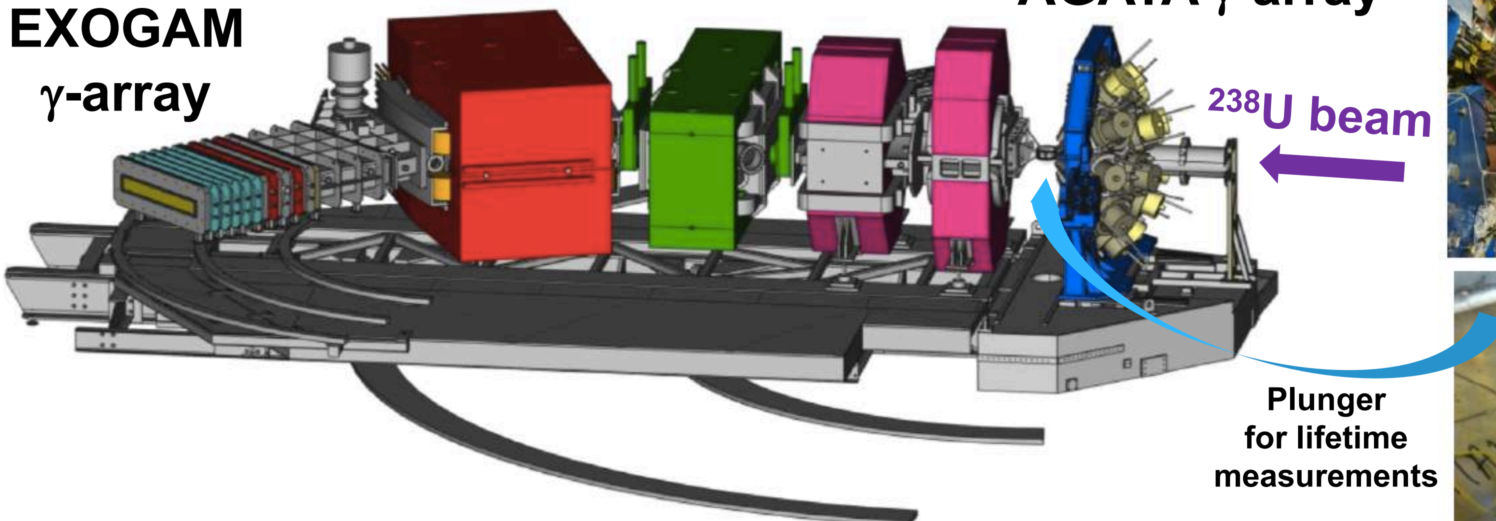
AGATA 4π

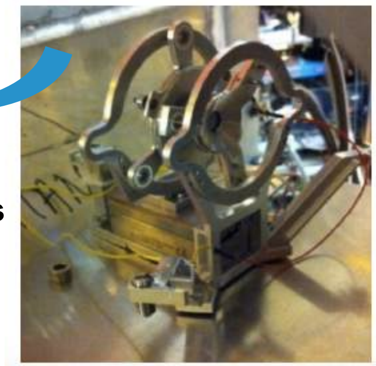


Tripple Cluster

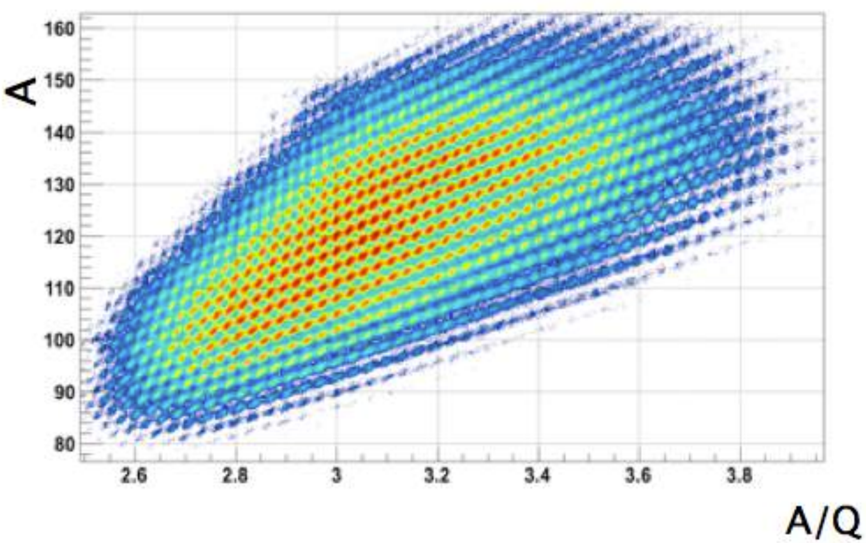


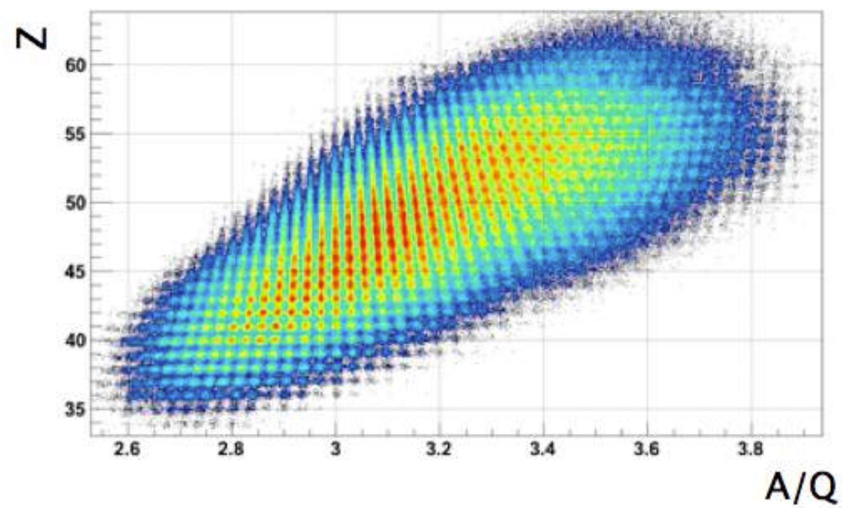
Advanced fragment – γ-ray on-line spectroscopy



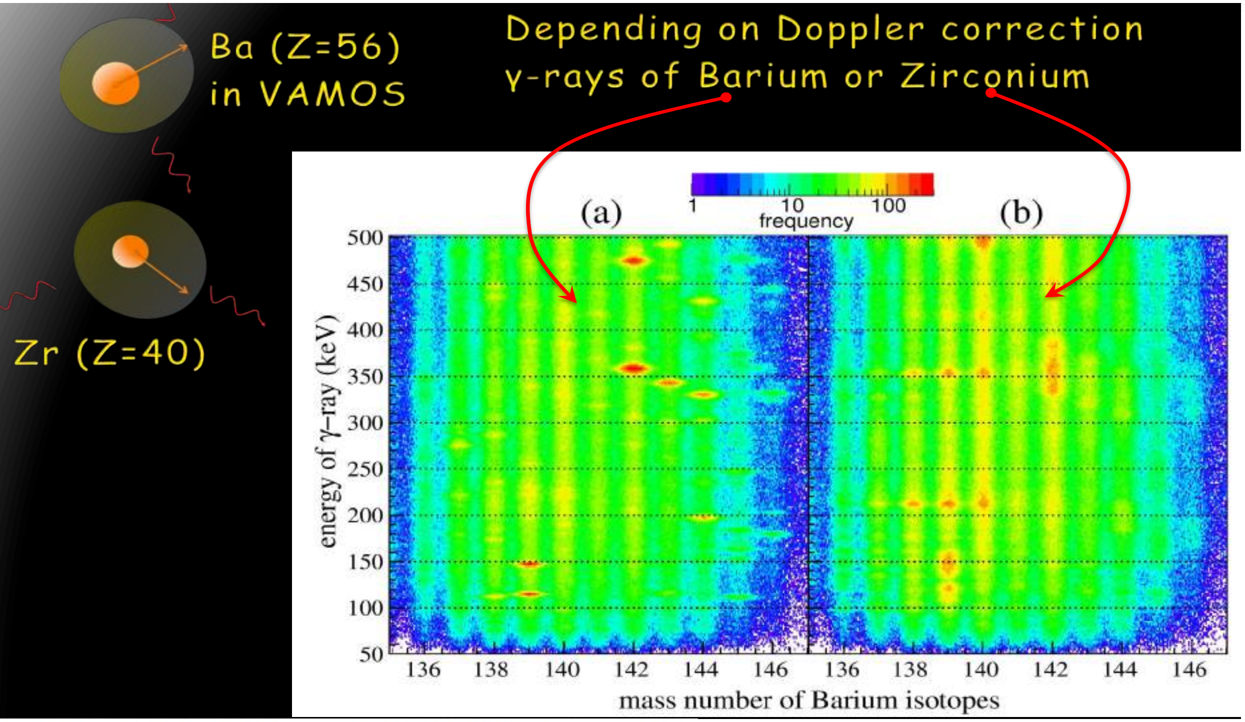


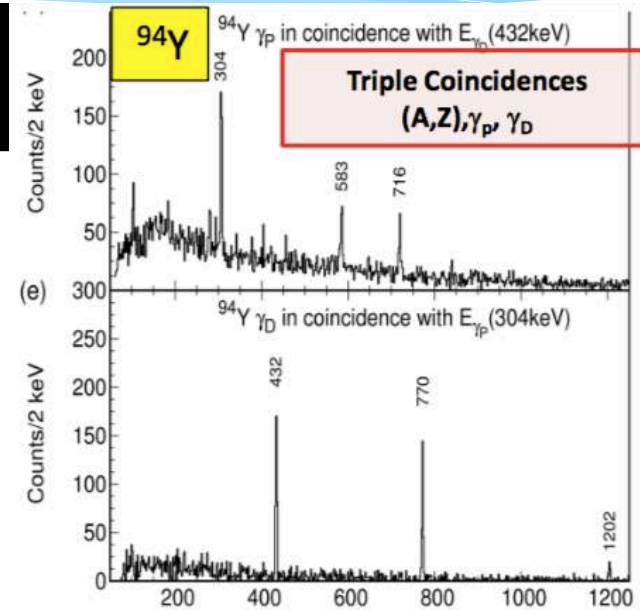
Full identification of produced isotopes in Z, Q & A



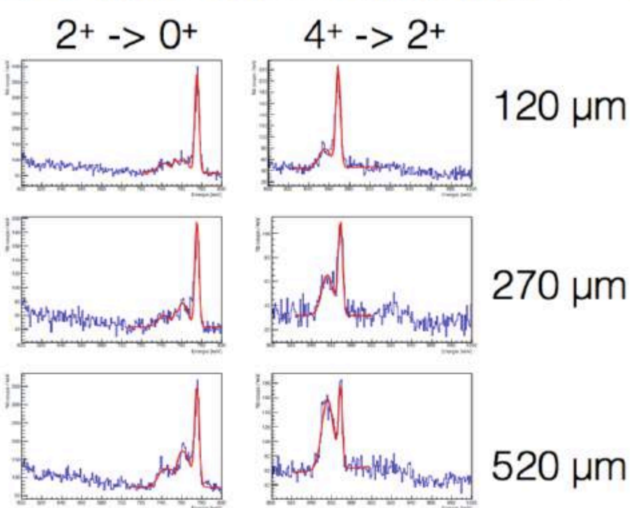


Advanced fragment – γ-ray on-line spectroscopy

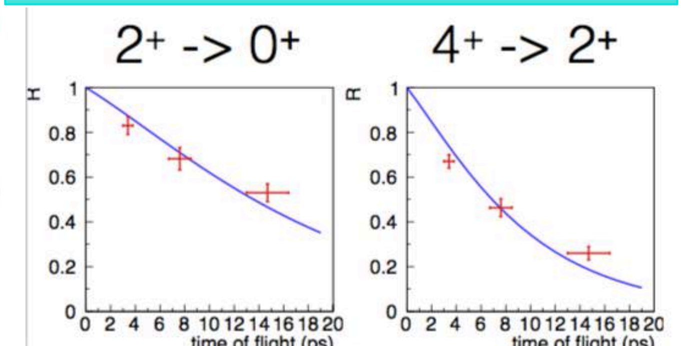




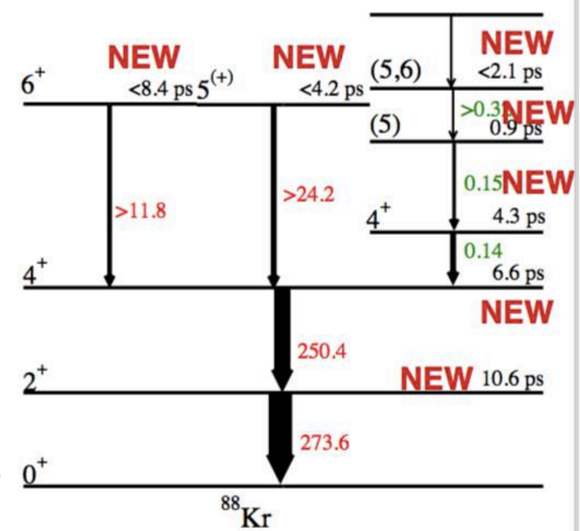
Eur. Phys. J A **53** 162 (2017)



Lifetime measurements: 88Kr



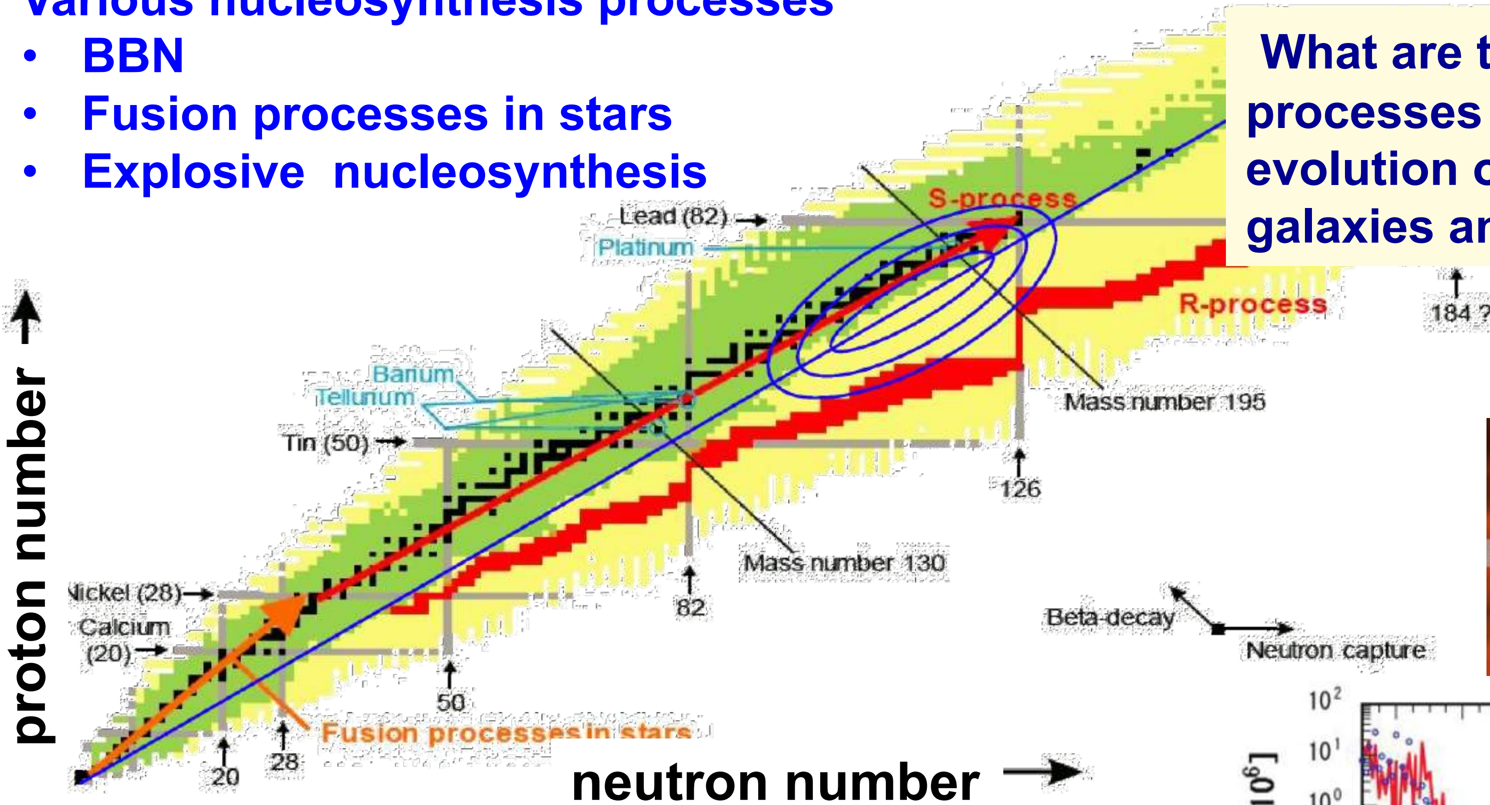
B(E2)↓ (e^2fm^4)
B(M1)↓ (μ_N^2)



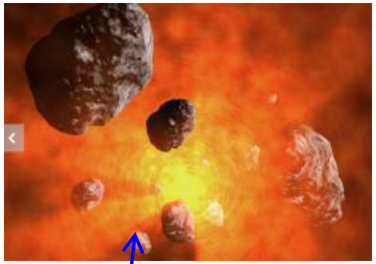
Nuclear astrophysics

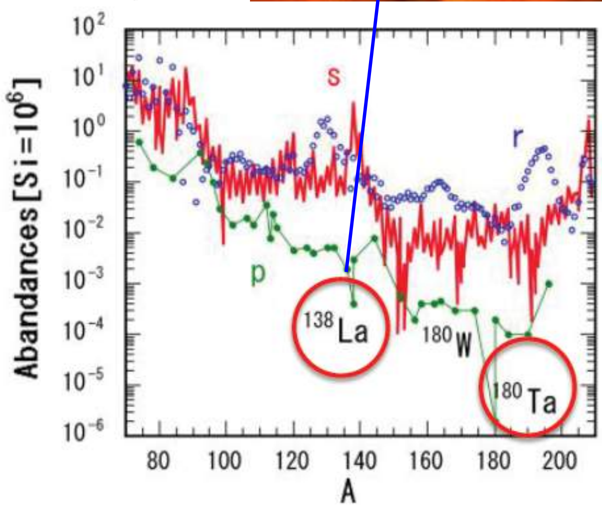
Various nucleosynthesis processes

- **BBN**
- **Fusion processes in stars**
- **Explosive nucleosynthesis**



What are the nuclear processes that drive the evolution of the stars, galaxies and the Universe?





Interplay of:

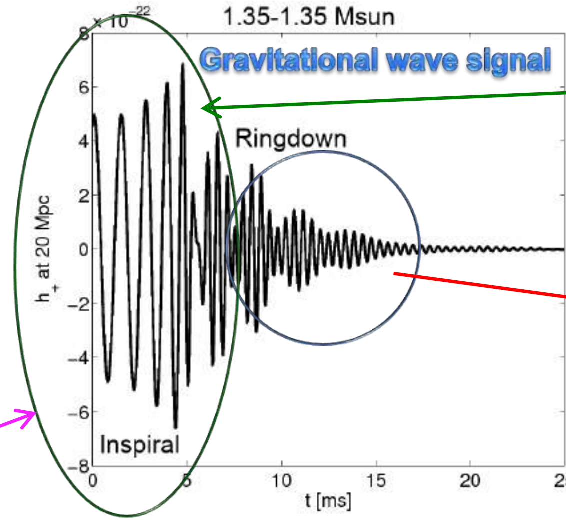
- **nuclear structure**
- **nuclear decays**
- **half-lives**
- **nuclear reactions**
- **nucler masses**

Proton and neutron rich side nuclei – our precursors need to be investigated with different tools

Neutron star mergers: Gravitational waves and production of heavy elements

The messengers from neutron star mergers :

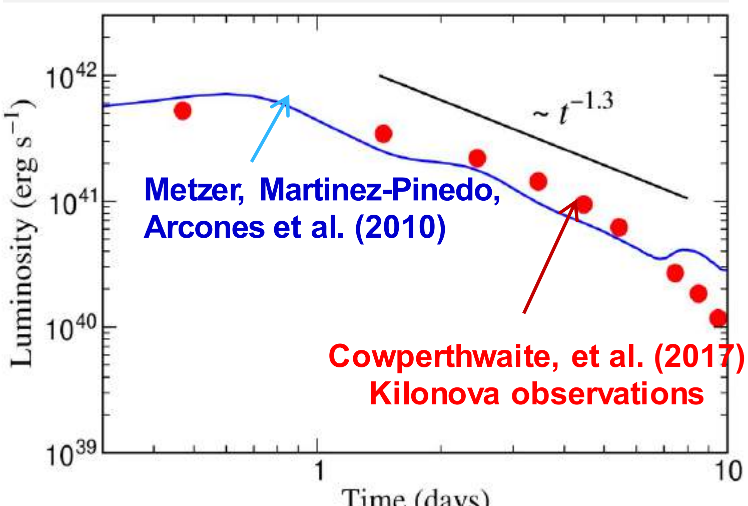
- Gravitational waves
- Electromagnetic signals characterizing the nuclei in the ejecta
- neutrinos

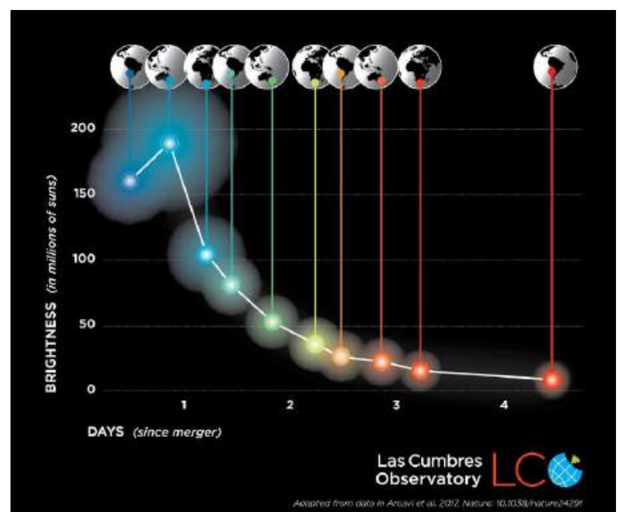


Neutron star mass

This depends on the Nuclear Equation of state

Gravitational wave emission seen together with electromagnetic signals

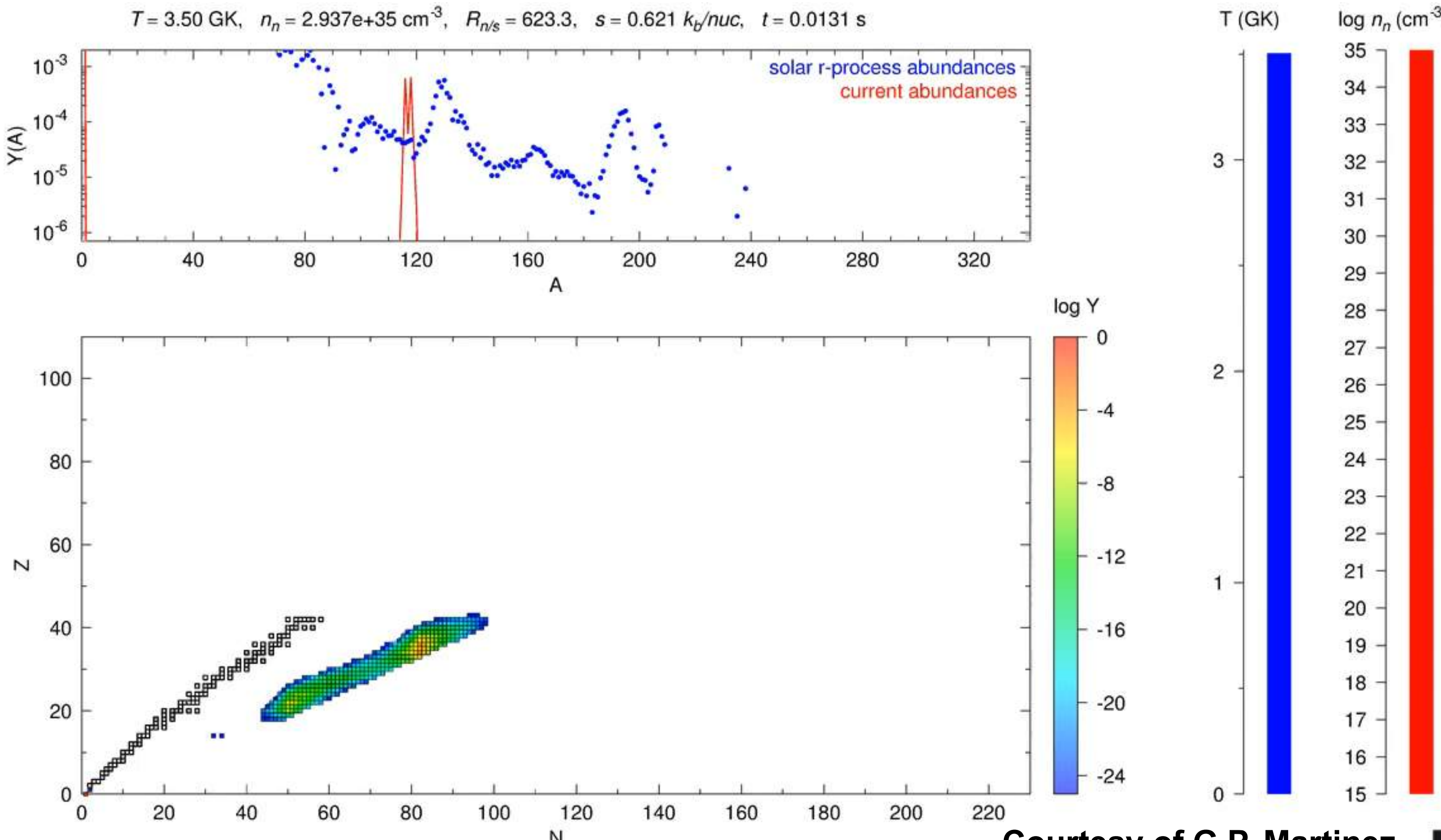




Time evolution determined by the radioactive decay of r-process nuclei (science drive of facilities with RIB)

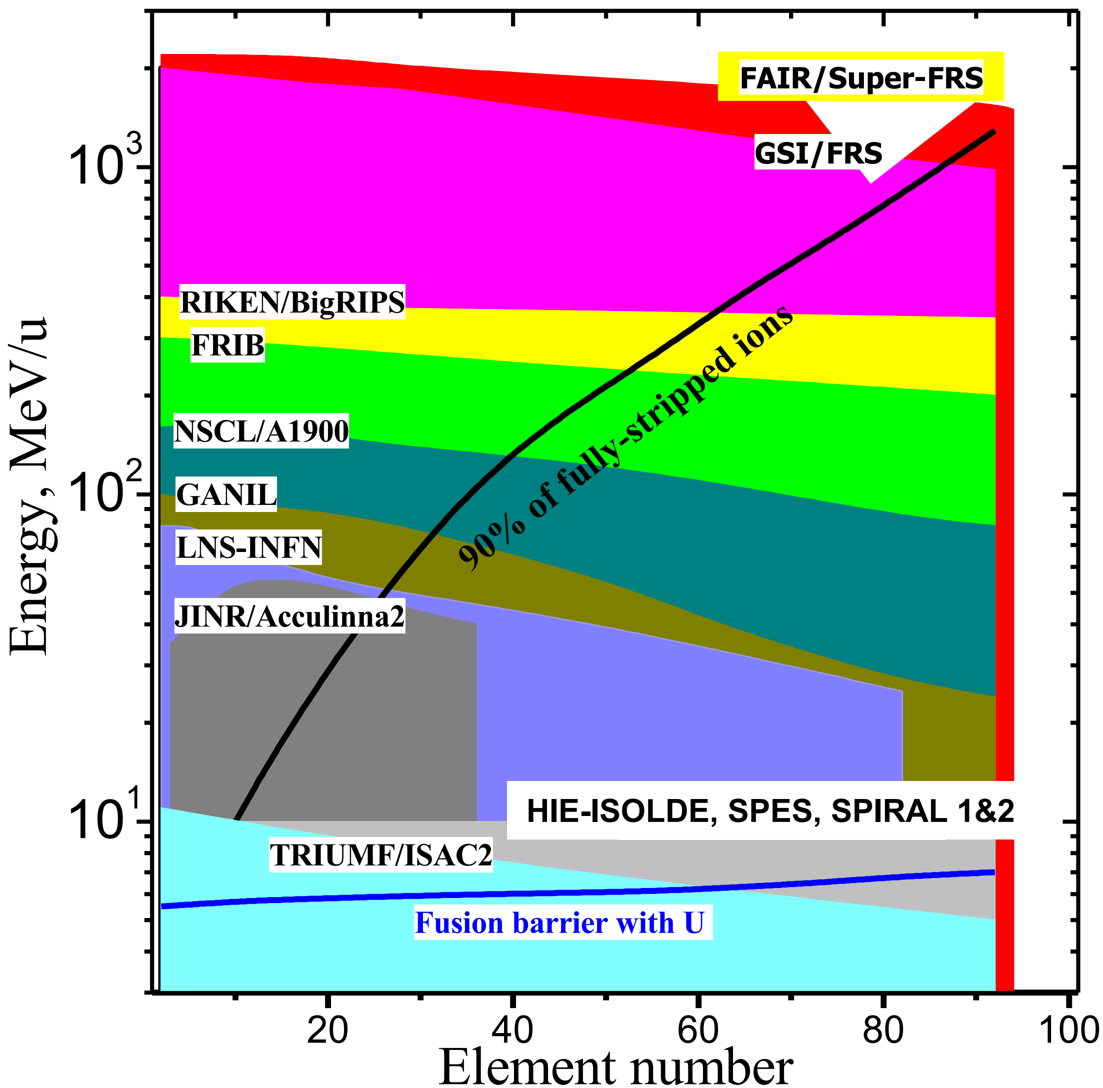
r-process in n-star mergers

…. a simulation of the r-process



Courtesy of G.P. Martinez

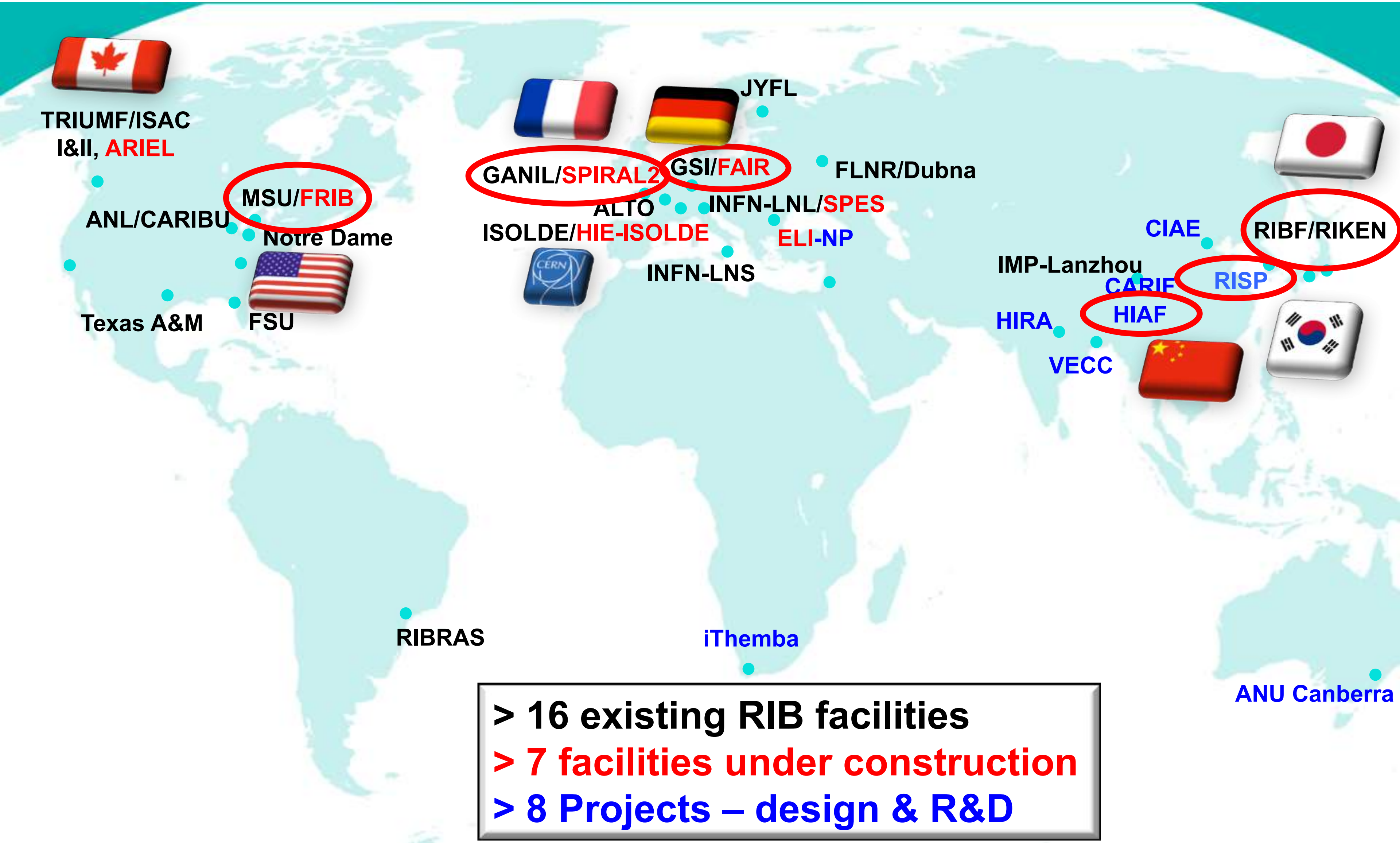
Physics with Radioactive Ion Beams – Energy domain



Energy range from 0 to 2 GeV/n

ISOL facilities: from 0 to 20 MeV/n

Major Radioactive Ion Beam Facilities worldwide



> 16 existing RIB facilities

> 7 facilities under construction

> 8 Projects – design & R&D

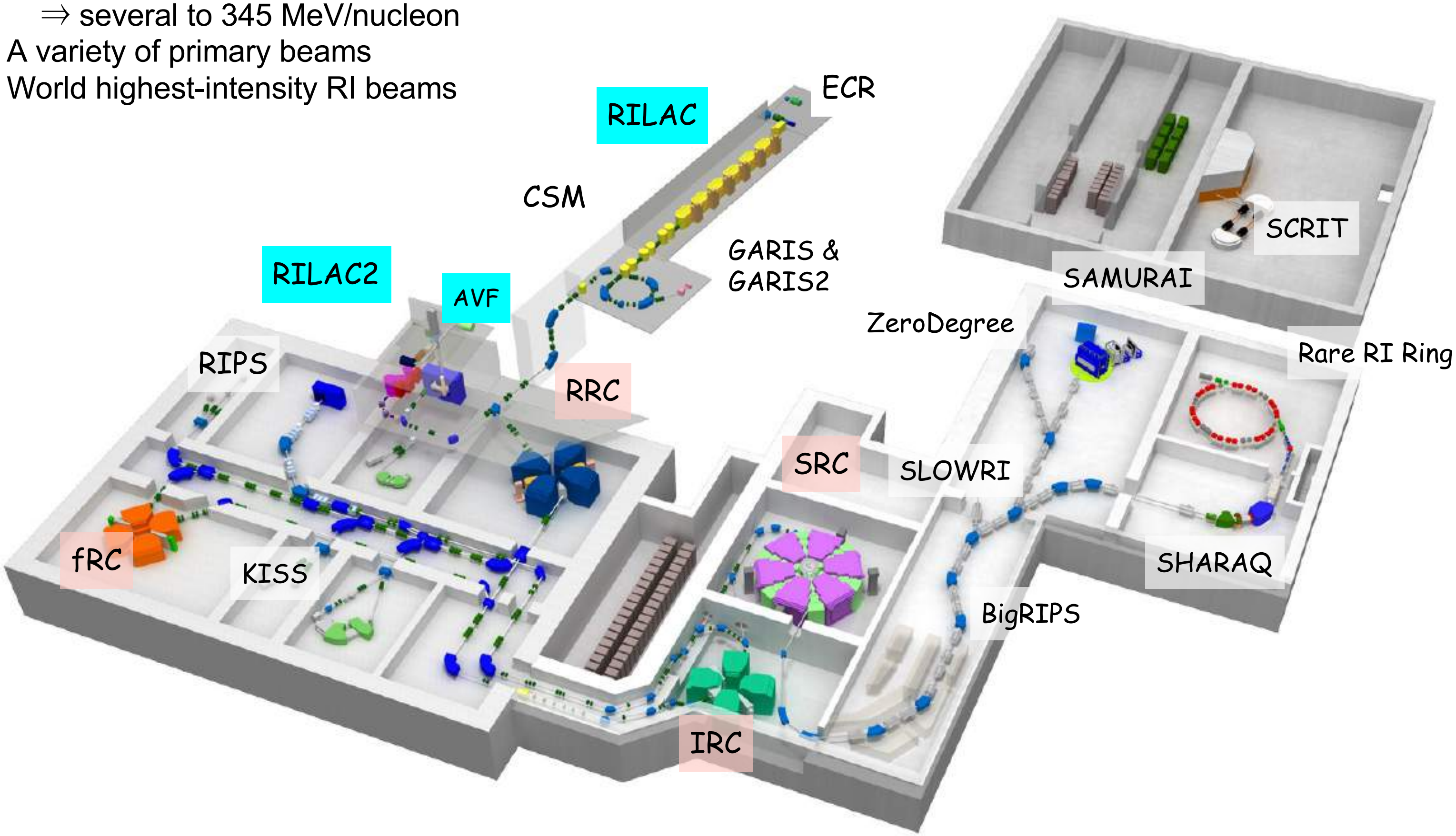
RI Beam Factory at RIKEN

3 injectors + cascade of 4 cyclotrons

⇒ several to 345 MeV/nucleon

A variety of primary beams

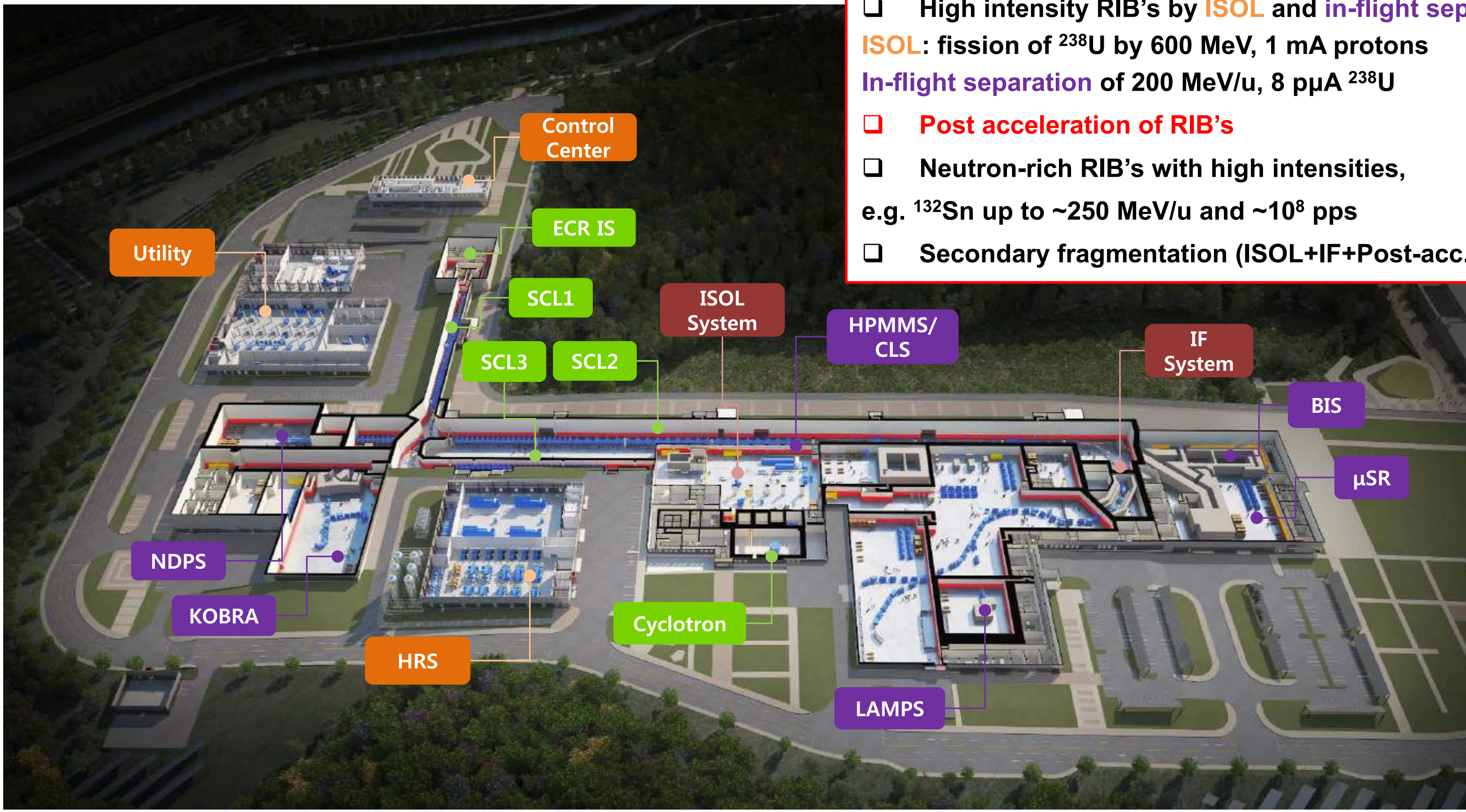
World highest-intensity RI beams



≥ 500 M$, operation started in 2007

40M$ upgrade is ongoing -> intensity x30

Layout of RAON facility in Korea



- ❑ High intensity RIB's by ISOL and in-flight sep.

ISOL: fission of ^{238}U by 600 MeV, 1 mA protons

In-flight separation of 200 MeV/u, 8 pμA ^{238}U

- ❑ Post acceleration of RIB's
- ❑ Neutron-rich RIB's with high intensities,

e.g. ^{132}Sn up to ~250 MeV/u and ~10^8 pps

- ❑ Secondary fragmentation (ISOL+IF+Post-acc.)

≥ 1 B$, construction started in 2017 and to be finished by 2023

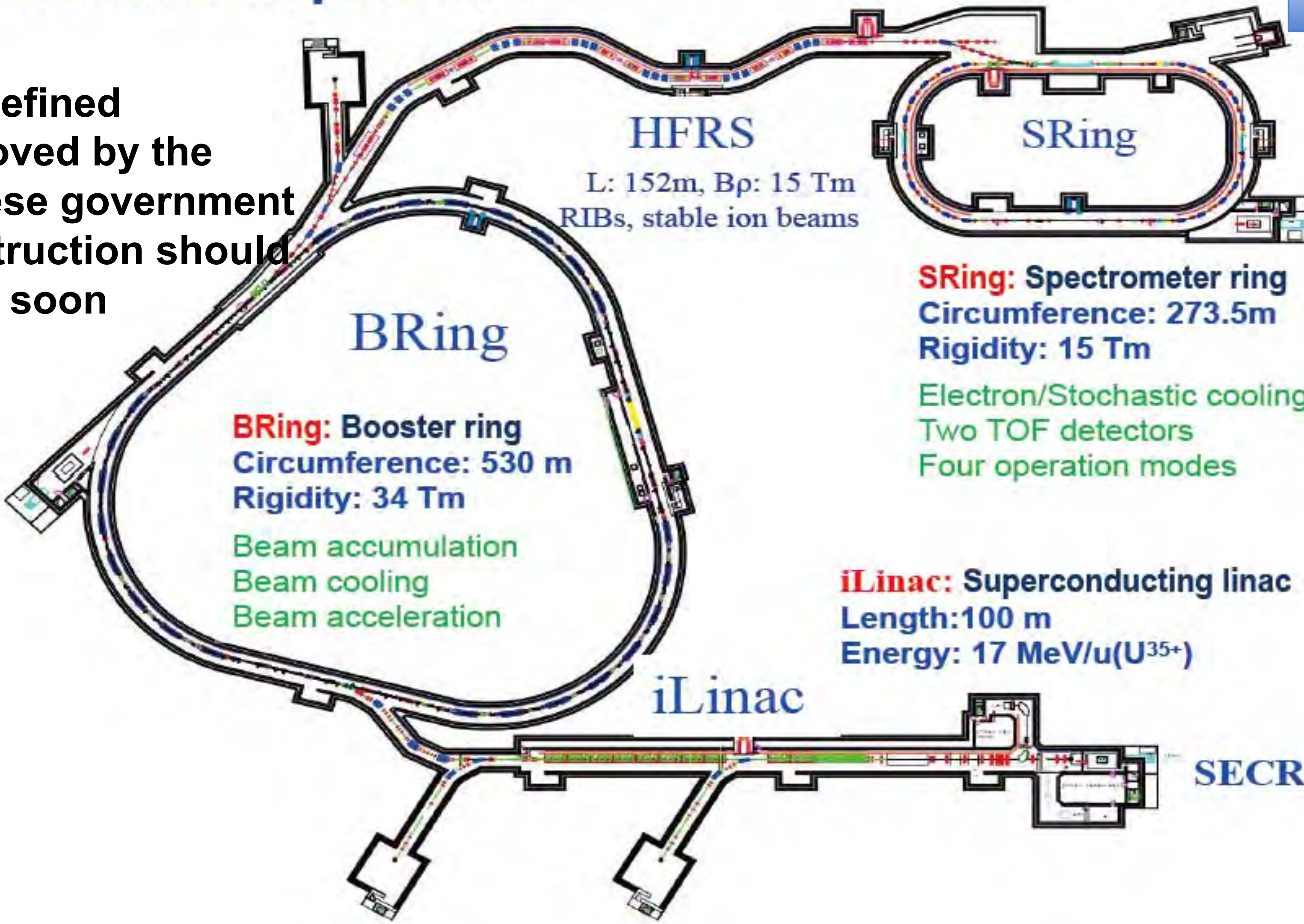
Layout and beam specification

HIAF

The main components

in China

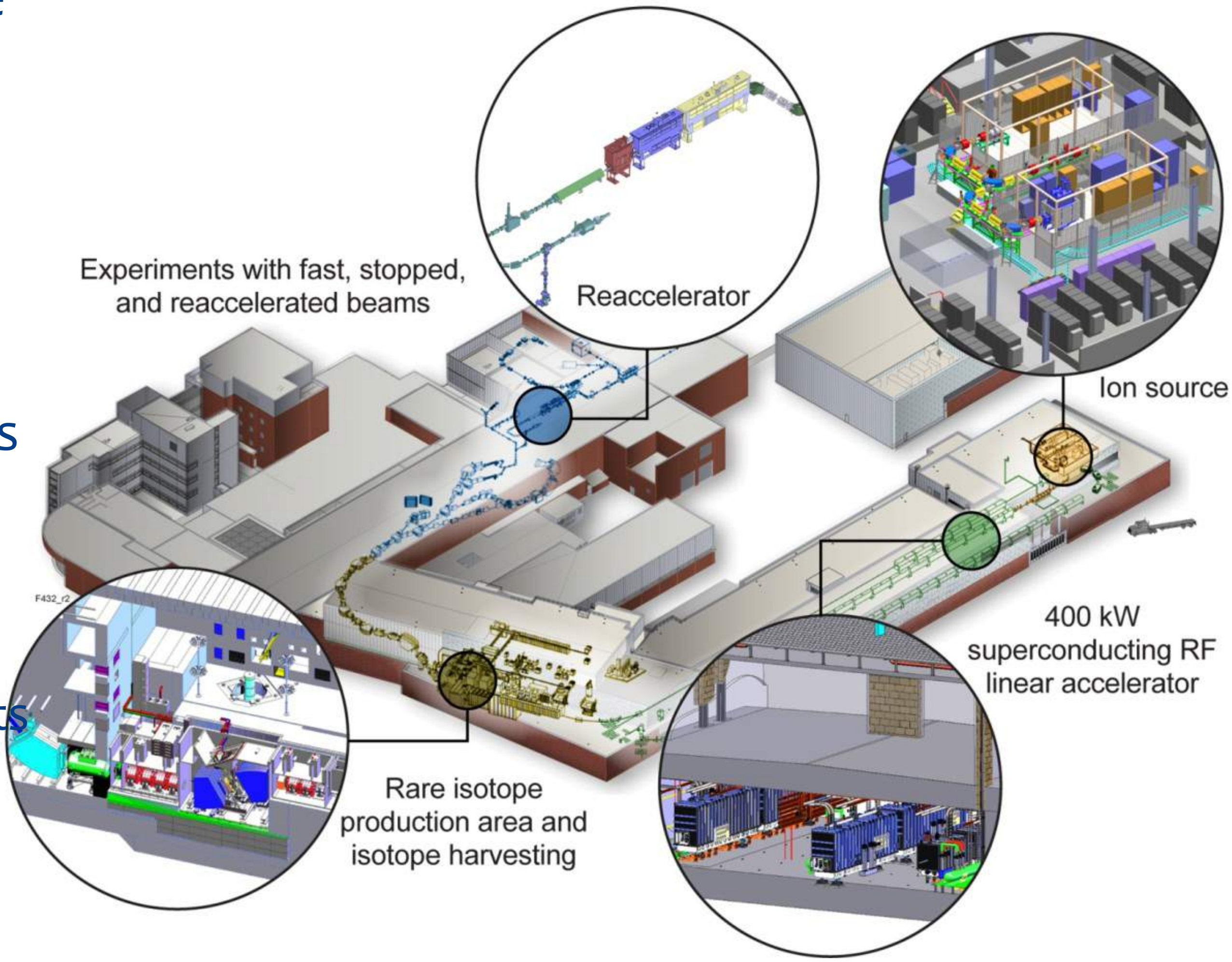
- **Site defined**
- **Approved by the Chinese government**
- **Construction should begin soon**



≥ 1 B$, site identified, construction will start in 2018

Major US Project – Facility for Rare Isotope Beams, FRIB

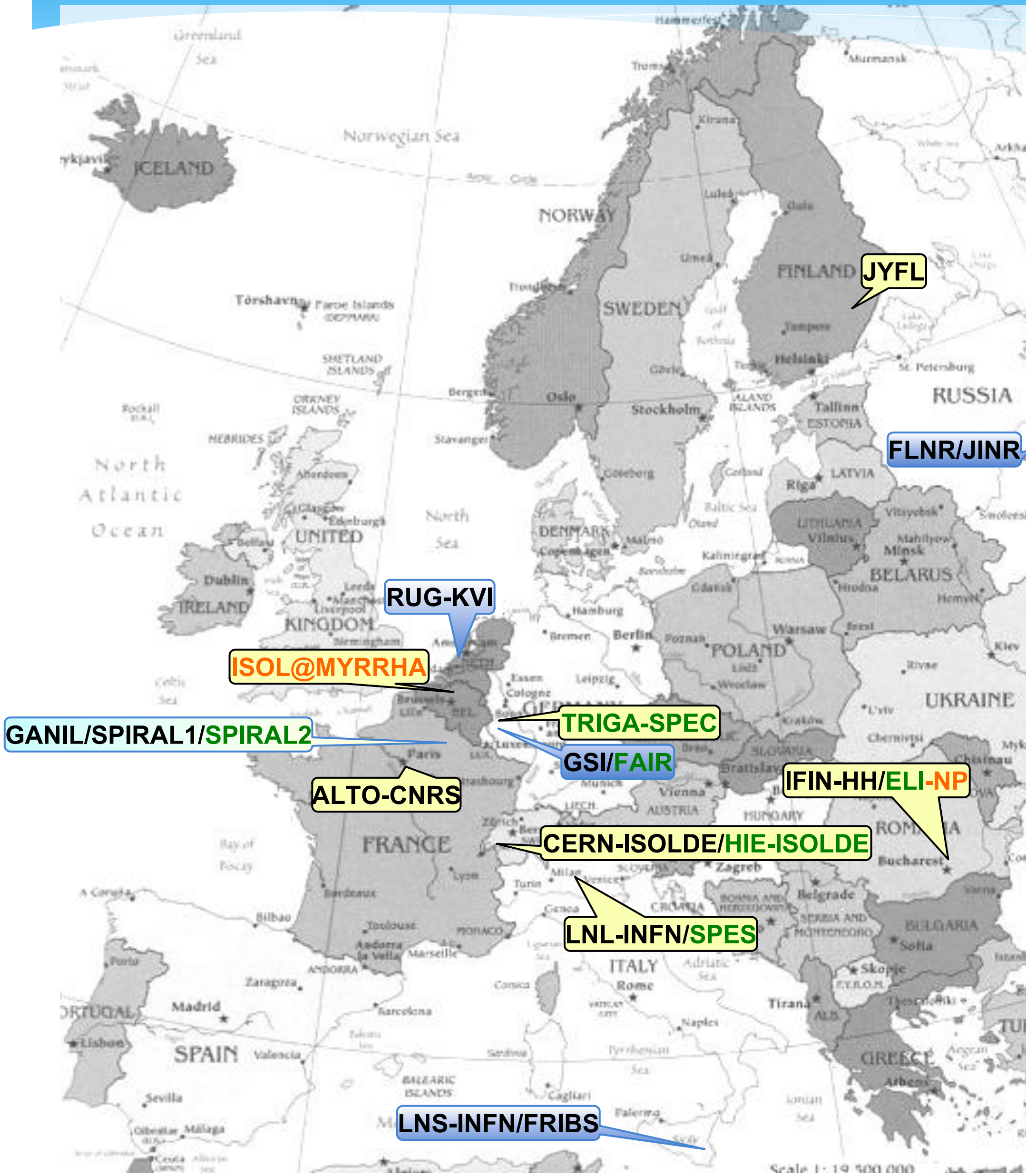
- Funded by DOE Office of Science – 2020 completion
- Key Feature is 400kW beam power (200 MeV/u 5 x10^{13} ^{238}U/s)
- Separation of isotopes in-flight
  - Fast development time for any isotope
  - Suited for all elements and short half-lives
- Reaccelerated beams up to 12 MeV/u



FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

> 700 M$, Operation starting by 2020

Radioactive Ion Beam Facilities in Europe



9 Existing RIB Facilities:

5 In-flight fragmentation

4 ISOL

5 Facilities/upgrades under construction or commissioning

2 Projects under design

Community: 2700-3000 scientists and highly qualified engineers

Transnational access within EU projects

ENSAR2

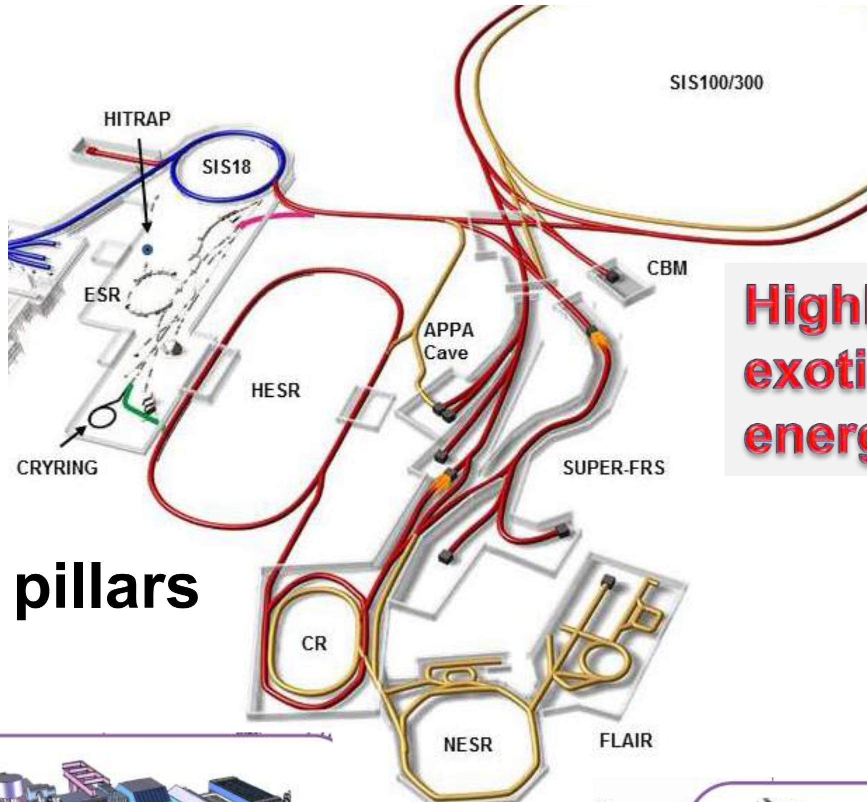
Nuclear structure reactions and applications

- GANIL (France)
- LNL-LNS (Italy)
- ISOLDE (CERN)
- JYFL (Finland)
- ALTO (CNRS, France)
- GSI (Germany)
- KVI (The Netherlands)
- NLC (HIL/IFJ PAN, Poland)
- IFIN-HH/ELI-NP (Romania)
- ECT* (Italy)

HadronPhysics

Hadron physics with hadronic and electromagnetic probes

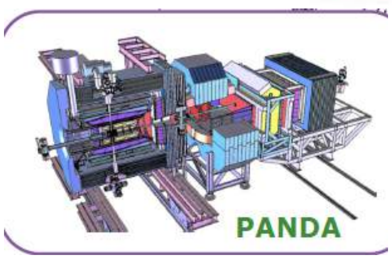
- CERN (LHC, COMPASS, fixed target)
- GSI/FAIR (Germany)
- LNF, Frascati Italy
- MAMI , Mainz Germany
- ECT*, Trento Italy
- ELSA, Bonn Germany
- COSY, Julich Germany

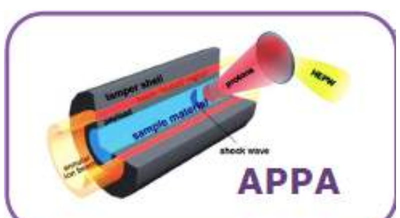


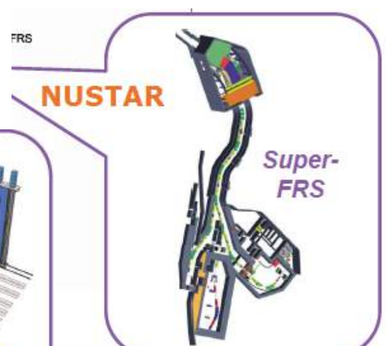
Large facility covering all nuclear physics domains !

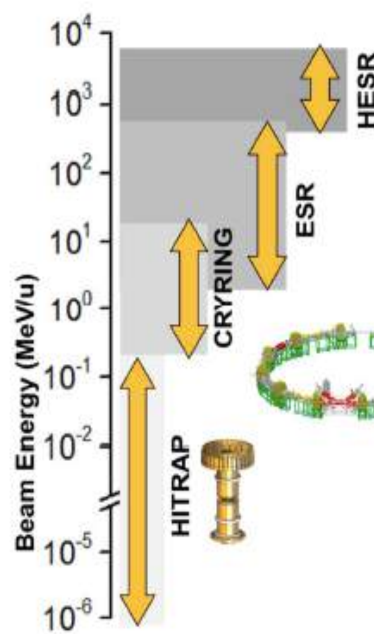
Highly charged ions (e.g. U^{92+}) and exotic Nuclei) from rest to relativistic energies 4.9 GeV/A

4 pillars







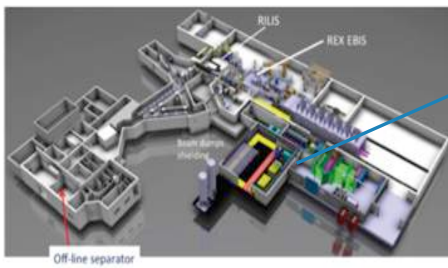


Worldwide Unique

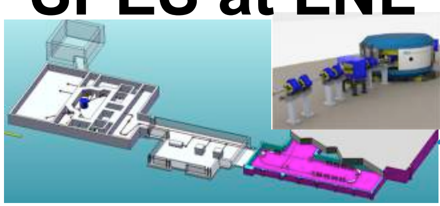
The European ISOL Facilities: EURISOL-DF

An effort to perform a coordinated program with existing and planned radioactive beams produced with the ISOL technique and to do R&D for the next step EURISOL

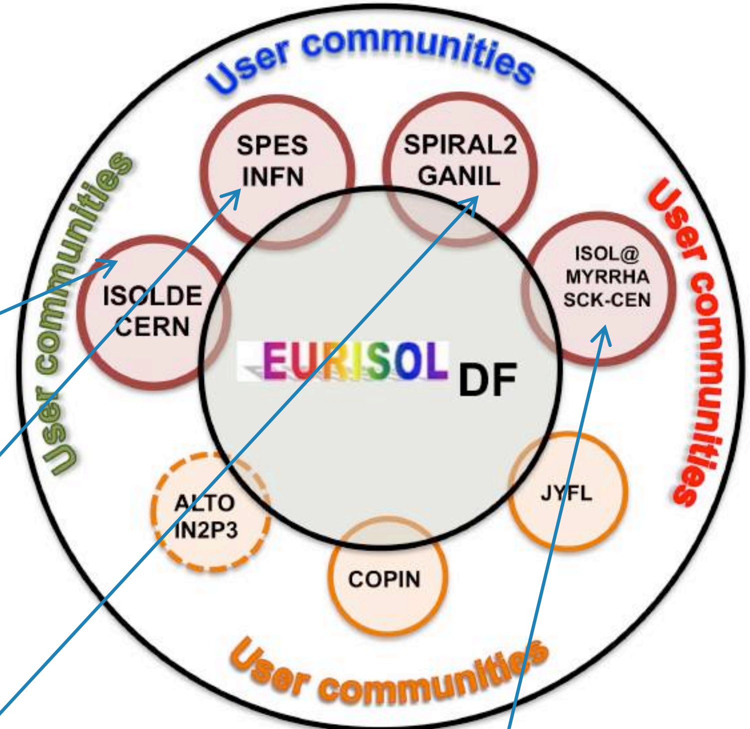
ISOLDE-CERN



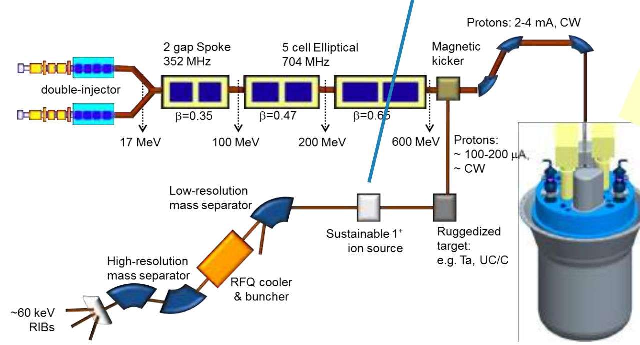
SPES at LNL



GANIL/SPIRAL2-France



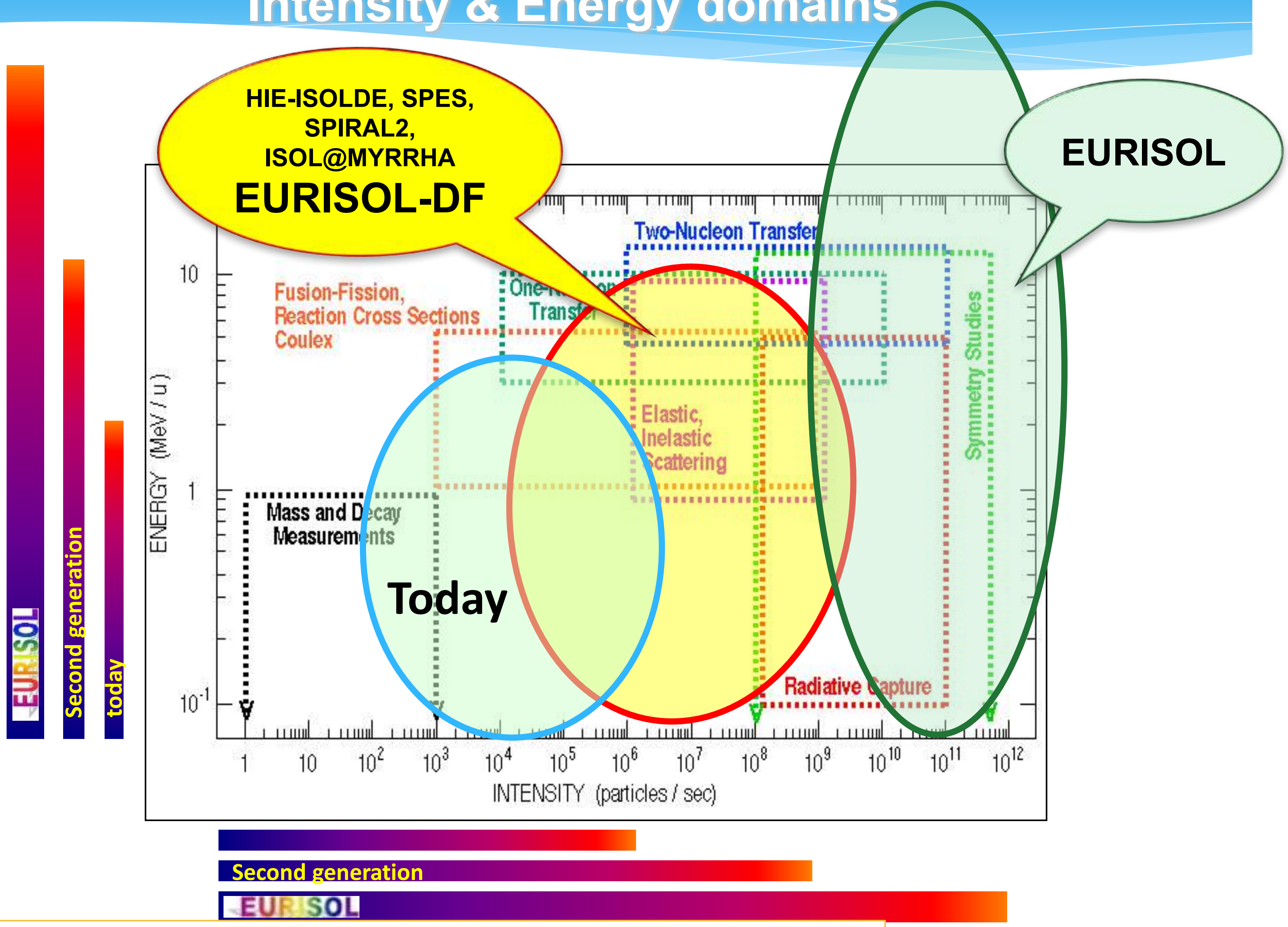
Focus is on nuclear structure, nuclear astrophysics and applications



ISOL@MYRRHA-Radioactive beams for science and appl.

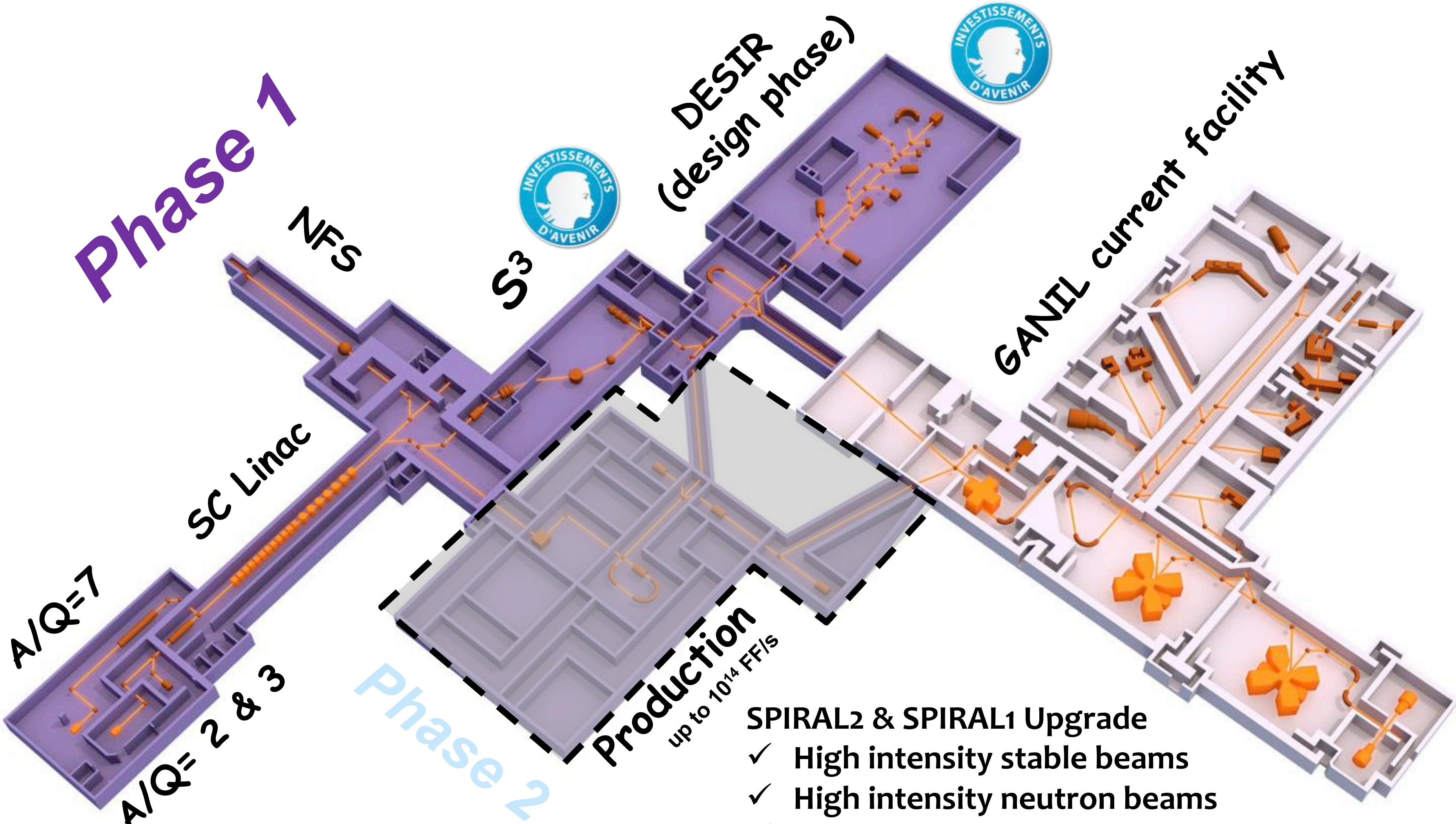
RIB Energies from 0 to 20MeV/nucl.

Physics with ISOL RIB
Intensity & Energy domains



-> EURISOL-DF (Distributed Facility) Initiative from 2014 as an intermediate step towards EURISOL

SPIRAL2@GANIL layout

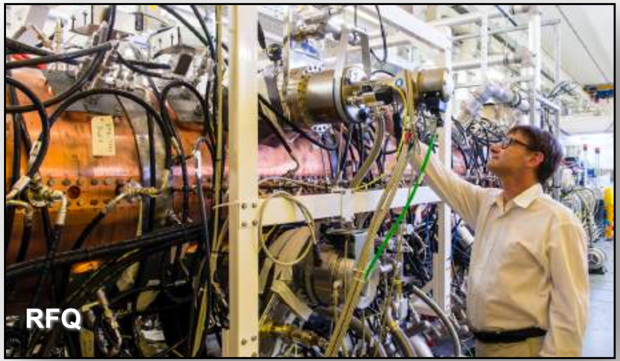


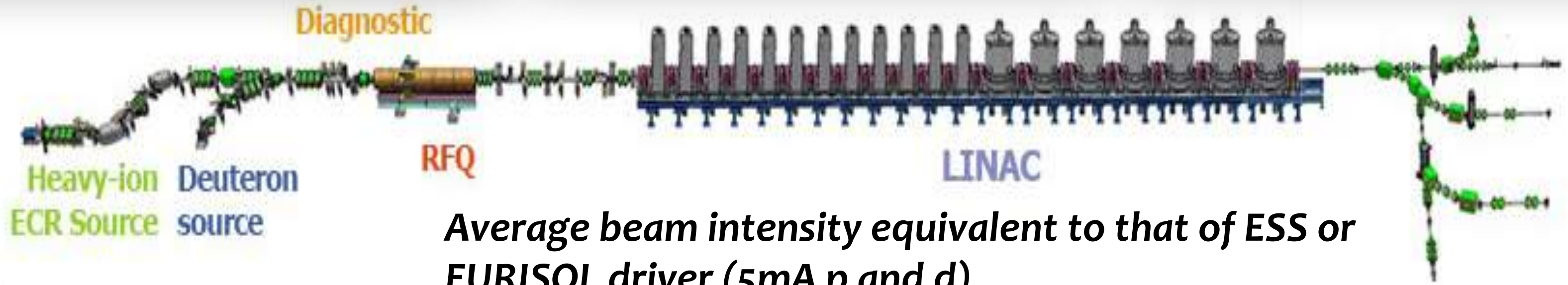
SPIRAL2 & SPIRAL1 Upgrade

- ✓ High intensity stable beams
- ✓ High intensity neutron beams
- ✓ High intensity RIBs

SPIRAL2

First Very-high intensity Super Conducting Heavy-Ion LINAC





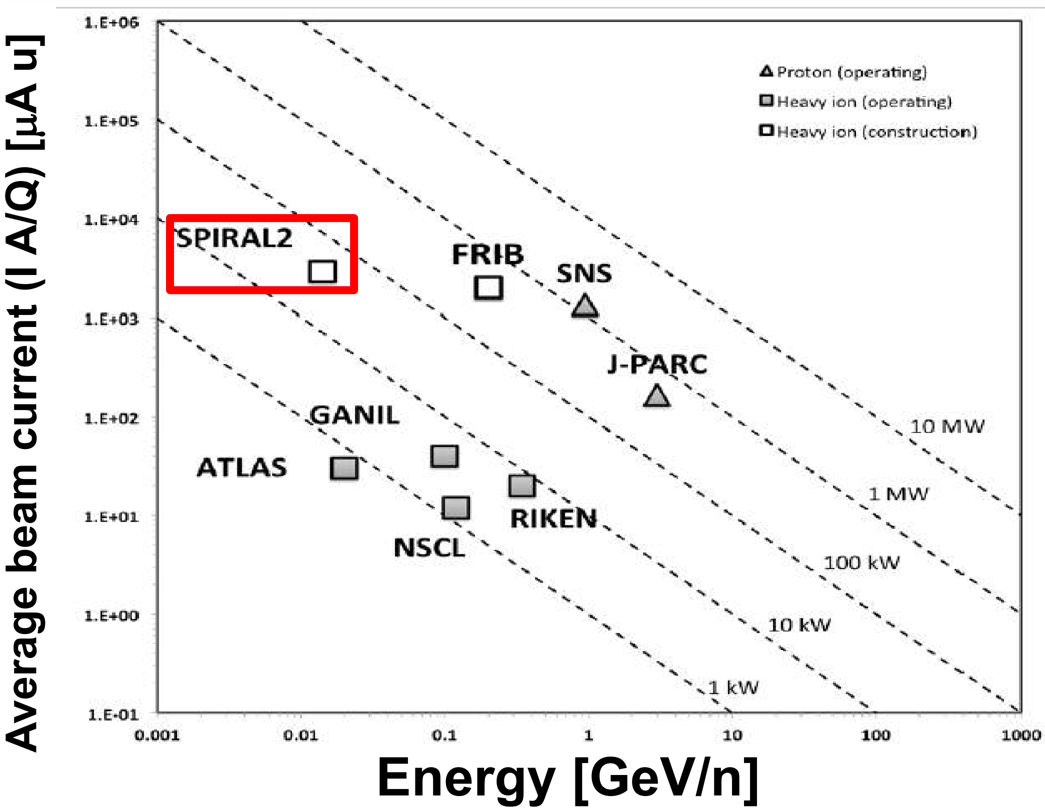
Average beam intensity equivalent to that of ESS or EURISOL driver (5mA p and d)

Installation is almost complete

SPIRAL 2 SC LINAC beams

1000 µAp $^{4}He^{2+}$
150 µAp $^{18}O^{6+}$
3,2 µAp $^{40}Ar^{14+}$ (60 kV)

5 mA protons (Q/A=1)
500 µAp $^{4}He^{2+}$ (Q/A=1/2)
100 µAp $^{18}O^{6+}$ (Q/A=1/3)



Ions	Intensity (pµA) [A/Q=3]	High Intensity (pµA) [A/Q=6-7]
^{18}O	216	375
^{19}F	28,6	50
^{36}Ar	17.5	40
^{40}Ar	2.9	30
^{36}S	4.6	30
^{40}Ca	3	20
^{48}Ca	1.25	15
^{58}Ni	1.1	10
^{84}Kr	0	20
^{124}Sn	0	10
^{139}Xe	0	10
^{238}U	0	2.5

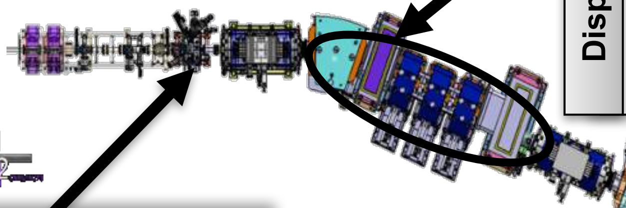
×5-10 (^{18}O – ^{58}Ni)

$\times 10^{x}$ (^{84}Kr – ^{238}U)

Super Separator Spectrometer @ SPIRAL2

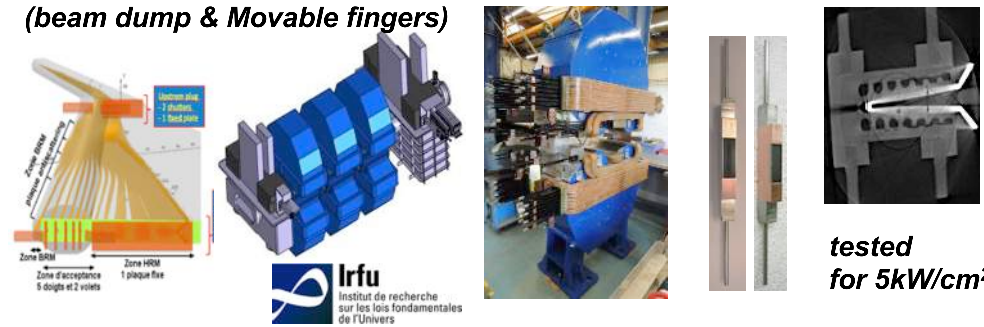
S^3 (L=26m)

Beam spot :
σ_X=0.5mm, σ_Y[0.5-2.5mm]
Energy precision ≈5.10^{-3}



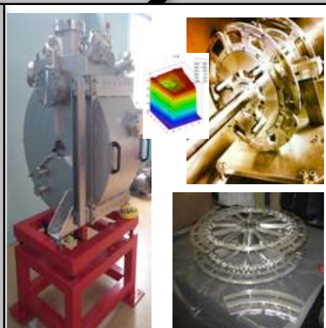
Dispersive zone

(beam dump & Movable fingers)



tested for 5kW/cm²

Target system



High power rotating targets (3000-5000 rpm)
Stable & Actinide systems

3 × M-dipoles

Large H & V gaps

E-Dipole

20 cm gap & +/- 350 kV
Epmax : 12-14 MeV
Open slit in the anode

SC Multipoles

Q+S+O fields *PSS* *Cold Box*

F. Dechery et al., Eur. Phys. J. A (2015) 51: 66
F. Dechery et al., in press NIMB

Full assembly & tests at GANIL planned in 2019

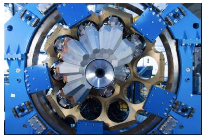
Recommendations for European facilities

Complete urgently the construction of the ESFRI flagship FAIR and develop and bring into operation the experimental programme of its four scientific pillars APPA, CBM, NUSTAR and PANDA.

Support for construction, augmentation and exploitation of world leading ISOL facilities in Europe towards EURISOL.

Support for the full exploitation of existing and emerging facilities.

Support for ALICE and the heavy-ion programme at the LHC with the planned experimental upgrades.



Support to the completion of AGATA in full geometry.

European Nuclear Physics
Ambitious goals, bright future

Thank you for your attention

Dziękuję za uwagę