Nuclear Physics at the extremes: exotic nuclei for research and applications. A glimpse of the SPES project.

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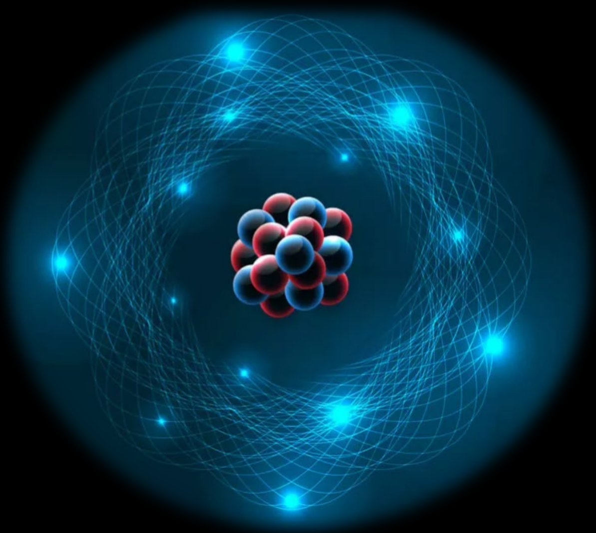
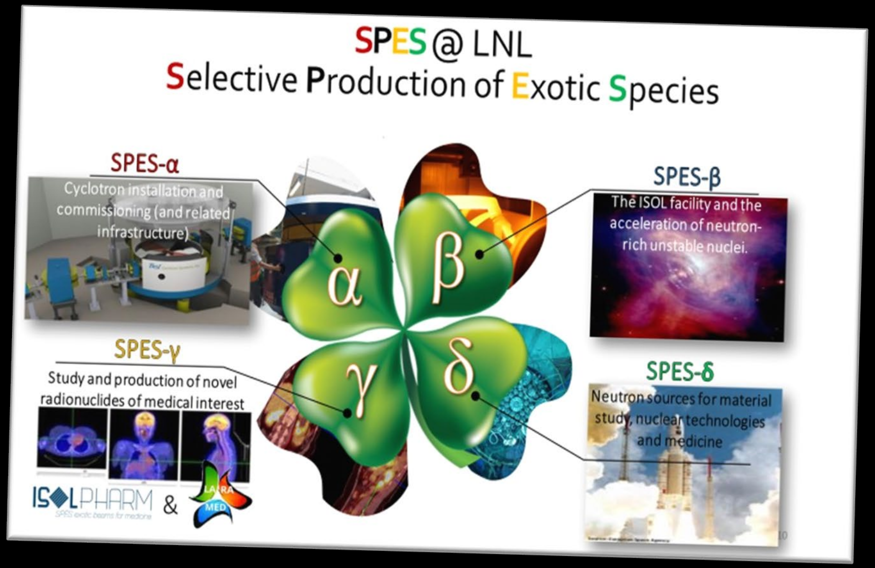
(slides by T. Marchi)
INFN – Laboratori Nazionali di Legnaro

July 21, 2023

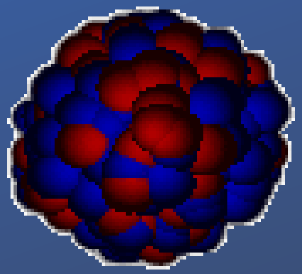


PART 1
The atomic nucleus

PART 2
The SPES project at INFN-LNL

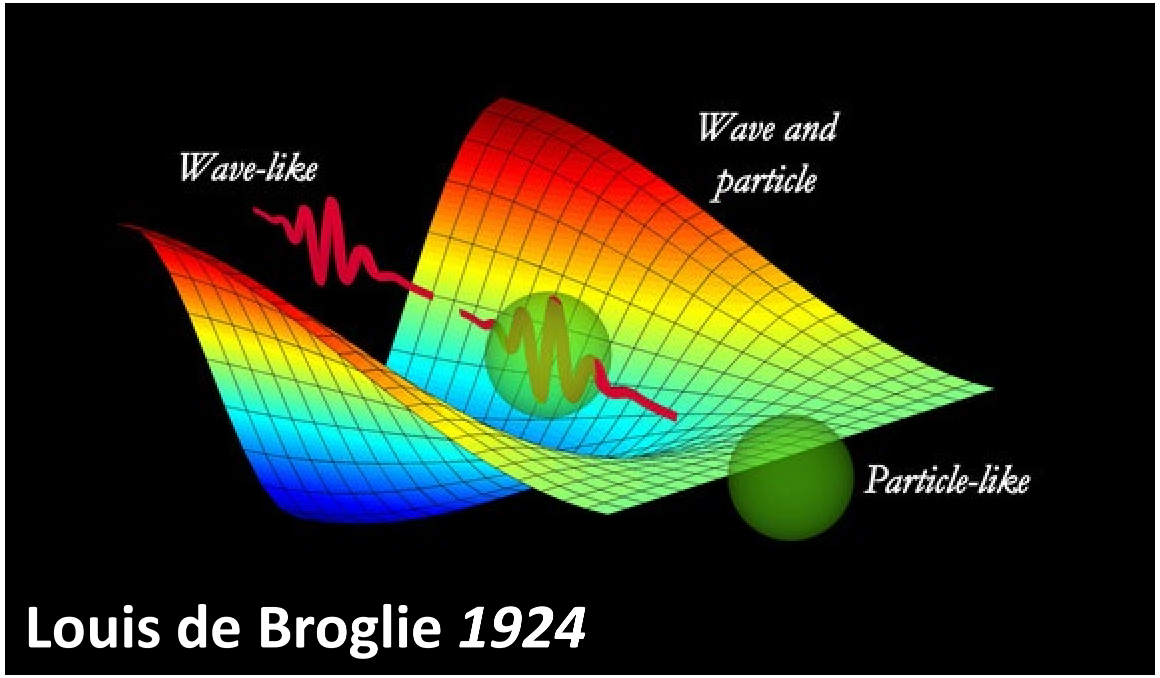


PART 1:
The atomic nucleus



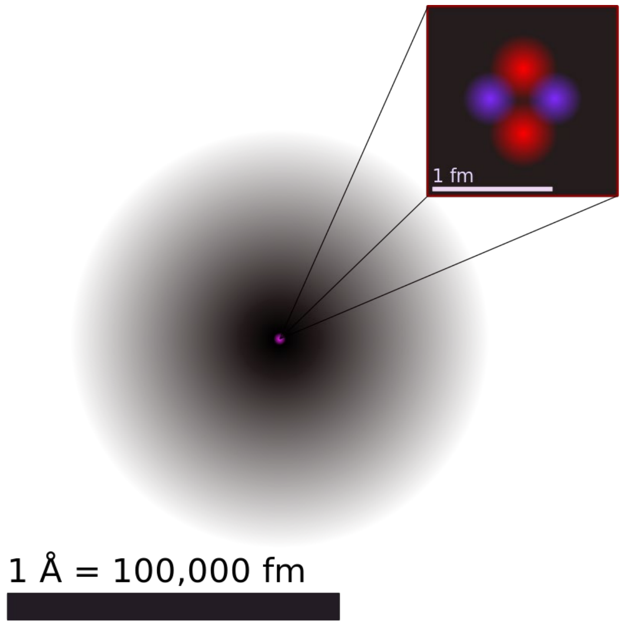
A many-body quantum system,
source of its binding force field

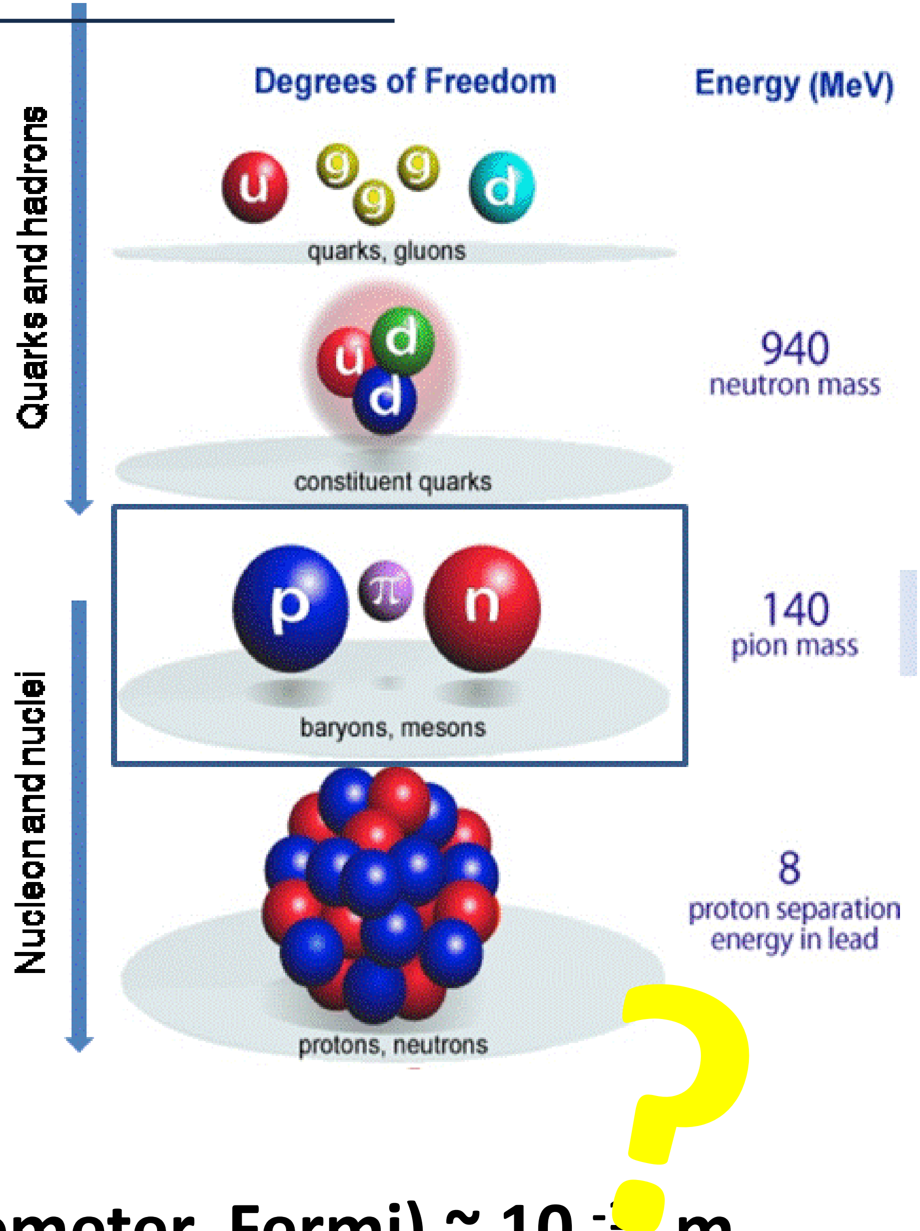
Disclaimer: waves and particles



$$\lambda = \frac{h}{P} = \frac{h}{mv}$$

Size of the atomic nucleus

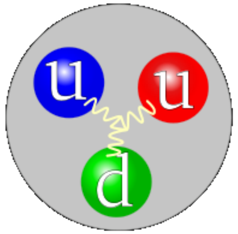




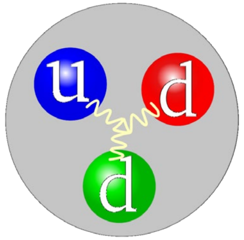
Order of magnitude: 1 fm (femtometer, Fermi) ~ 10 ? m

Nucleons

Nucleone	Carica (Q_e)	Massa (MeV/c^2)	Spin	Vita media
Protone	+1	938,27	1/2	>1,6 × 10^{33} anni
Neutrone	0	939,57	1/2	880,2 s

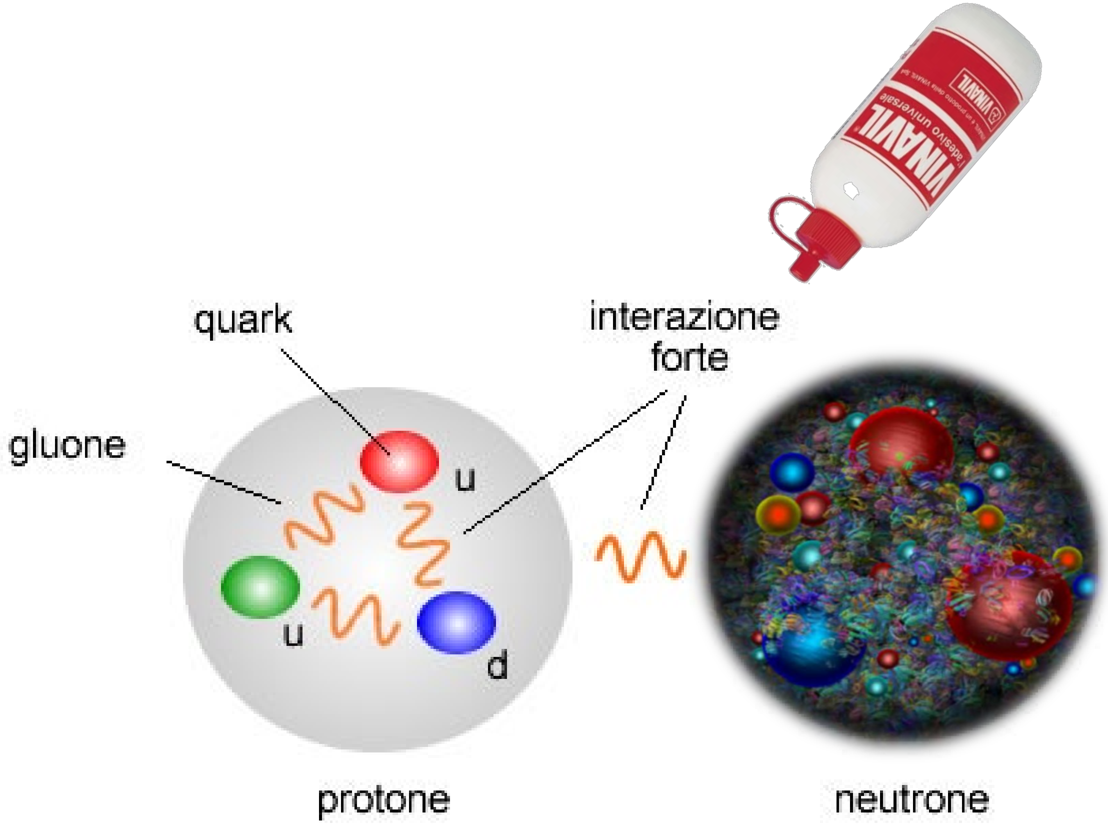


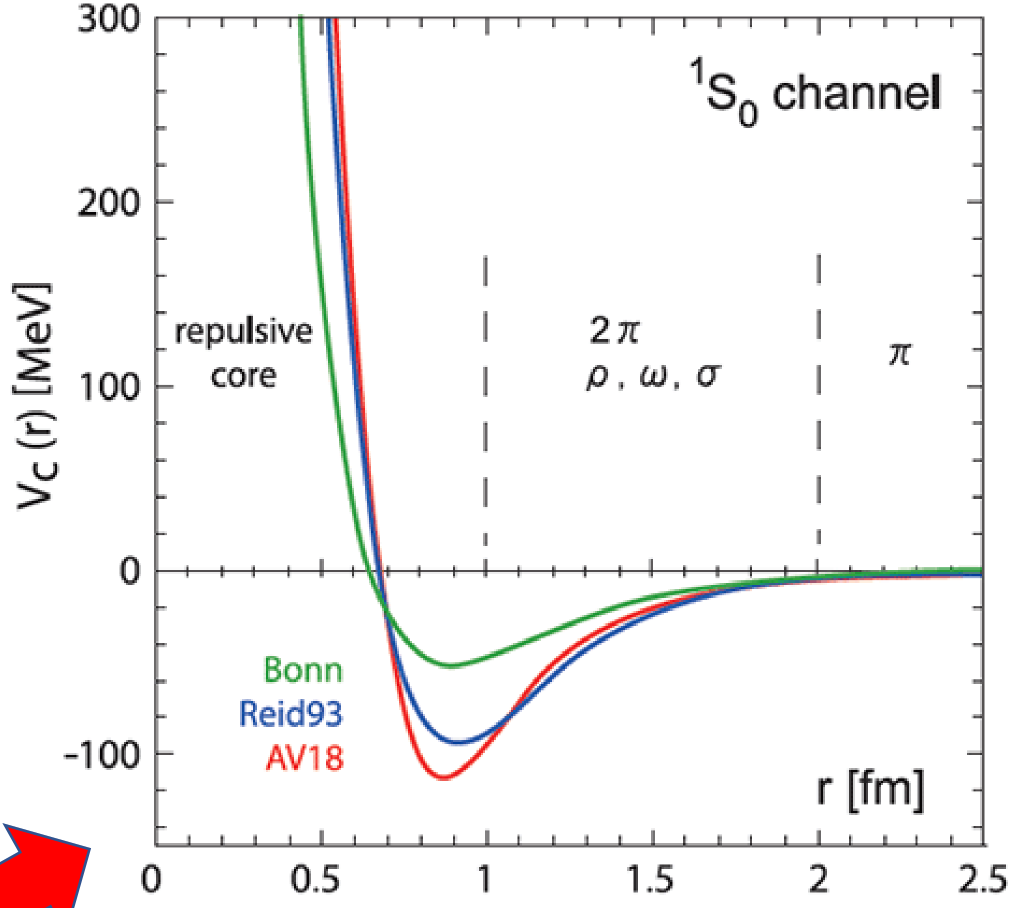
Proton



Neutron

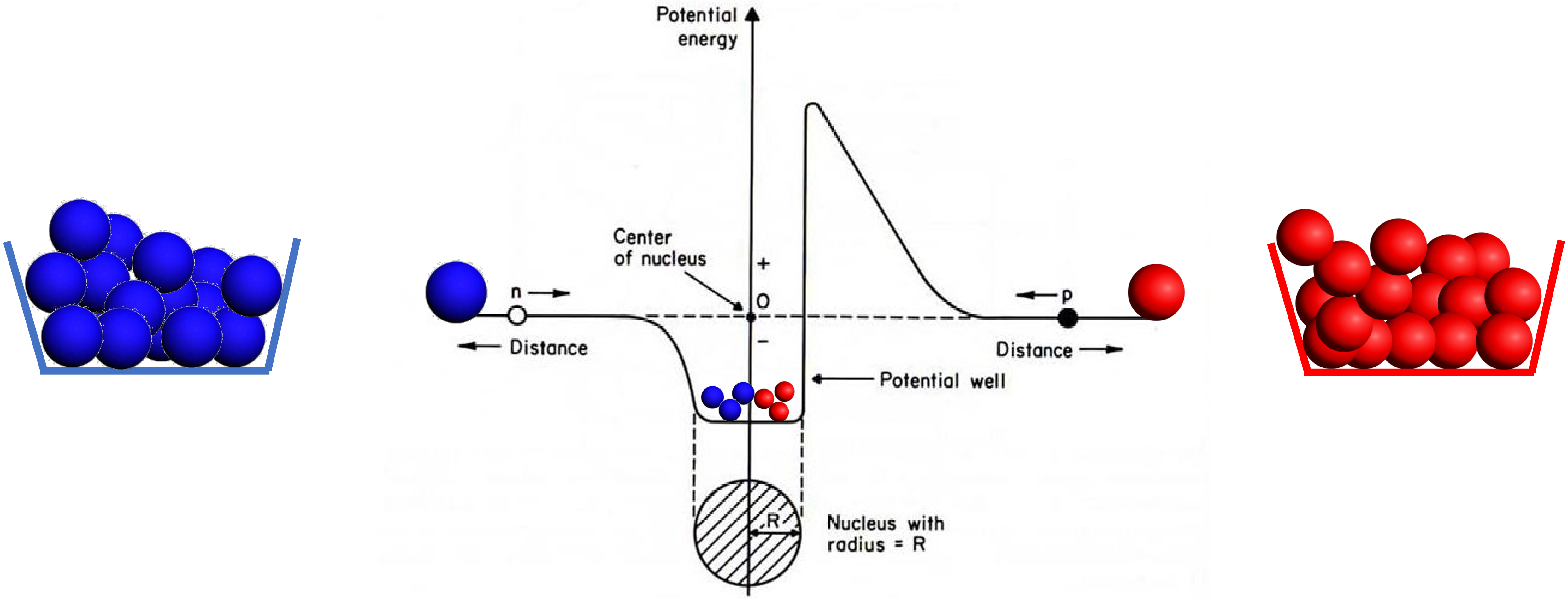
The strong force



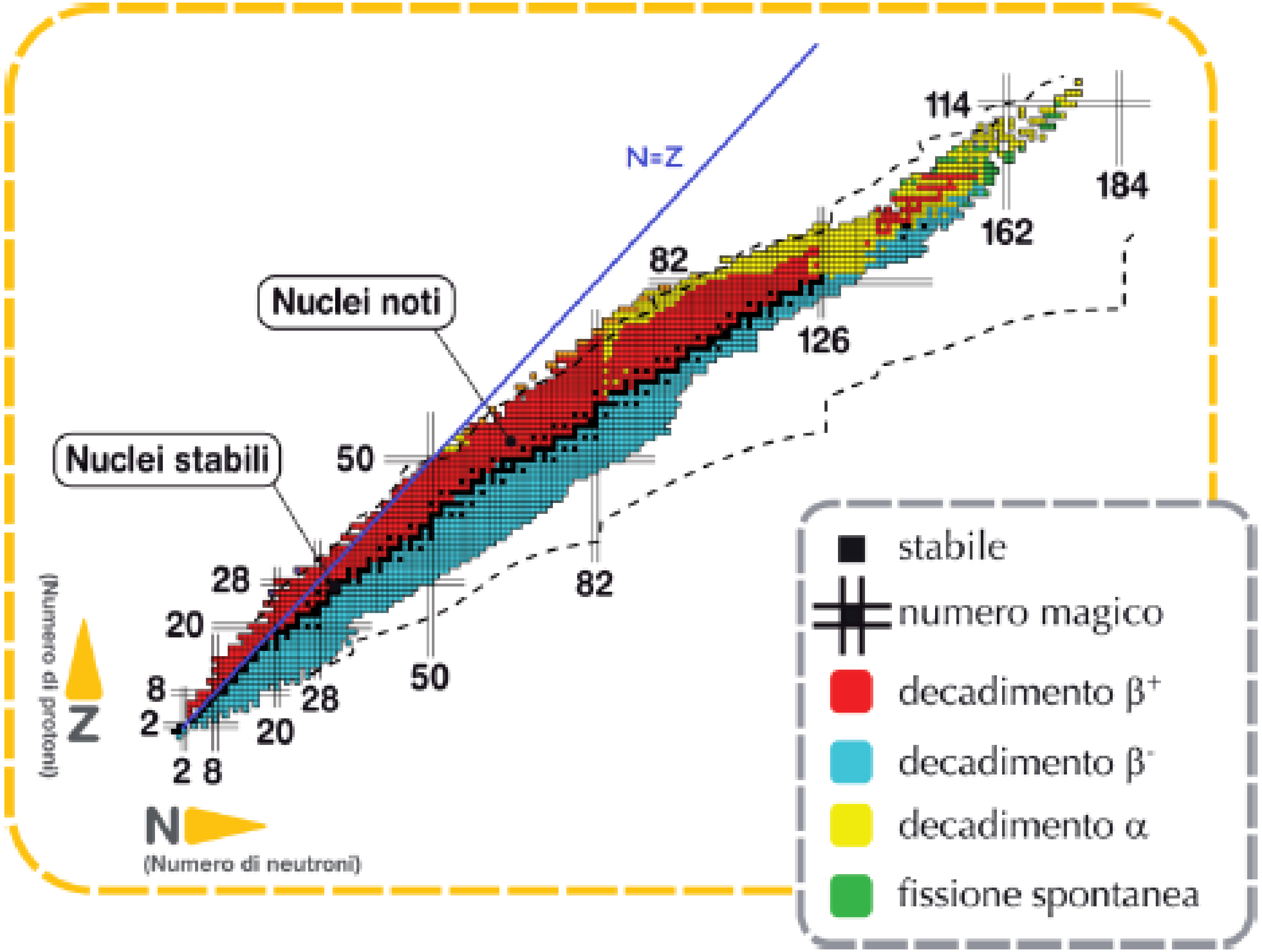


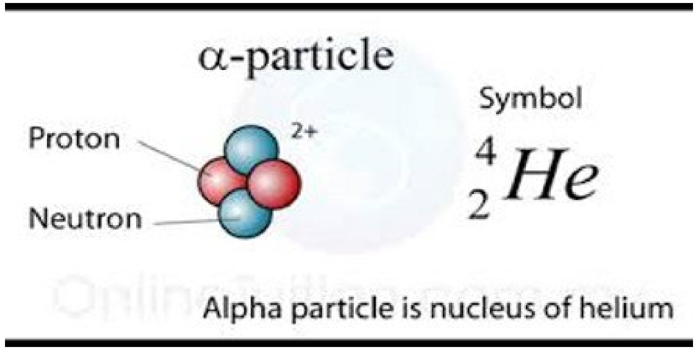
…and the *residual* interaction

Let us build a nucleus

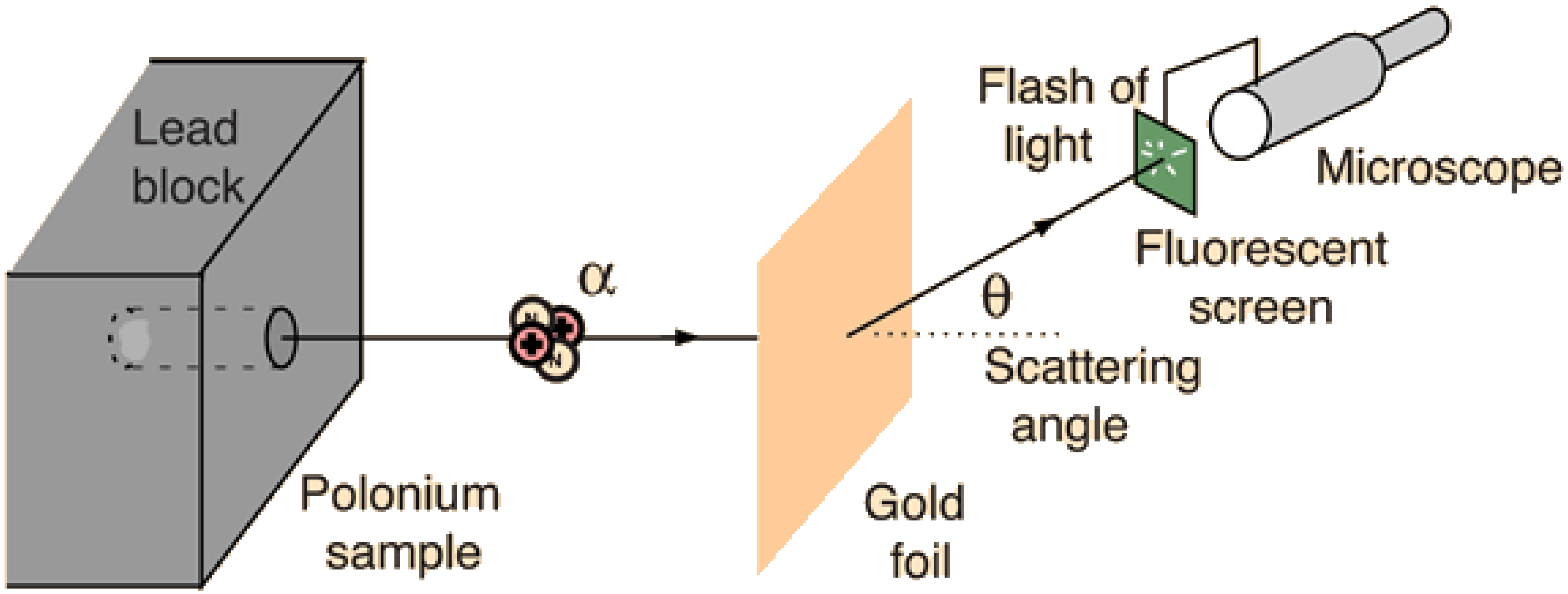


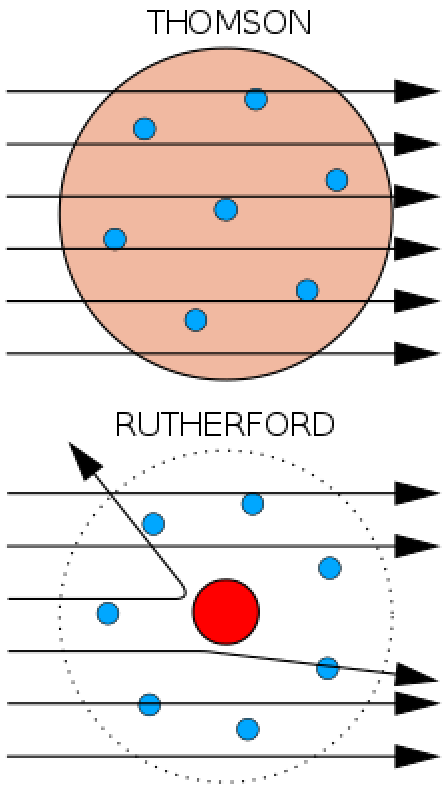
The Nuclear Chart

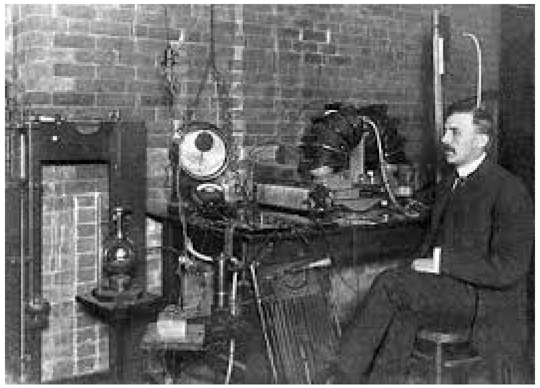




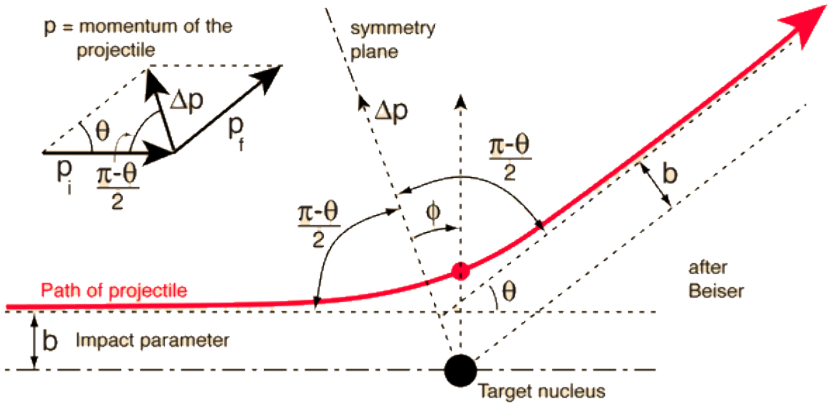
Rutherford experiment - observation



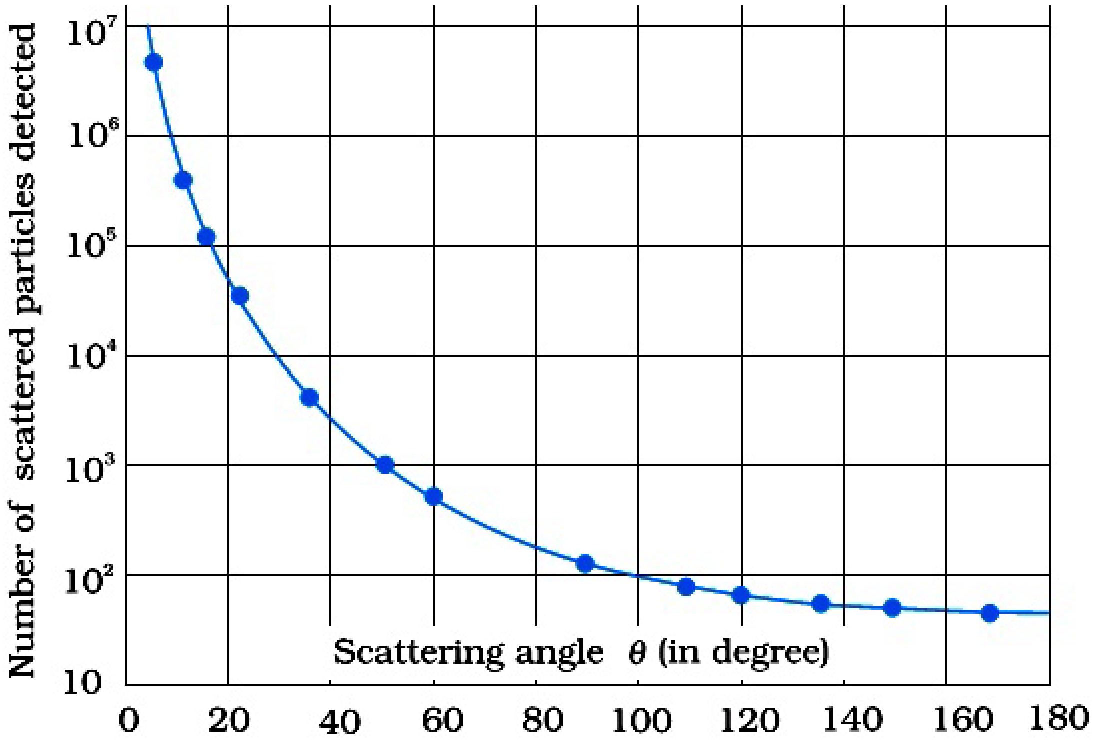




Rutherford experiment - model



$$N(\theta) = \frac{nt}{4r^2}\left(\frac{zZ}{2K}\right)^2\left(\frac{e^2}{4\pi\epsilon_0}\right)^2\frac{1}{\sin^4(\frac{1}{2}\theta)}$$



Rutherford experiment - publication

[669]

LXXIX. *The Scattering of α and β Particles by Matter and the Structure of the Atom.* By Professor E. RUTHERFORD, F.R.S., University of Manchester *.

§ 1. IT is well known that the α and β particles suffer deflexions from their rectilinear paths by encounters with atoms of matter. This scattering is far more marked for the β than for the α particle on account of the much smaller momentum and energy of the former particle. There seems to be no doubt that such swiftly moving particles pass through the atoms in their path, and that the deflexions observed are due to the strong electric field traversed within the atomic system. It has generally been supposed that the scattering of a pencil of α or β rays in passing through a thin plate of matter is the result of a multitude of small scatterings by the atoms of matter traversed. The observations, however, of Geiger and Marsden † on the scattering of α rays indicate that some of

the α particles must suffer a deflexion of more than a right angle at a single encounter. They found, for example, that a small fraction of the incident α particles, about 1 in 20,000, were turned through an average angle of 90° in passing through a layer of gold-foil about ·00004 cm. thick, which was equivalent in stopping-power of the α particle to 1·6 millimetres of air. Geiger ‡ showed later that the most probable angle of deflexion for a pencil of α particles traversing a gold-foil of this thickness was about 0°·87. A simple calculation based on the theory of probability shows that the chance of an α particle being deflected through 90° is vanishingly small. In addition, it will be seen later that the distribution of the α particles for various angles of large deflexion does not follow the probability law to be expected if such large deflexions are made up of a large number of small deviations. It seems reasonable to suppose that the deflexion through a large angle is due to a single atomic encounter, for the chance of a second encounter of a kind to produce a large deflexion must in most cases be exceedingly small. A simple calculation shows that the atom must be a seat of an intense electric field in order to produce such a large deflexion at a single encounter.

Recently Sir J. J. Thomson § has put forward a theory to

* Communicated by the Author. A brief account of this paper was communicated to the Manchester Literary and Philosophical Society in February, 1911.

† Proc. Roy. Soc. lxxxii. p. 495 (1909).

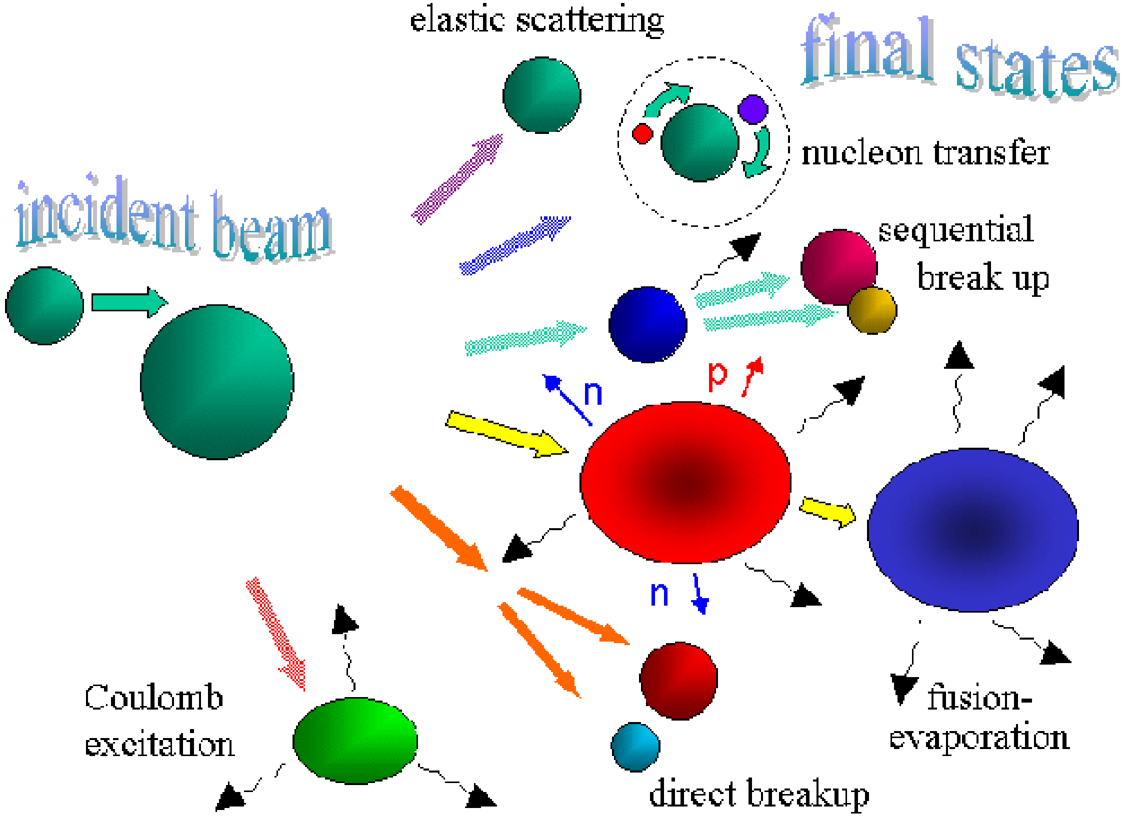
‡ Proc. Roy. Soc. lxxxiii. p. 492 (1910).

§ Camb. Lit. & Phil. Soc. xv. pt. 5 (1910).

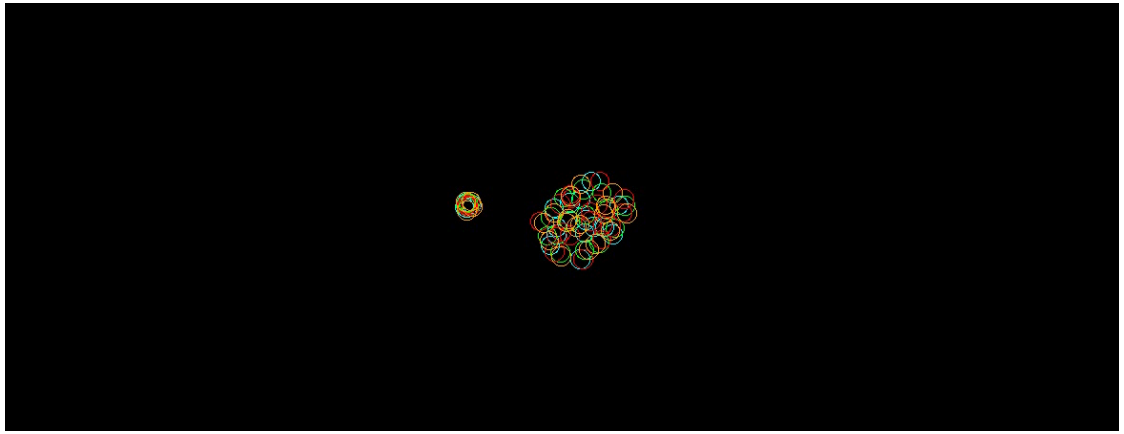
Philosophical Magazine, 21 (1911) 669

The Rutherford experiment is the prototype of any Nuclear Physics experiment

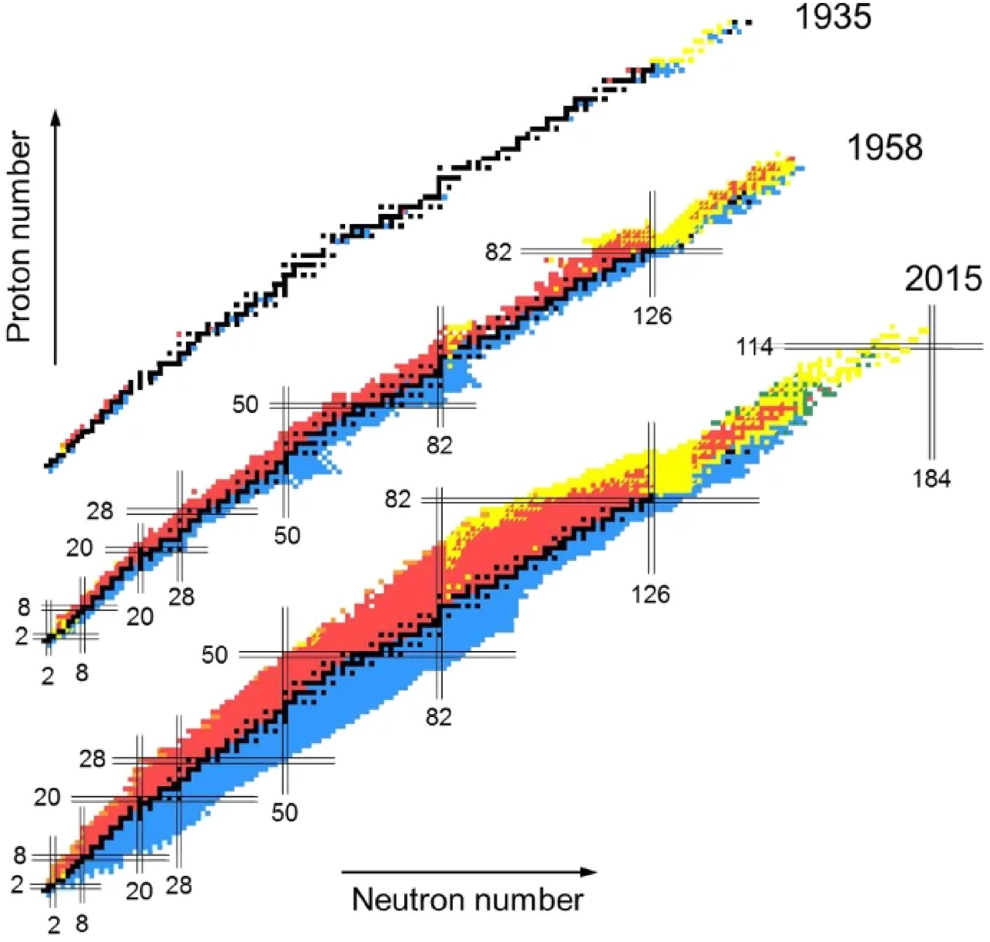
Nuclear reactions

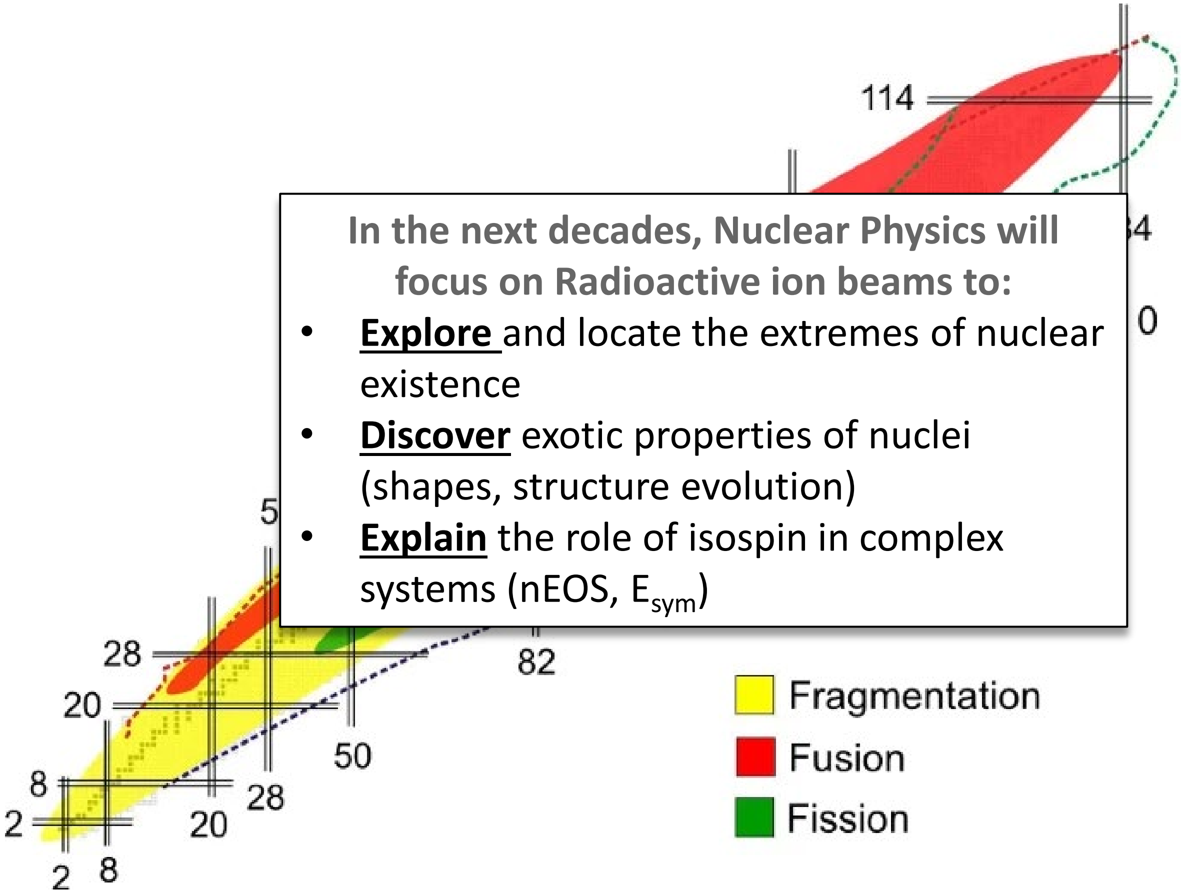


Modeling reaction dynamics



Exploring the nuclear chart with nuclear reactions



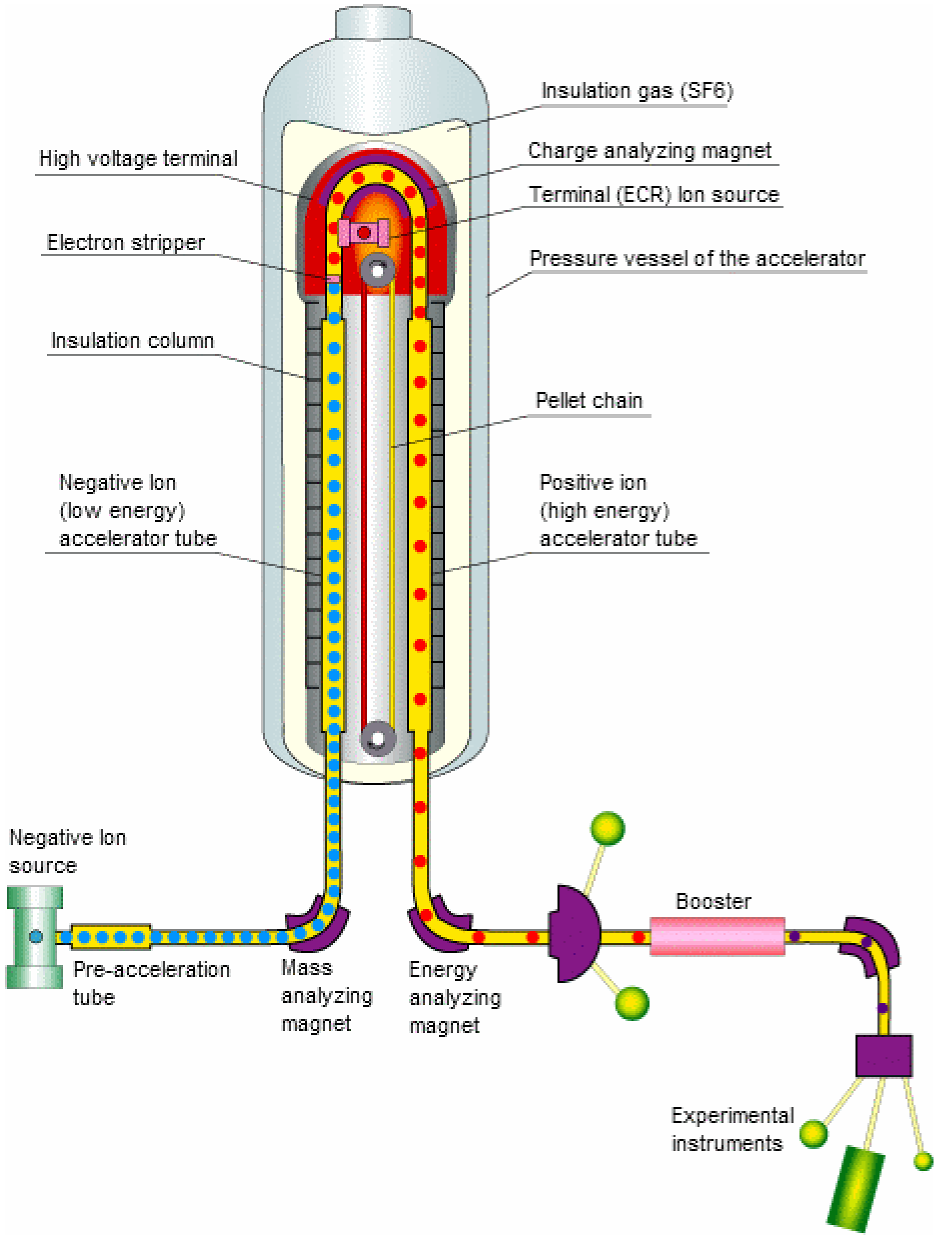


In the next decades, Nuclear Physics will focus on Radioactive ion beams to:

- **<u>Explore</u>** and locate the extremes of nuclear existence
- **<u>Discover</u>** exotic properties of nuclei (shapes, structure evolution)
- **<u>Explain</u>** the role of isospin in complex systems (nEOS, E_{sym})

Nuclear Physics at particle accelerators

Ion source → Accelerator → Experiment

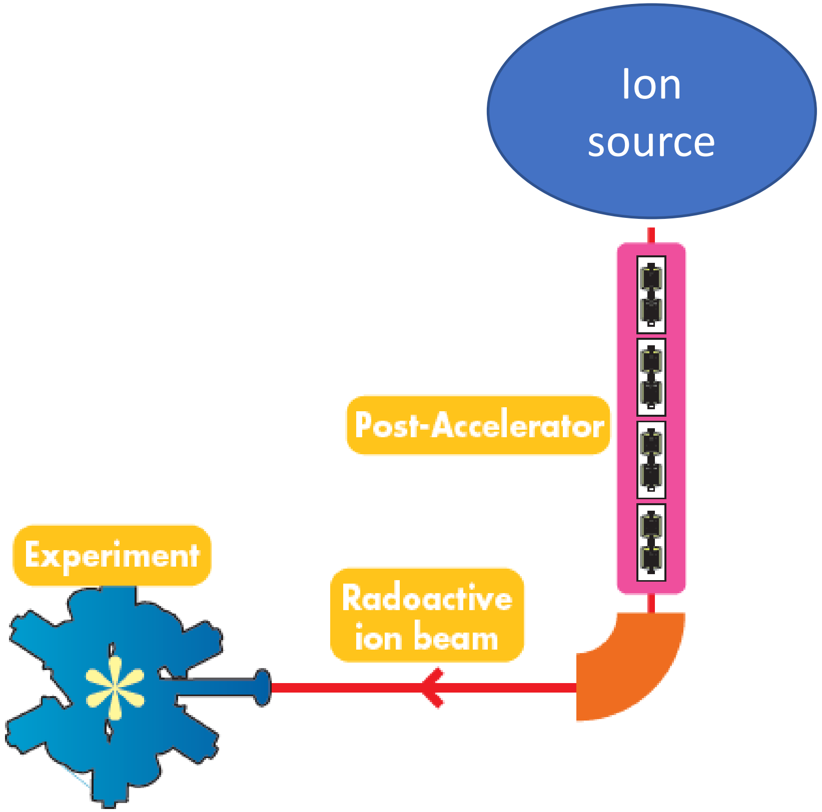


PART 2:
The SPES project at LNL

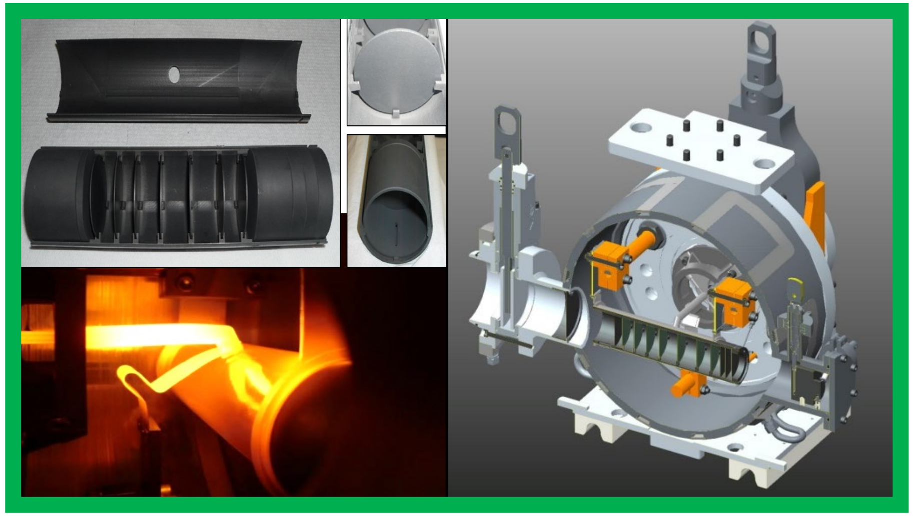
"A broadband facility"

SPES @ LNL
Selective Production of Exotic Species

Stable vs Radioactive ion beams



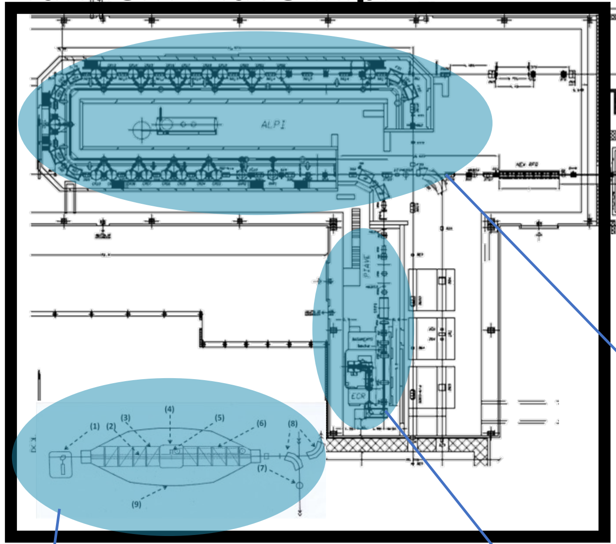
SPES ISOL Target:
UCx, SiC,...
10^{13} fiss./s
T ~ 2000°C
3 sources SIS, LIS, PIS
~ 8 kW power

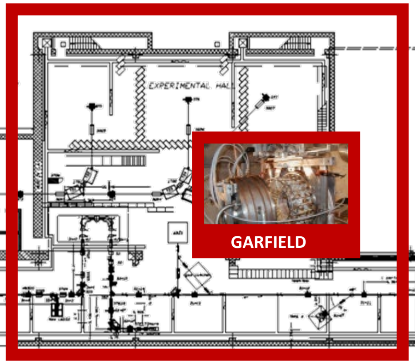



Istituto Nazionale
di Fisica Nucleare...
Google
2D
INFN
SPES
Oct 2013
28/10/2013
13:00

Operating facilities at LNL

Tandem-Piave-Alpi





ALPI

SC- LINAC
(V_{eq}~50 MV)

PIAVE

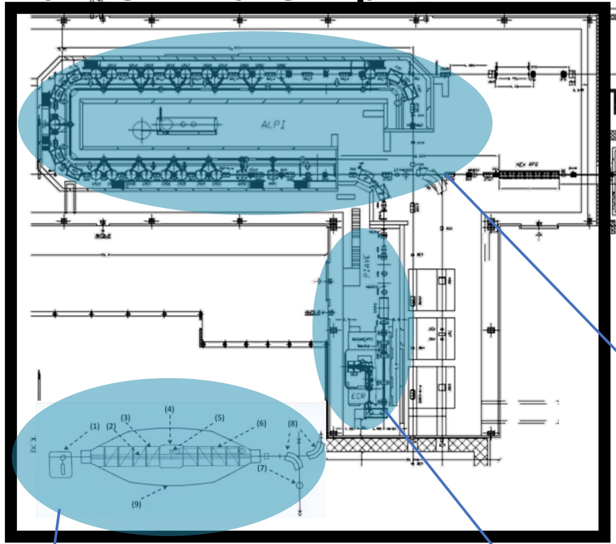
ECR Ion source + RFQ injector

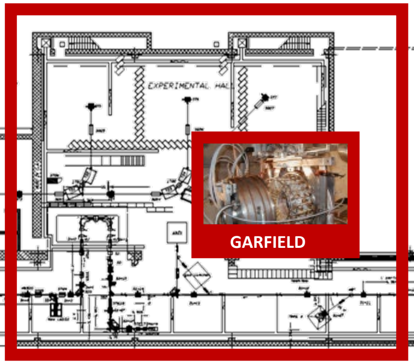
TANDEM-XTU

14 MV - Tandem

Operating facilities at LNL and SPES

Tandem-Piave-Alpi





ALPI

SC- LINAC

(V_{eq}~50 MV)

PIAVE

ECR Ion source + RFQ injector

TANDEM-XTU

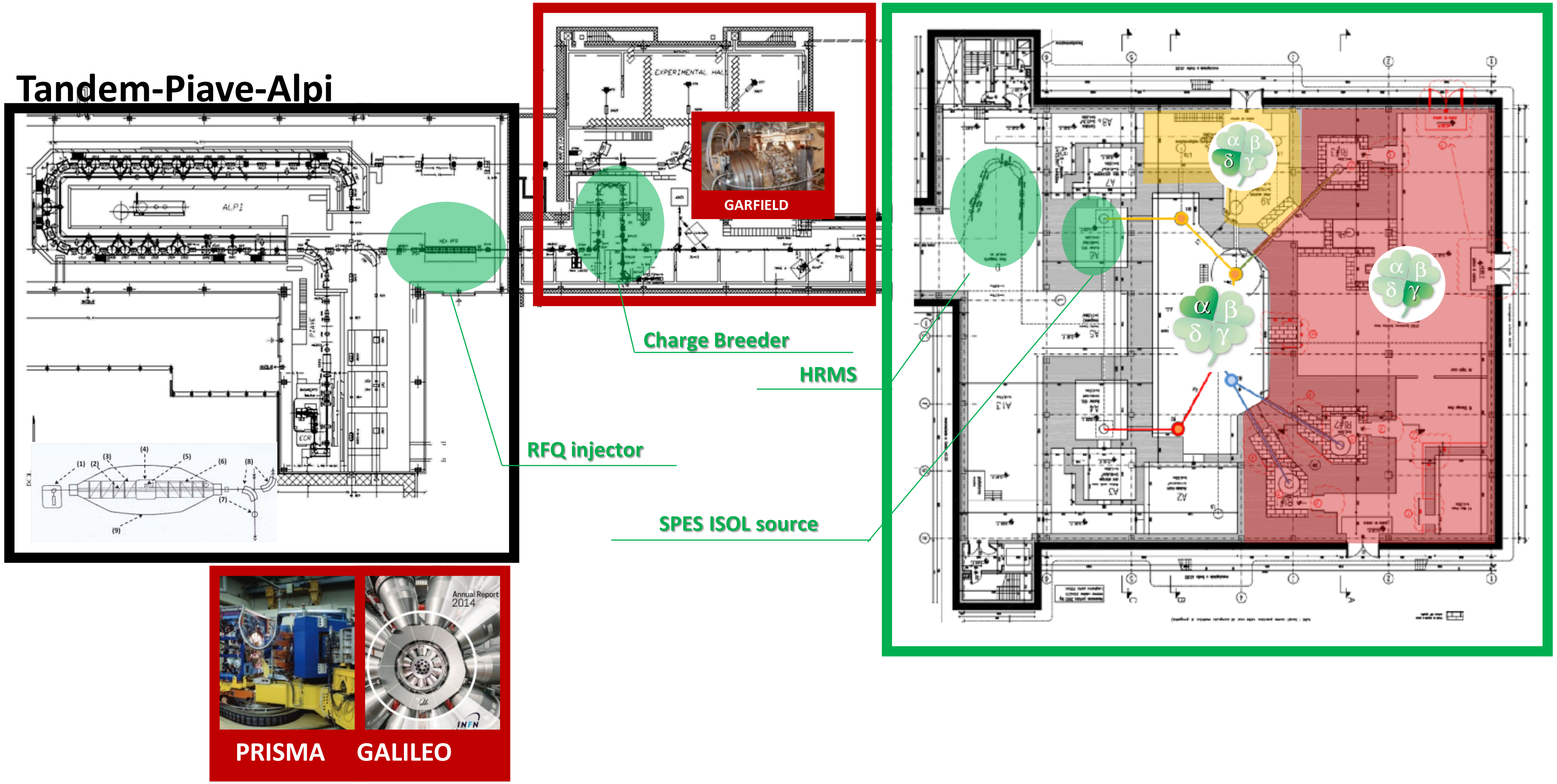
14 MV - Tandem

ISOL RIBs+ Post-Acc.

Nuclear Medicine

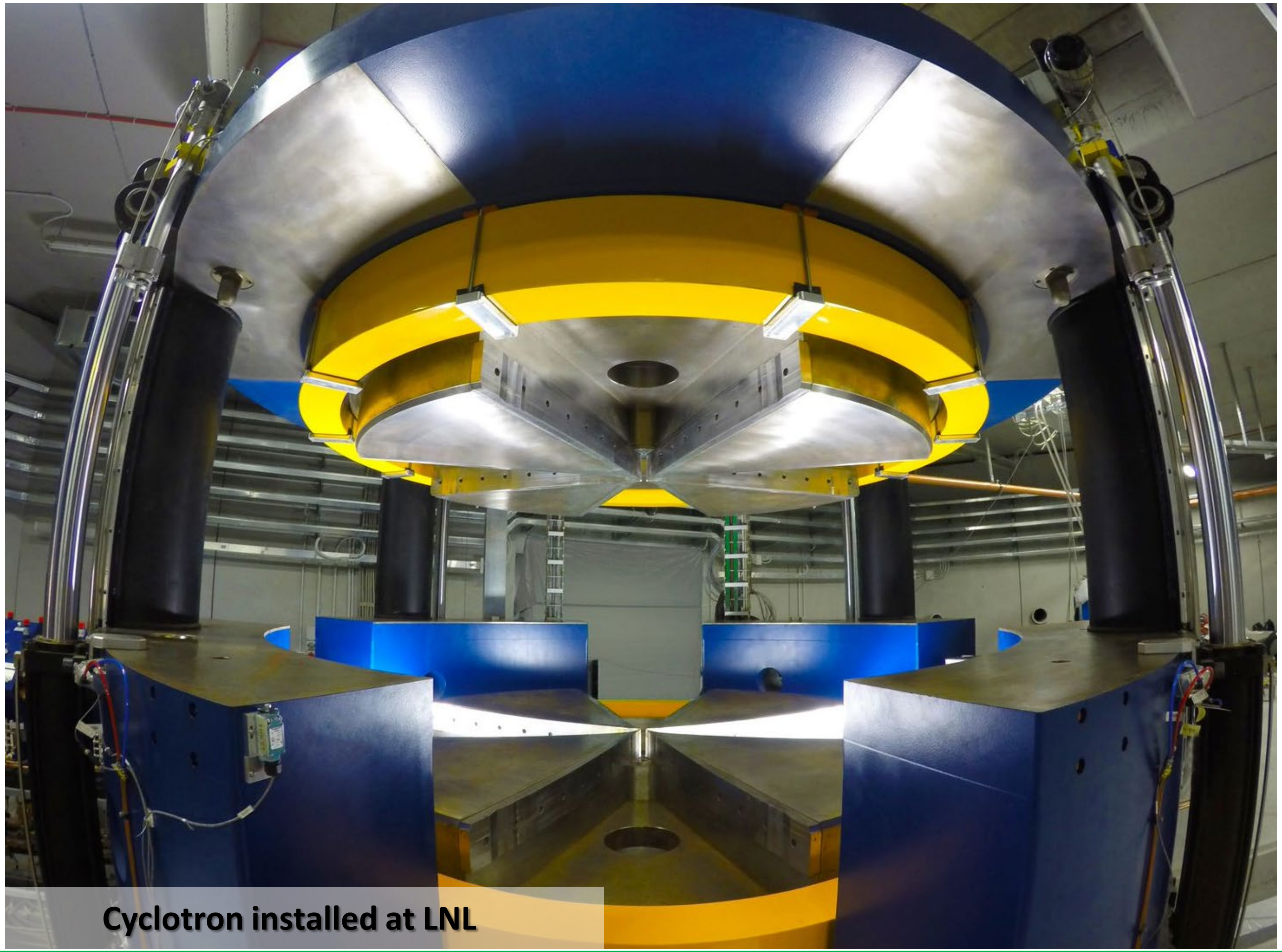
Nuclear Applications

The SPES project at LNL.



The weight of science: *déjà-vu…*

The SPES cyclotron

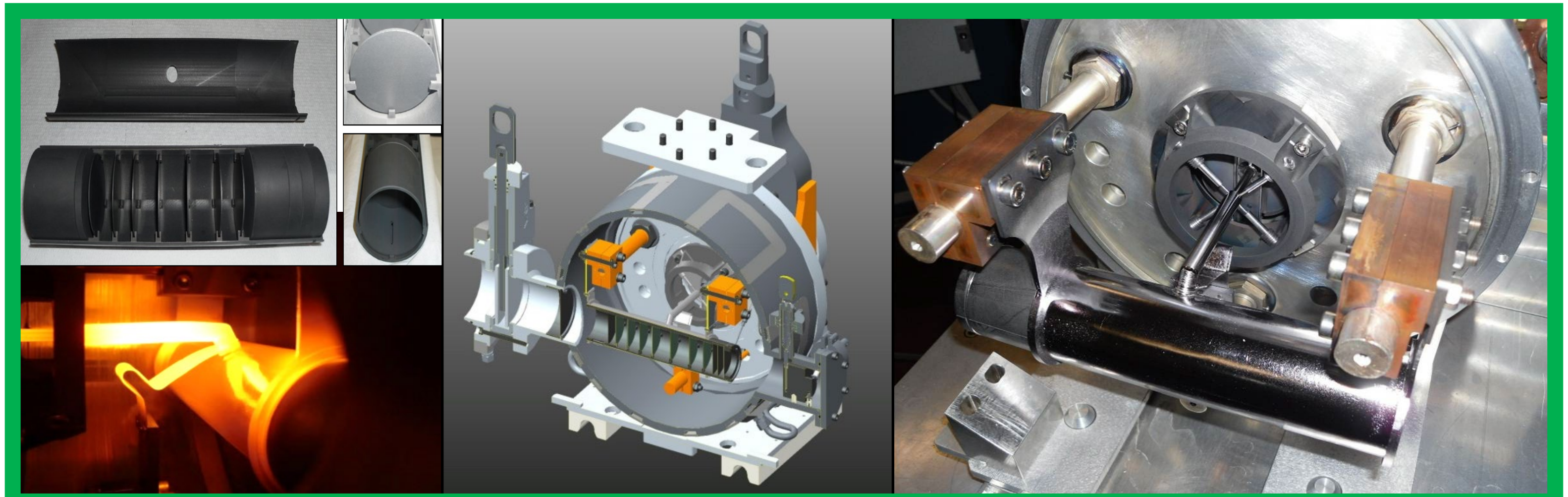


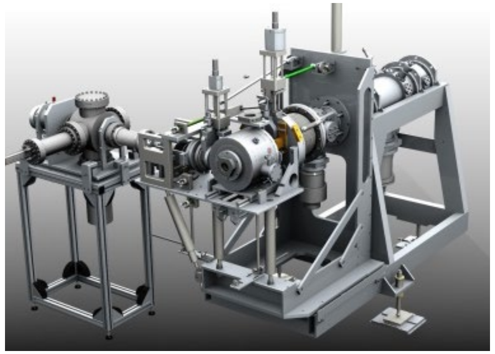
Cyclotron installed at LNL

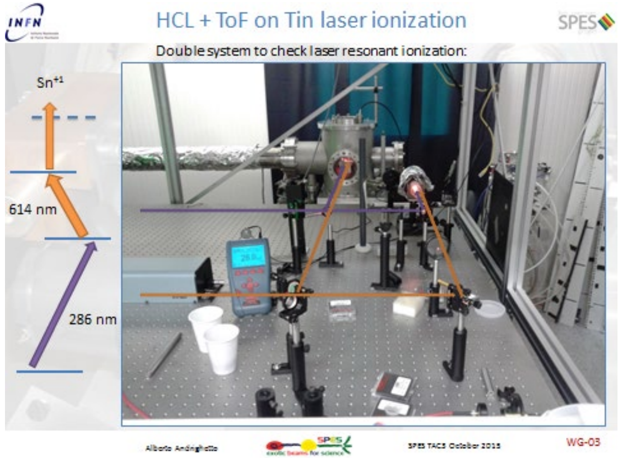
Main Parameters	
Accelerator Type	Cyclotron AVF 4 sectors
Particle	**Protons (H^- accelerated)**
Energy	**Variable within 30-70 MeV**
Max Current Accelerated	**750 µA** (52 kW max beam power)
Available Beams	**2 beams at the same energy** (upgrade to different energies)
Max Magnetic Field	1.6 Tesla
RF frequency	56 MHz, 4^{th} harmonic mode
Ion Source	Multicusp H^- I=15 mA, Axial Injection
Dimensions	Φ=4.5 m, h=1.5 m
Weight	150 tons

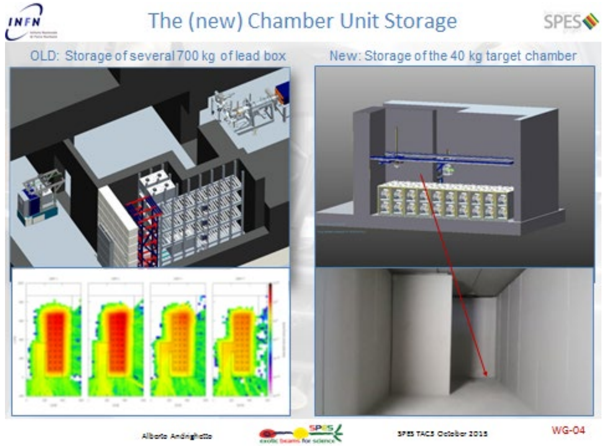
The core of SPES-β: the ISOL target

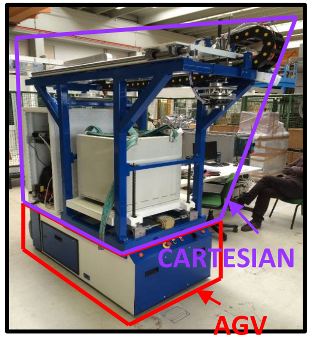
SPES ISOL Target:
UCx, SiC,...
10^{13} fiss./s
T ~ 2000°C
3 sources SIS, LIS, PIS
~ 8 kW power



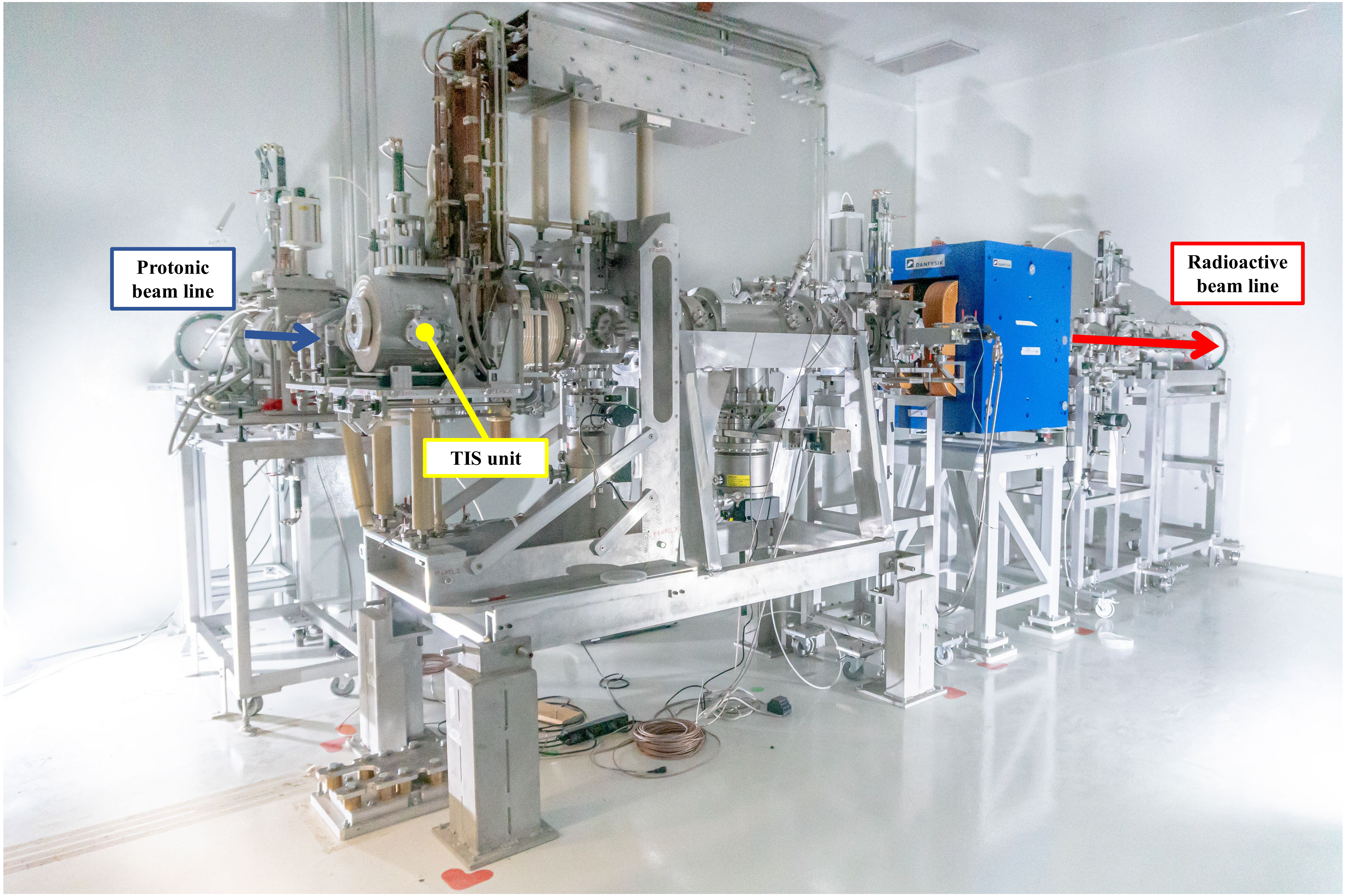




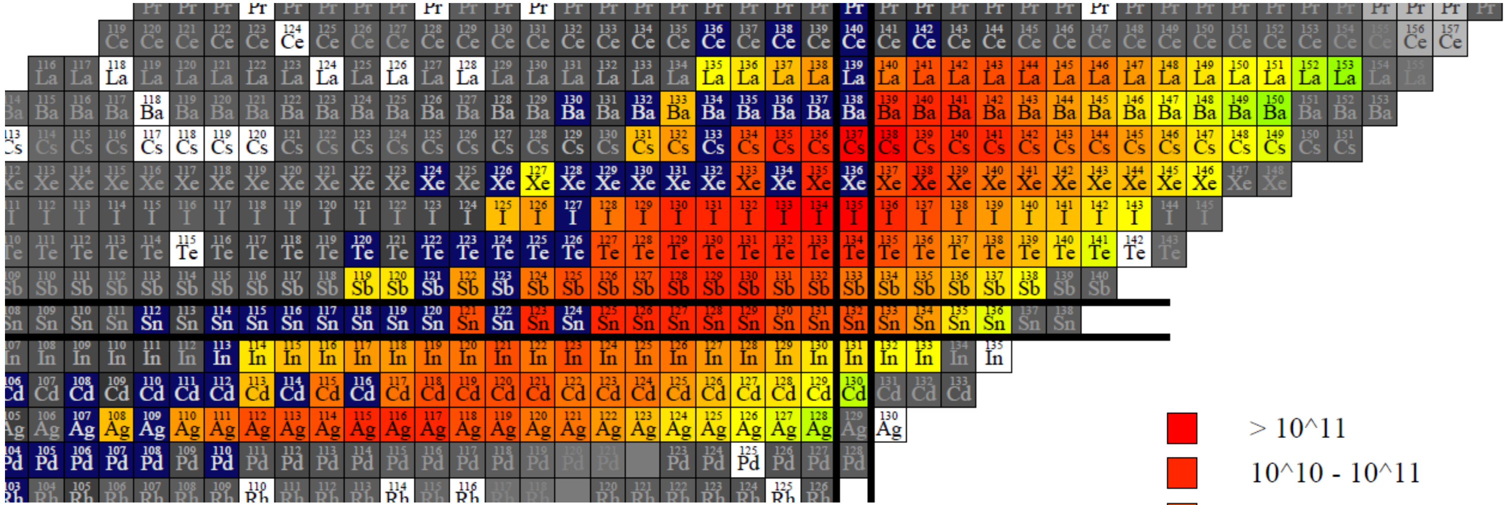


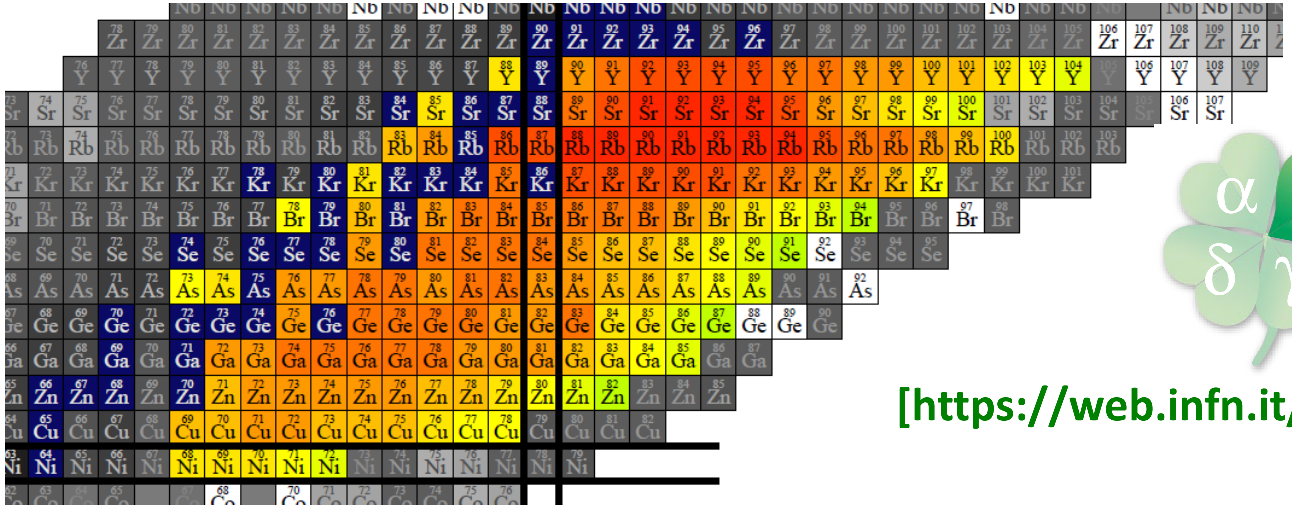


Beam test at iThemba lab. (2014): 66MeV protons, 60 μA on full scale SiC prototype at 1600 °C (FEM sim. Validation)
Former beam tests: ORNL (2007, 2010-2011) SiC, Ucx; ISOLDE(2009) UCx, IPNO (2013) UCx.
Front End and Target System: procured.
Target handling systems, <u>Heat resistance tests</u>, Nuclear Safety.


Protonic beam line
TIS unit
Radioactive beam line

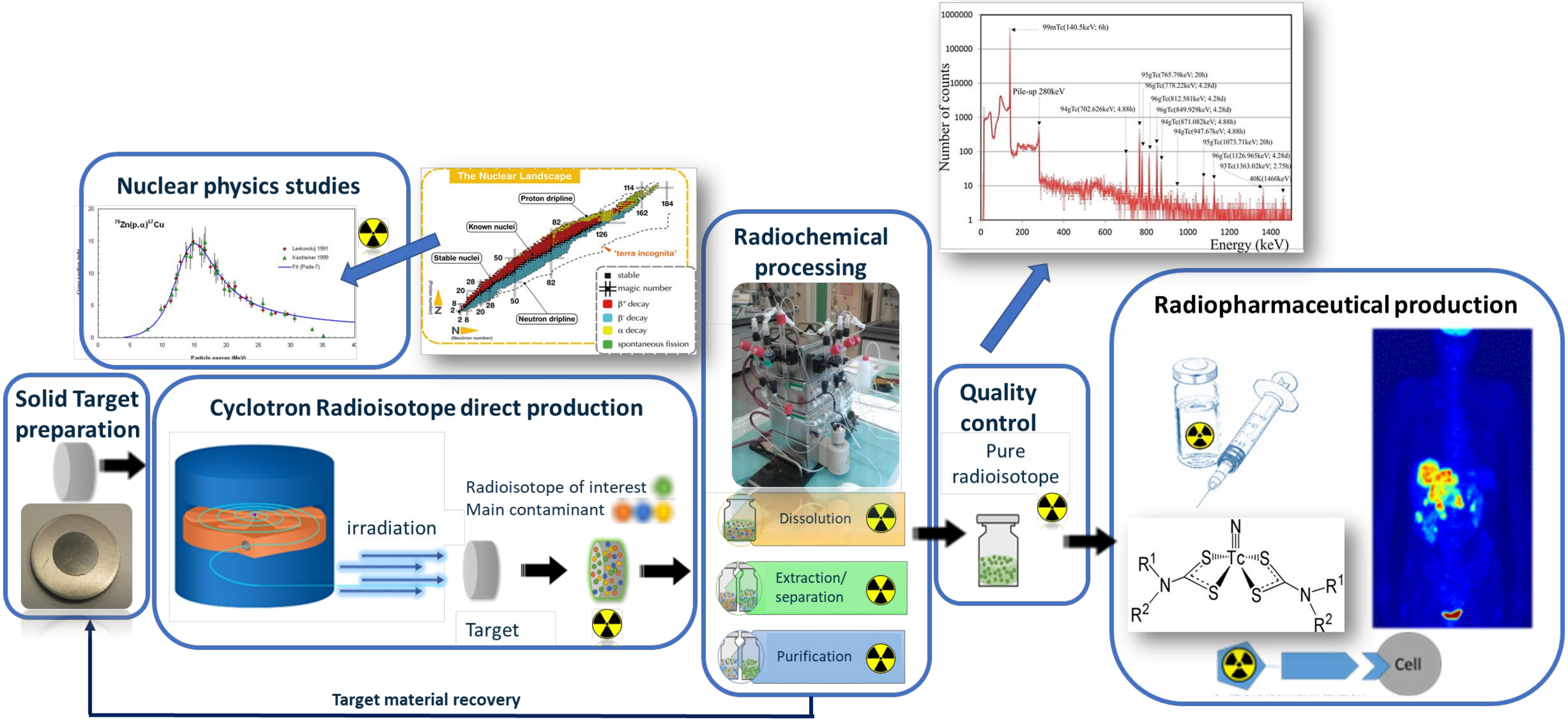
SPES beams "menu"



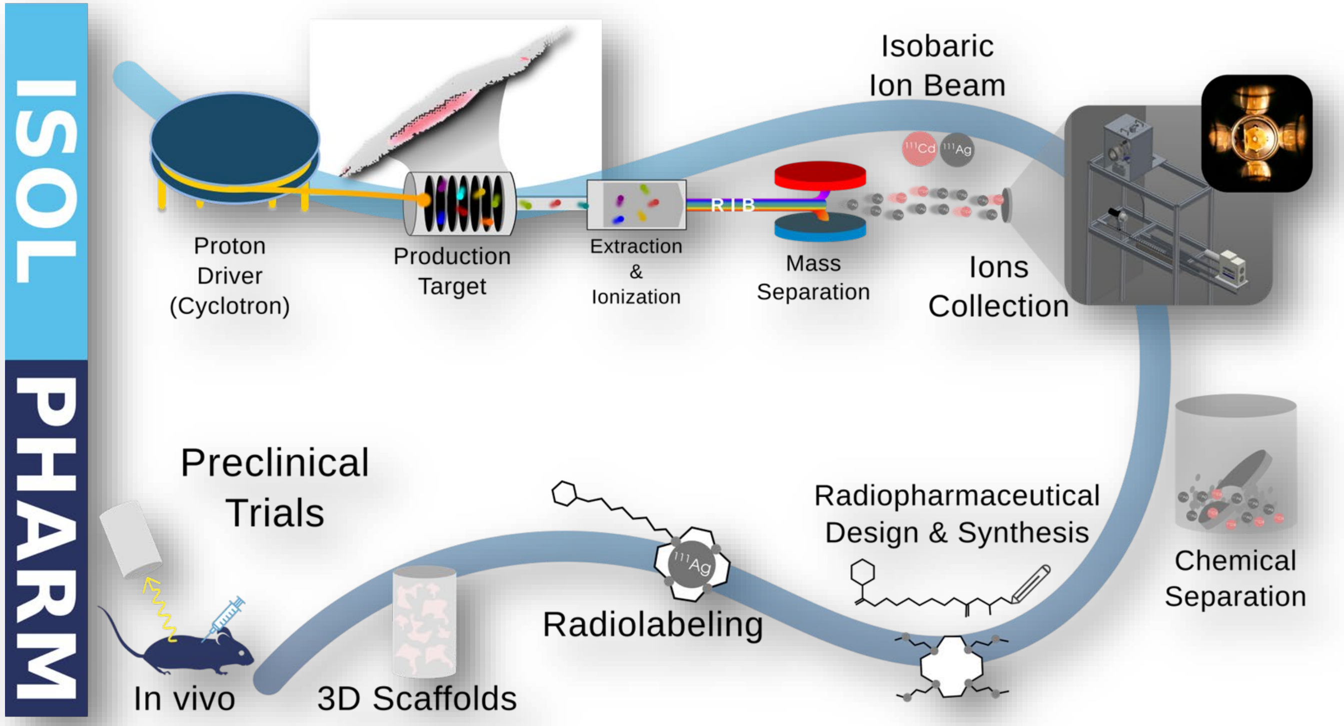


[https://web.infn.it/spes/]

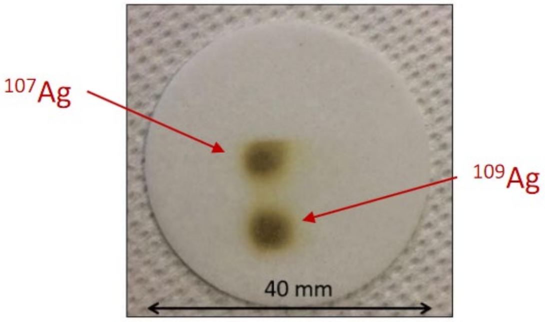
SPES-γ: the LARAMED project

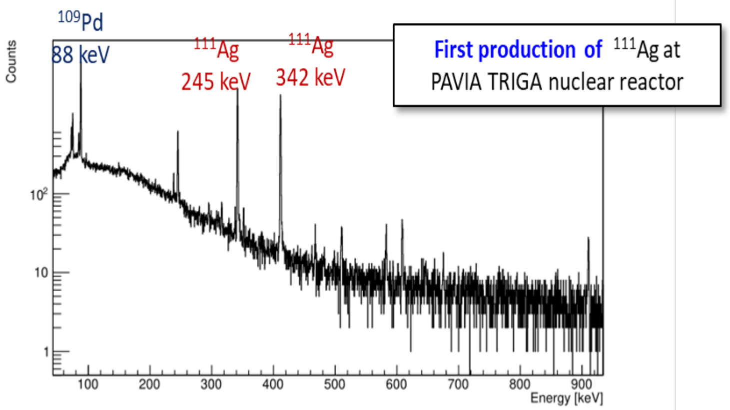


SPES-γ: the ISOLPHARM project



Collection on $NaNO_3$ substrate



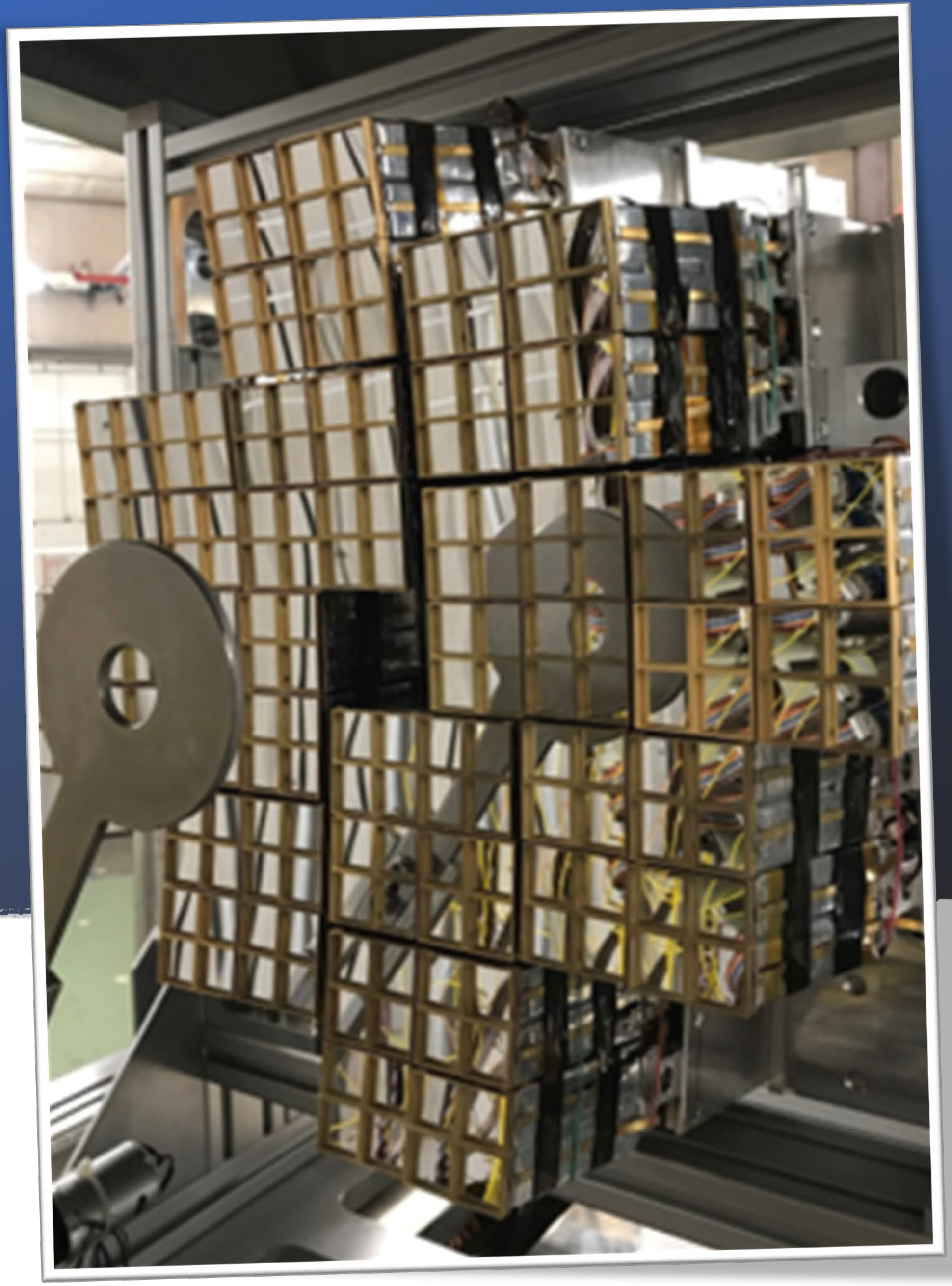


Capable of selecting and isolating a SINGLE RADIO-ISOTOPE

- high Specific Activity
- high Radionuclide Purity

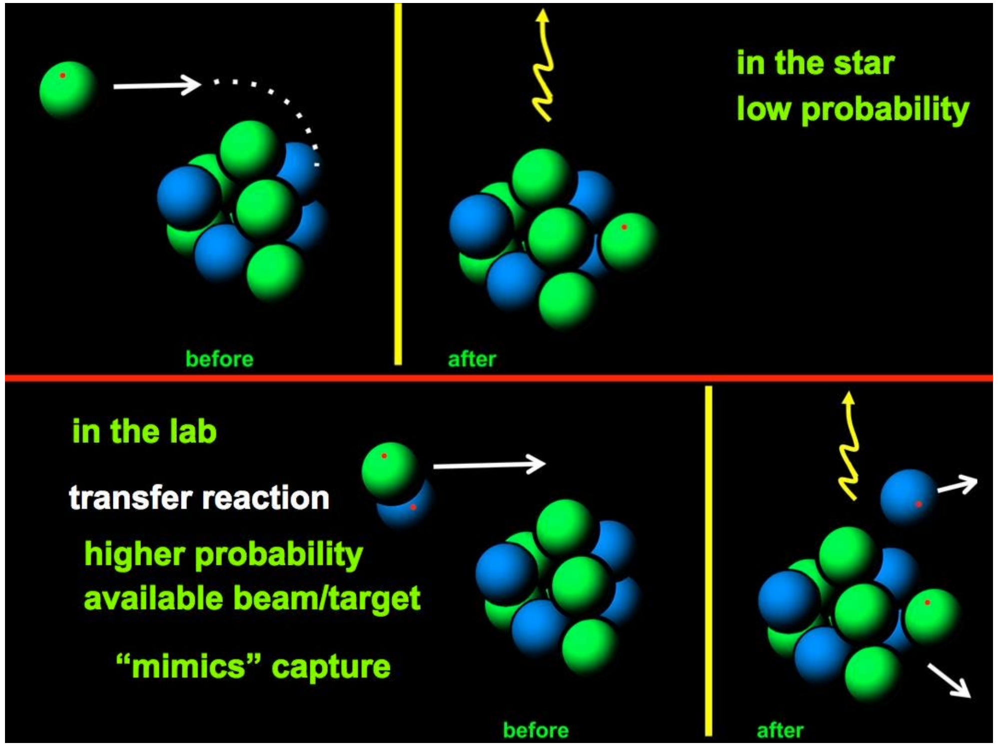
ISOLPHARM allows to produce unconventional medical radionuclides

PART 3:
experiments

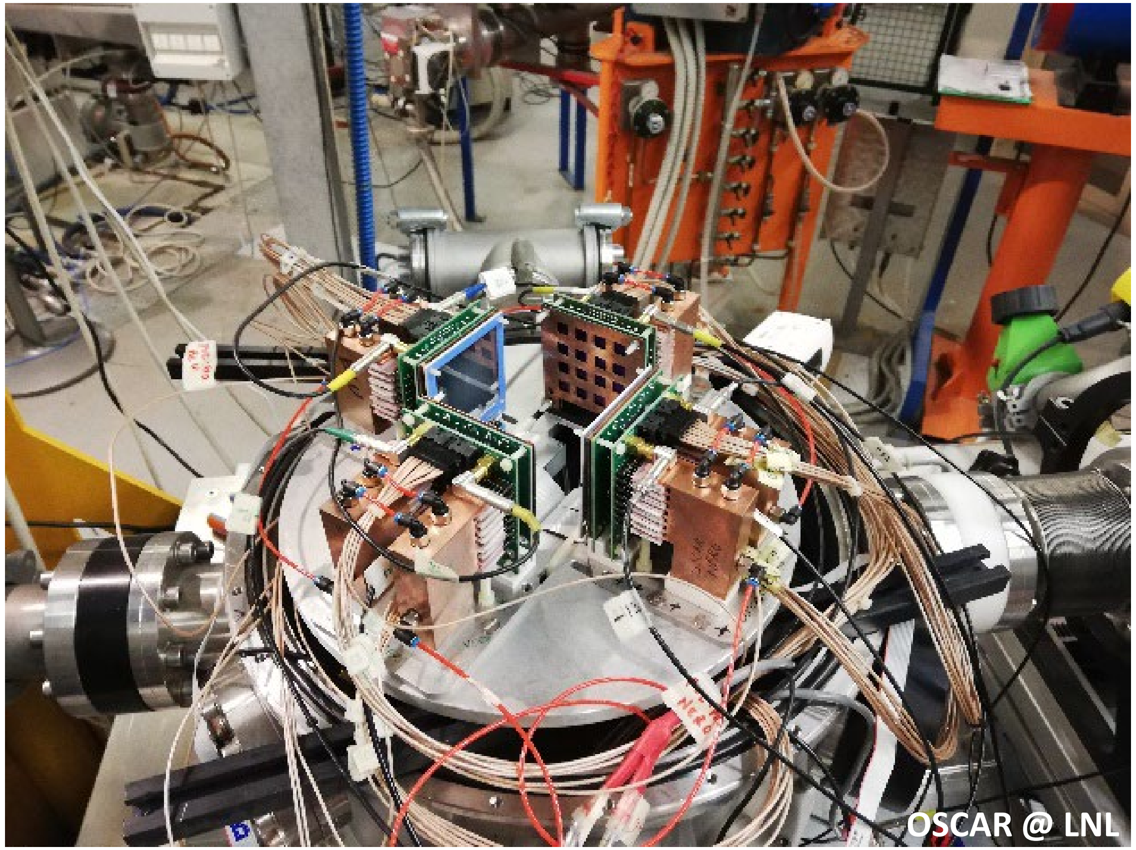


...Bonus track...

Stars in the lab: direct reactions

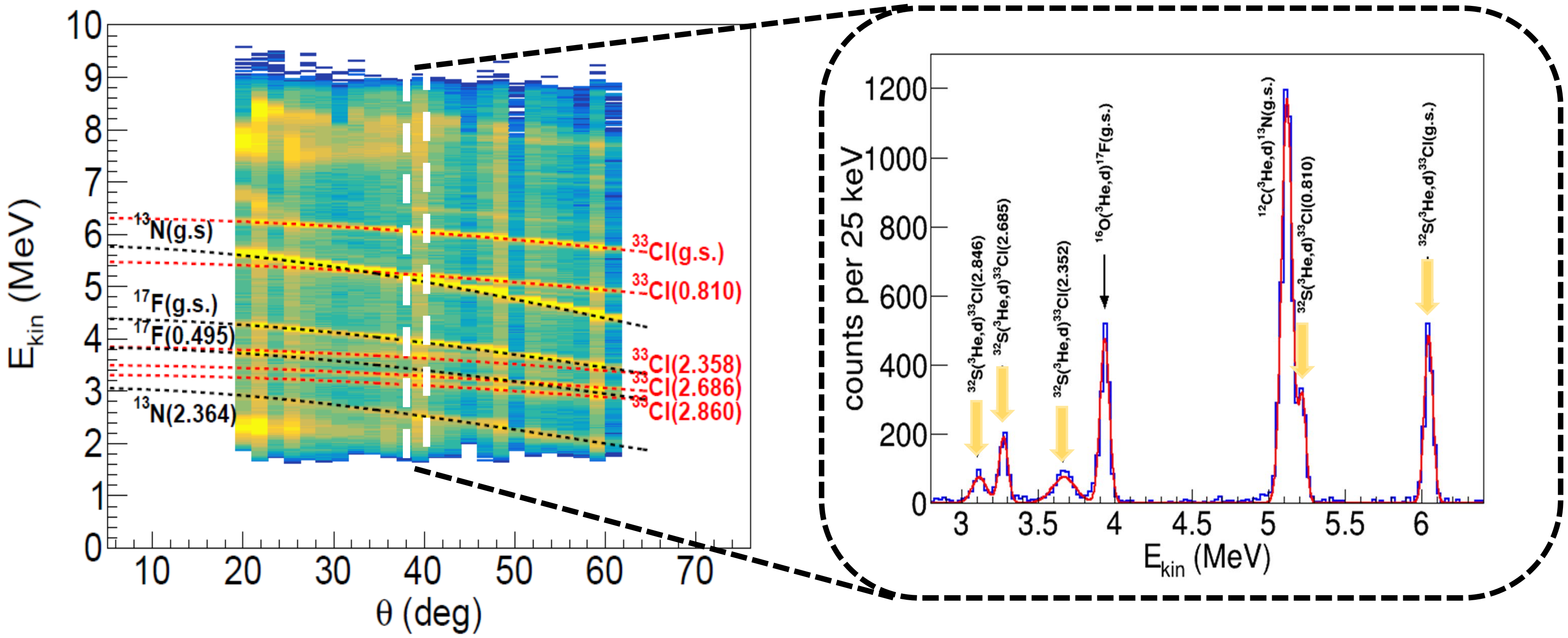


$^{32}S(^{3}He,d)^{33}Cl$

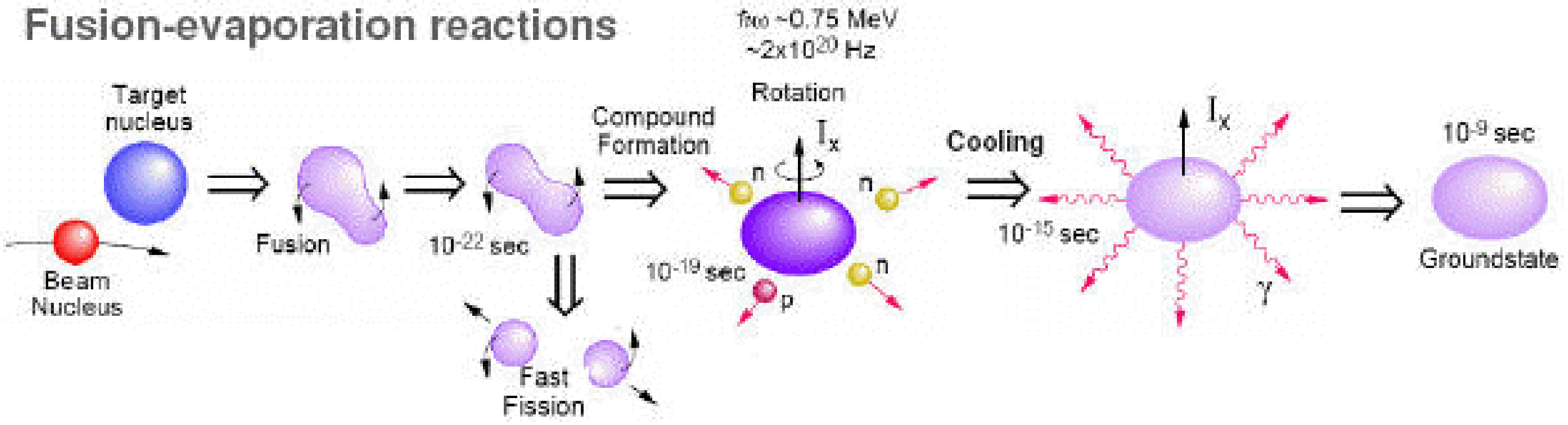


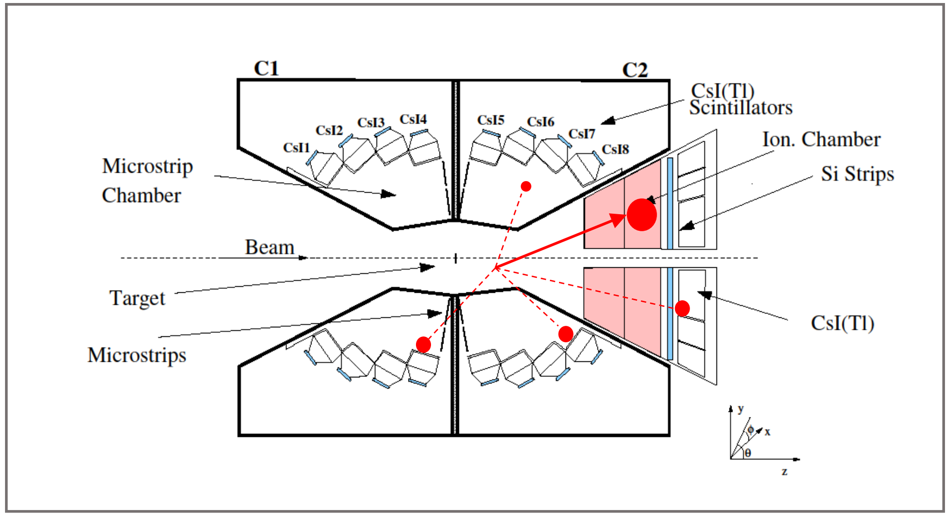
Courtesy of the NUCLEX collaboration

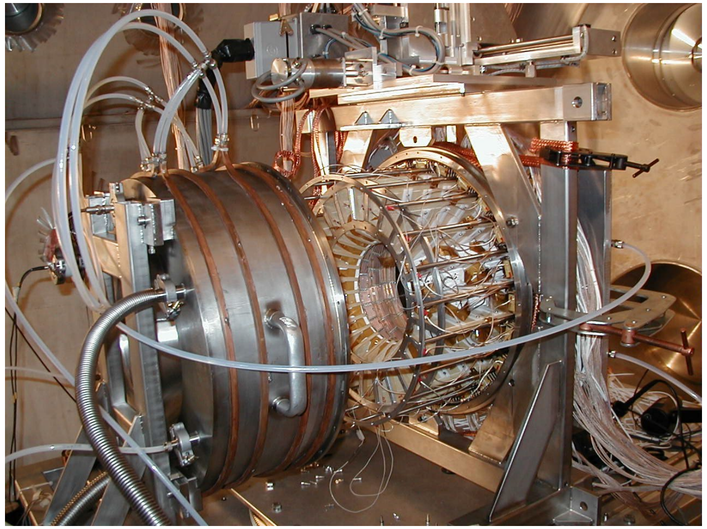
Kinematics and energy levels



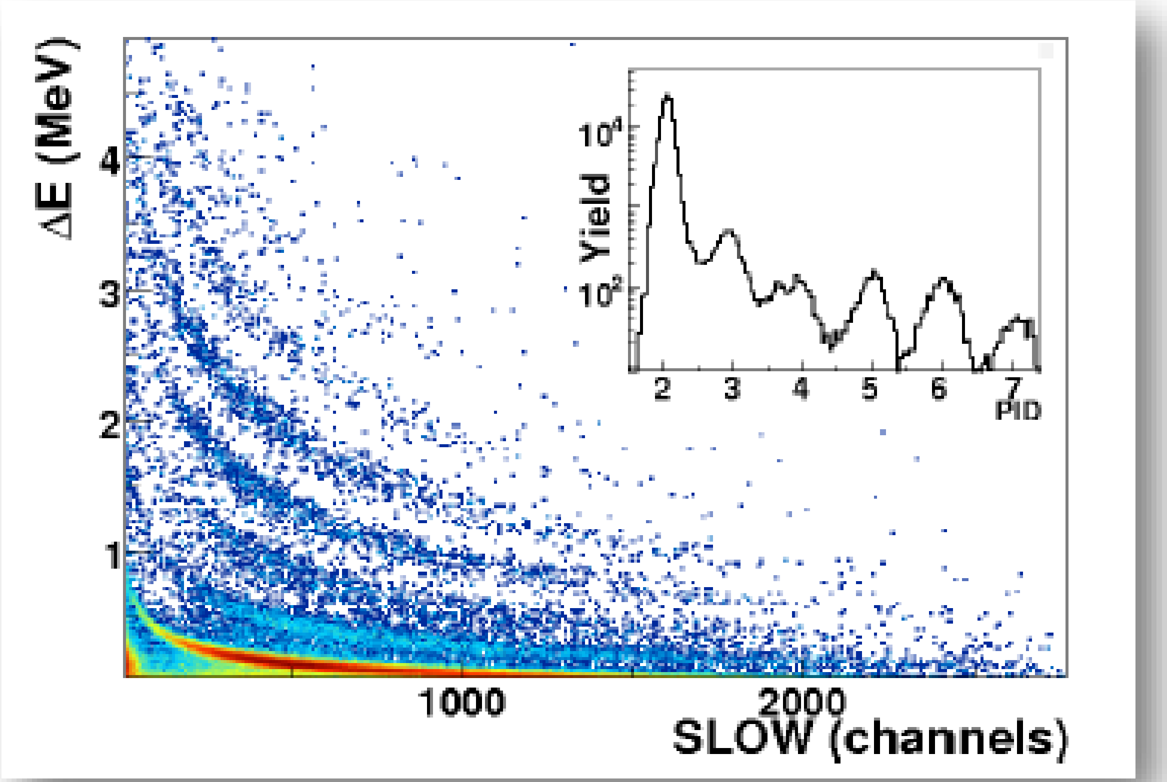
Fusion-evaporation reactions with the GARFIELD setup

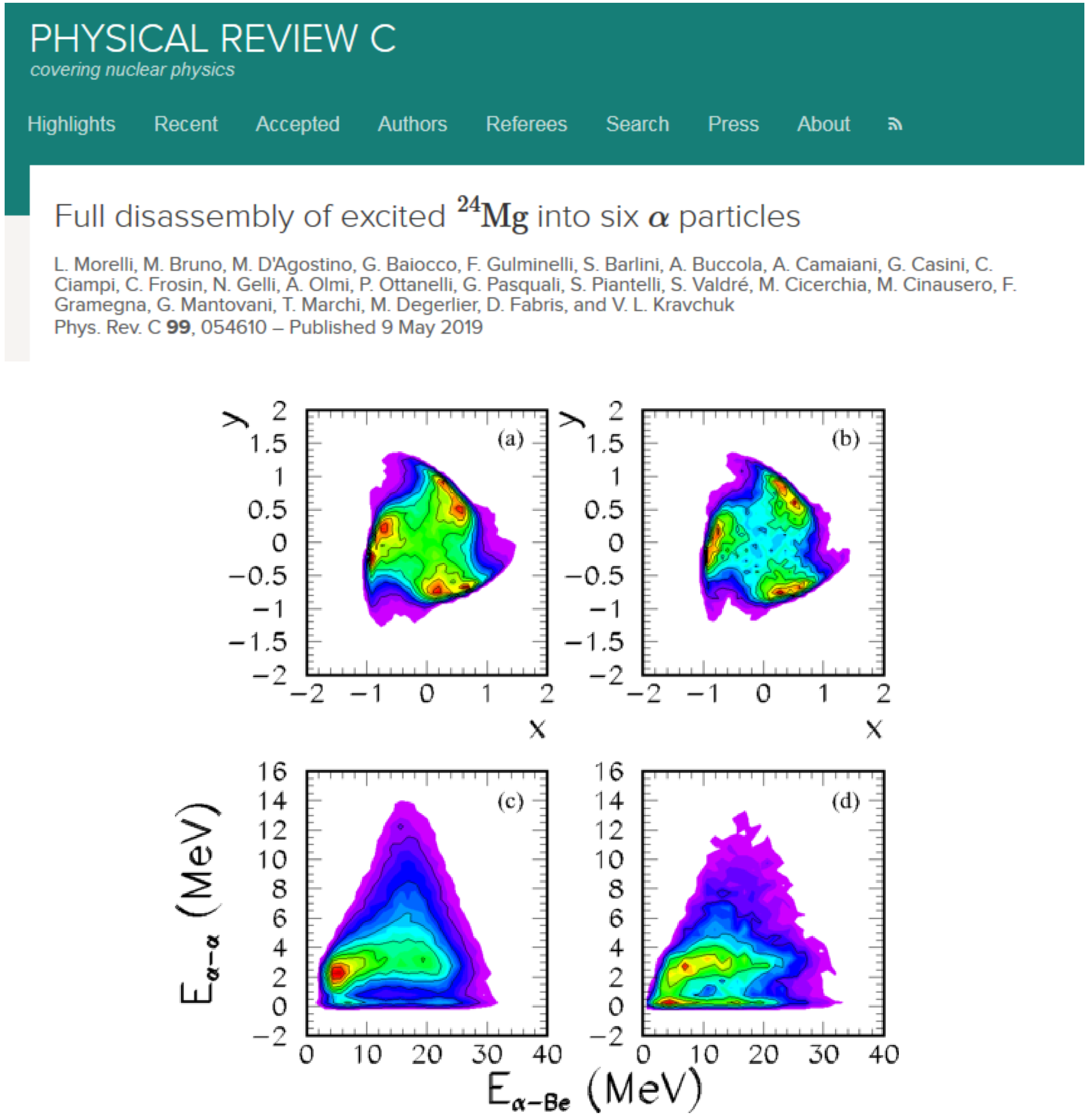




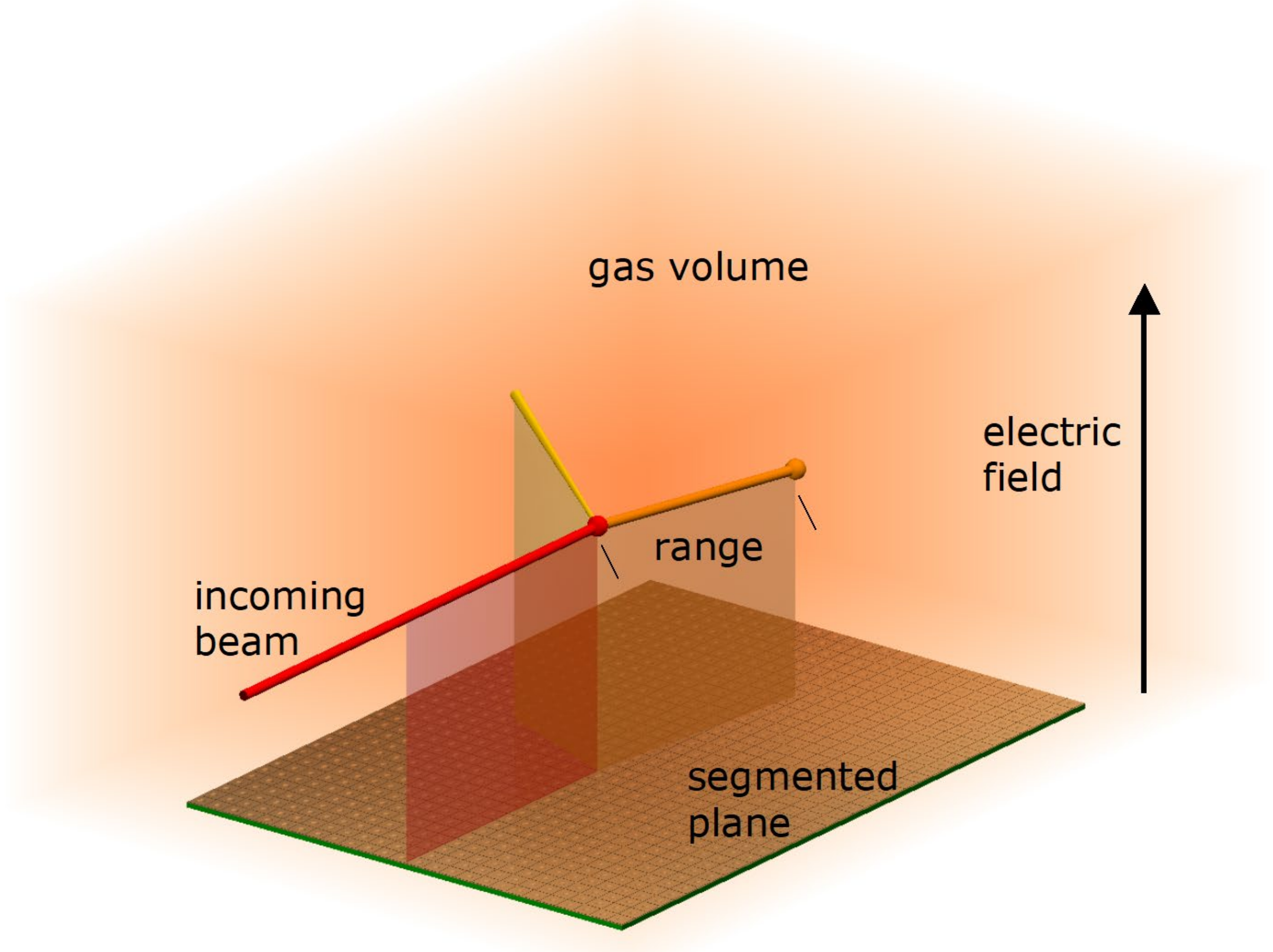


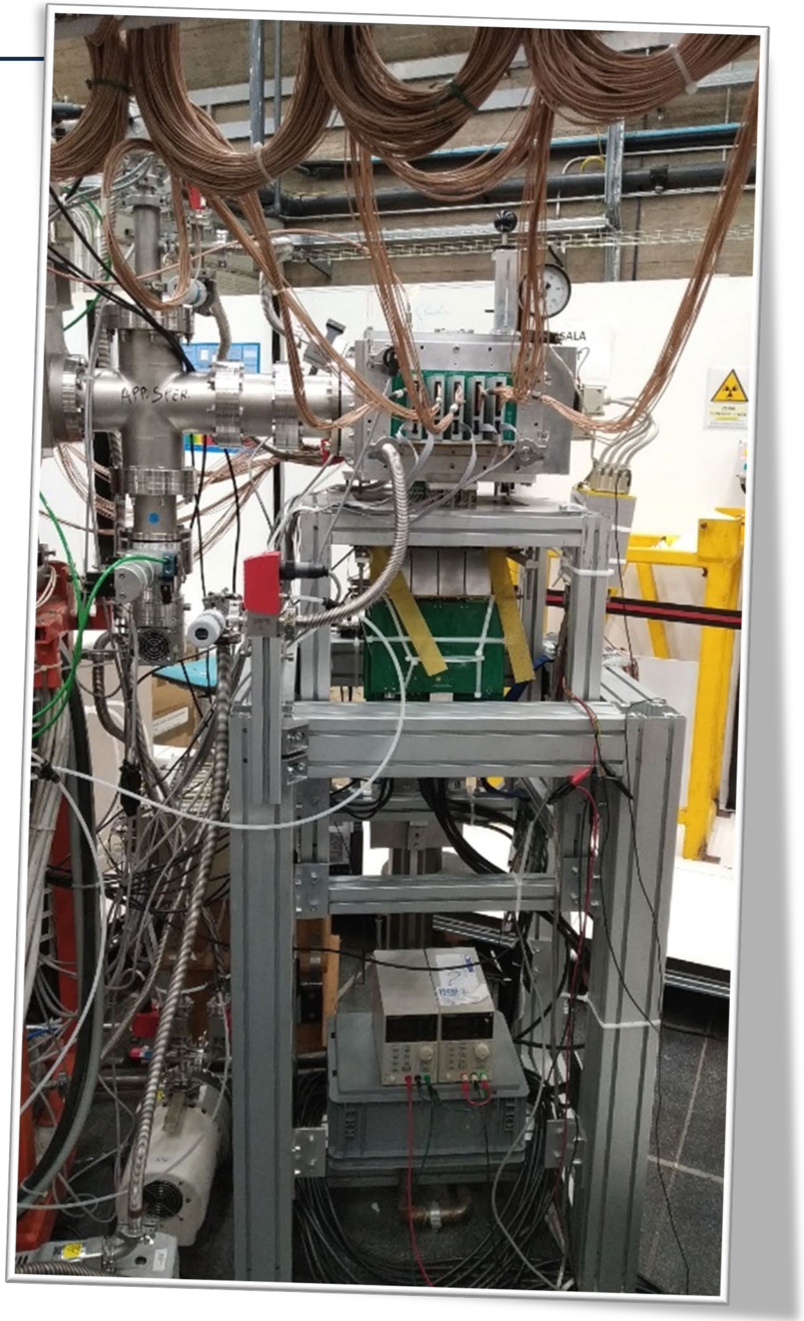
Fusion-evaporation reactions with the GARFIELD setup





Novel detectors for new experiments





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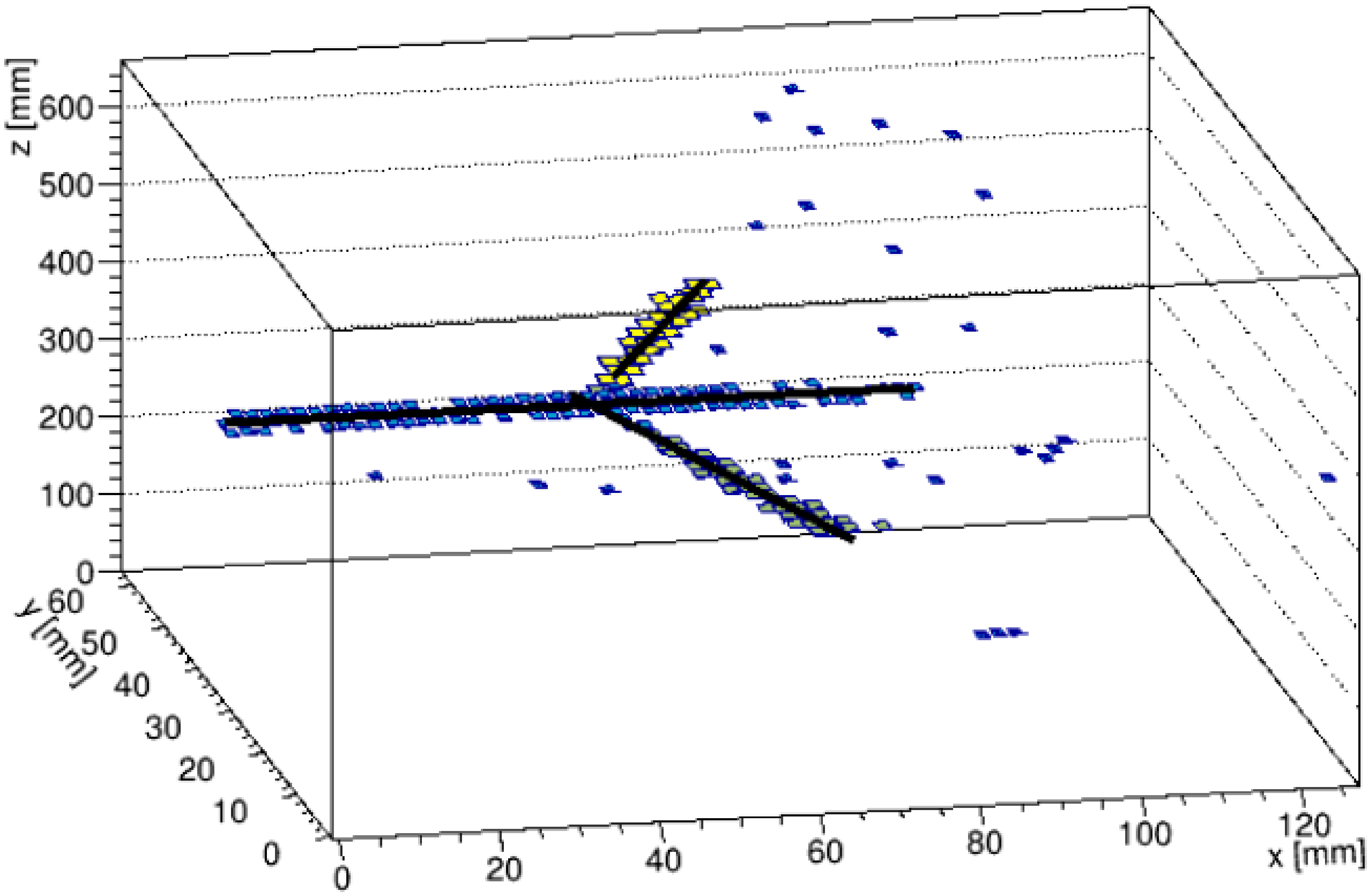
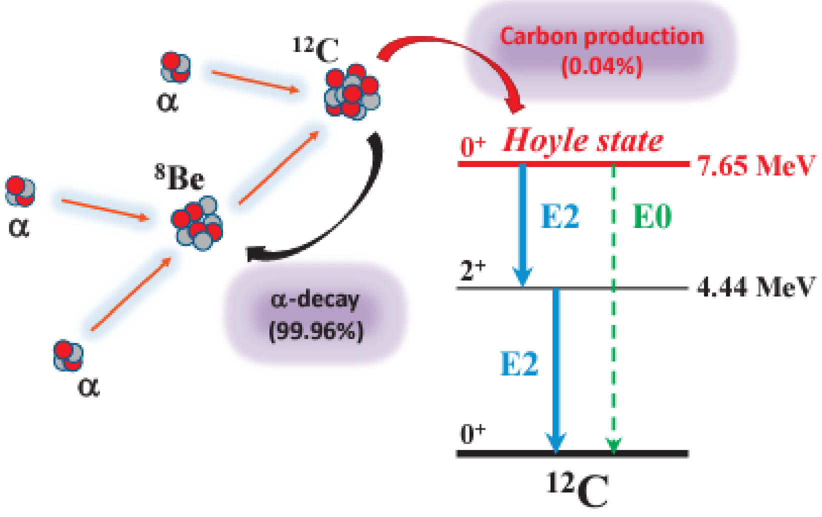


$^{11}B + p \rightarrow {}^{12}C \rightarrow \alpha + \alpha + \alpha$

Stardust



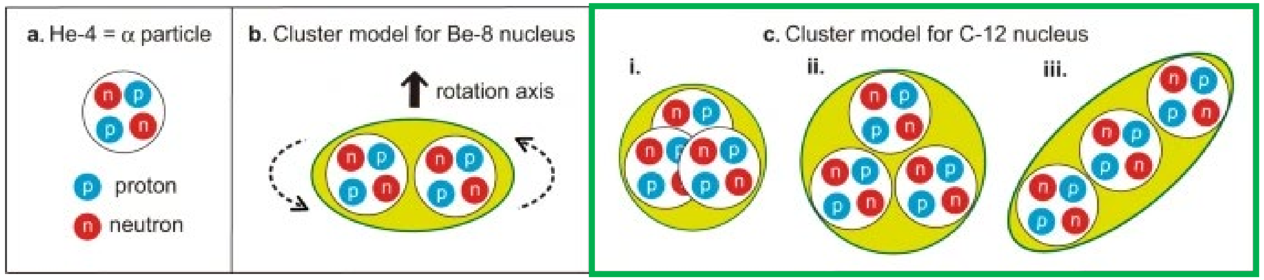
1953 – Fred Hoyle'shypothesis to explain the 12C abundance in the universe.

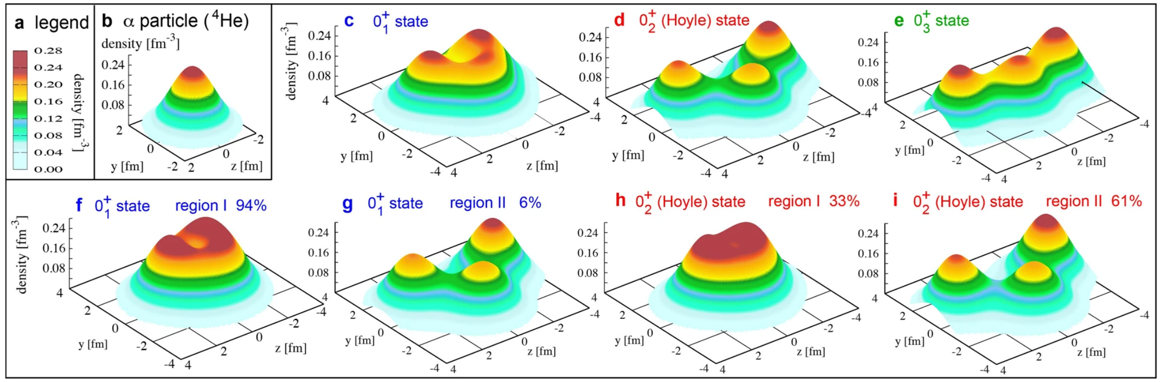
α-Clustering in atomic nuclei from first principles with statistical learning and the Hoyle state character

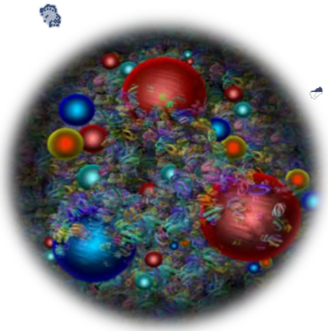
T. Otsuka, T. Abe, T. Yoshida, Y. Tsunoda, N. Shimizu, N. Itagaki, Y. Utsuno, J. Vary, P. Maris & H. Ueno

Nature Communications 13, Article number: 2234 (2022) | Cite this article

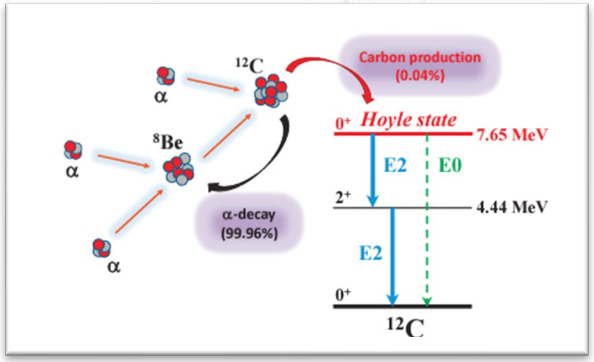
2022 – ^{12}C is still subject of forefront research







Thank you !!!


Carbon production
(0.04%)
12C
α
8Be
α
α
0+ Hoyle state
7.65 MeV
E2
E0
2+
4.44 MeV
E2
0+
12C
α-decay
(99.96%)