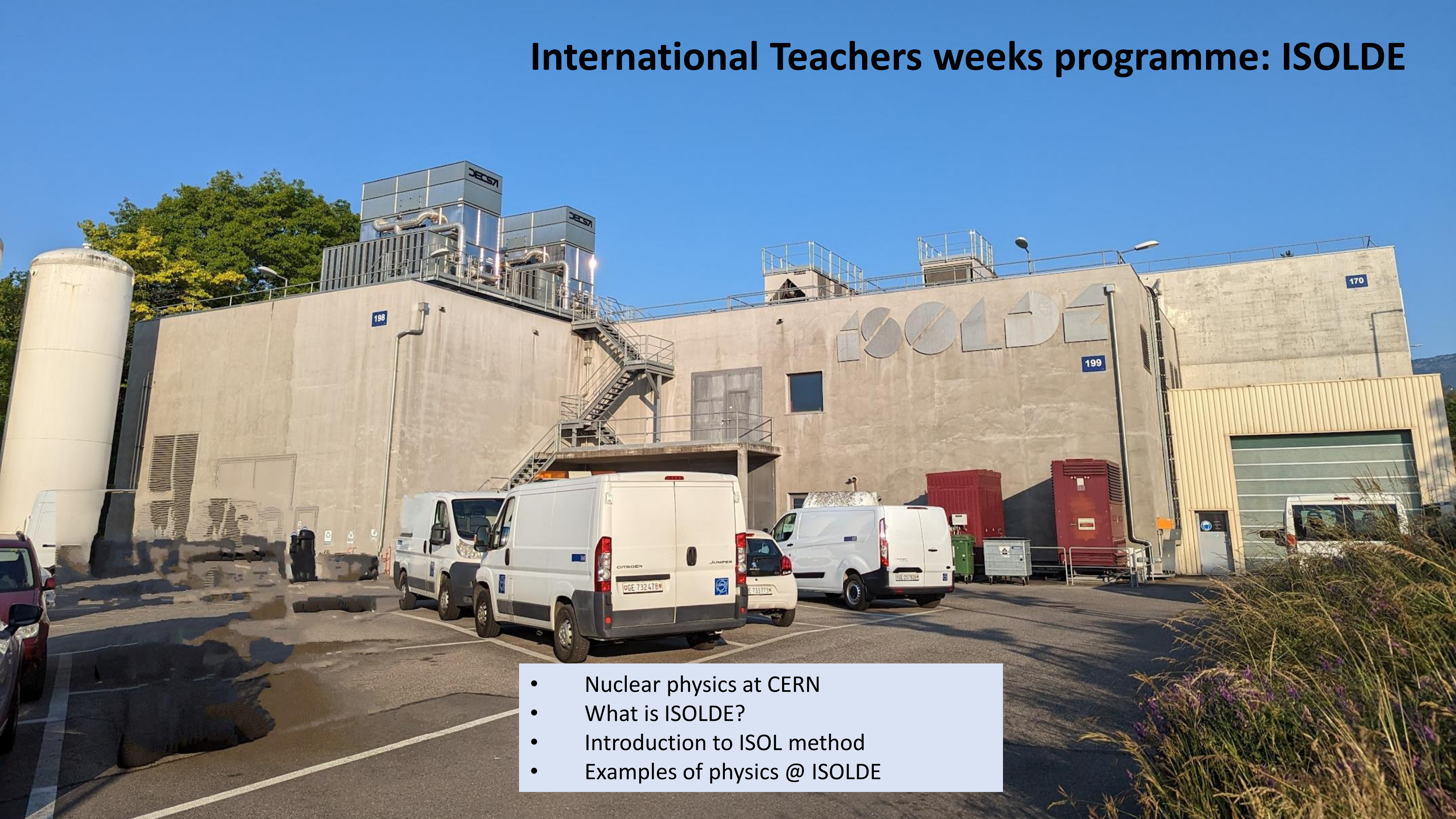
International Teachers weeks programme: ISOLDE



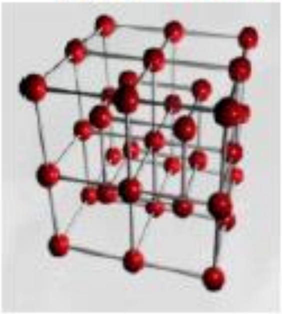
- Nuclear physics at CERN
- What is ISOLDE?
- Introduction to ISOL method
- Examples of physics @ ISOLDE

Nuclear physics and nuclear scale

Matter

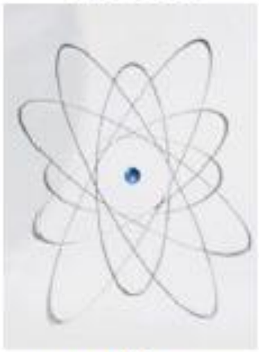
Macroscopic

Crystal



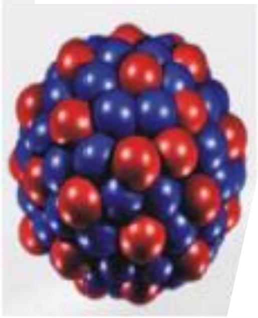
10^{-9} m

Atom



10^{-10} m

Atomic nucleus

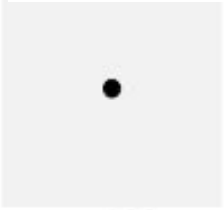


10^{-14} m
Angstrom

Nucleon

10^{-15} m
femtometer

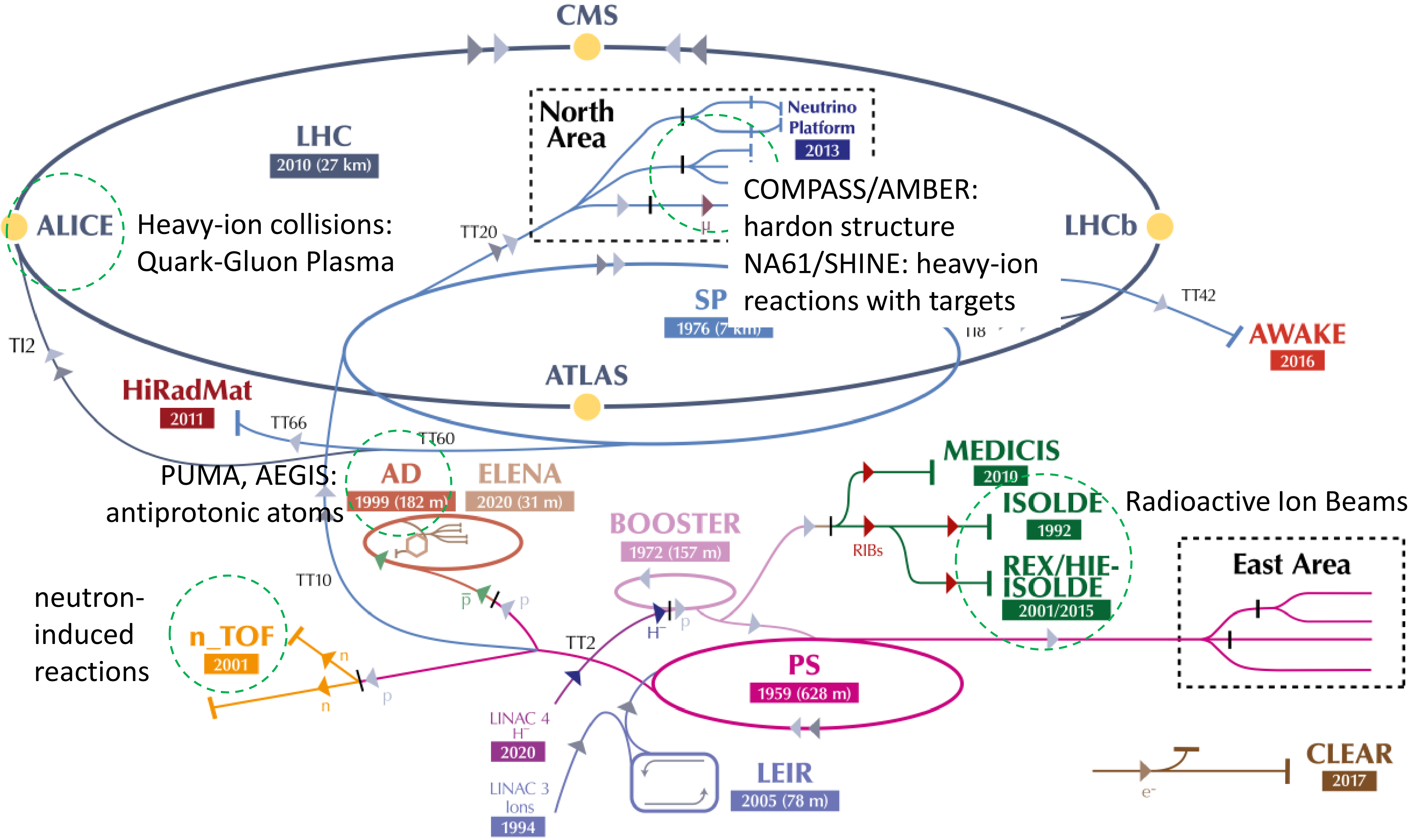
Quark



$< 10^{-18}$ m

Aim of nuclear physics:
- unravel <u>fundamental properties of nuclei</u> from their building blocks, protons and neutrons
- <u>determine emergent complexity</u> in realm of strong interaction from underlying quark and gluon degrees of freedom of Quantum Chromodynamics

Nuclear physics at CERN



Heavy-ion collisions: Quark-Gluon Plasma

COMPASS/AMBER: hardon structure

NA61/SHINE: heavy-ion reactions with targets

PUMA, AEGIS: antiprotonic atoms

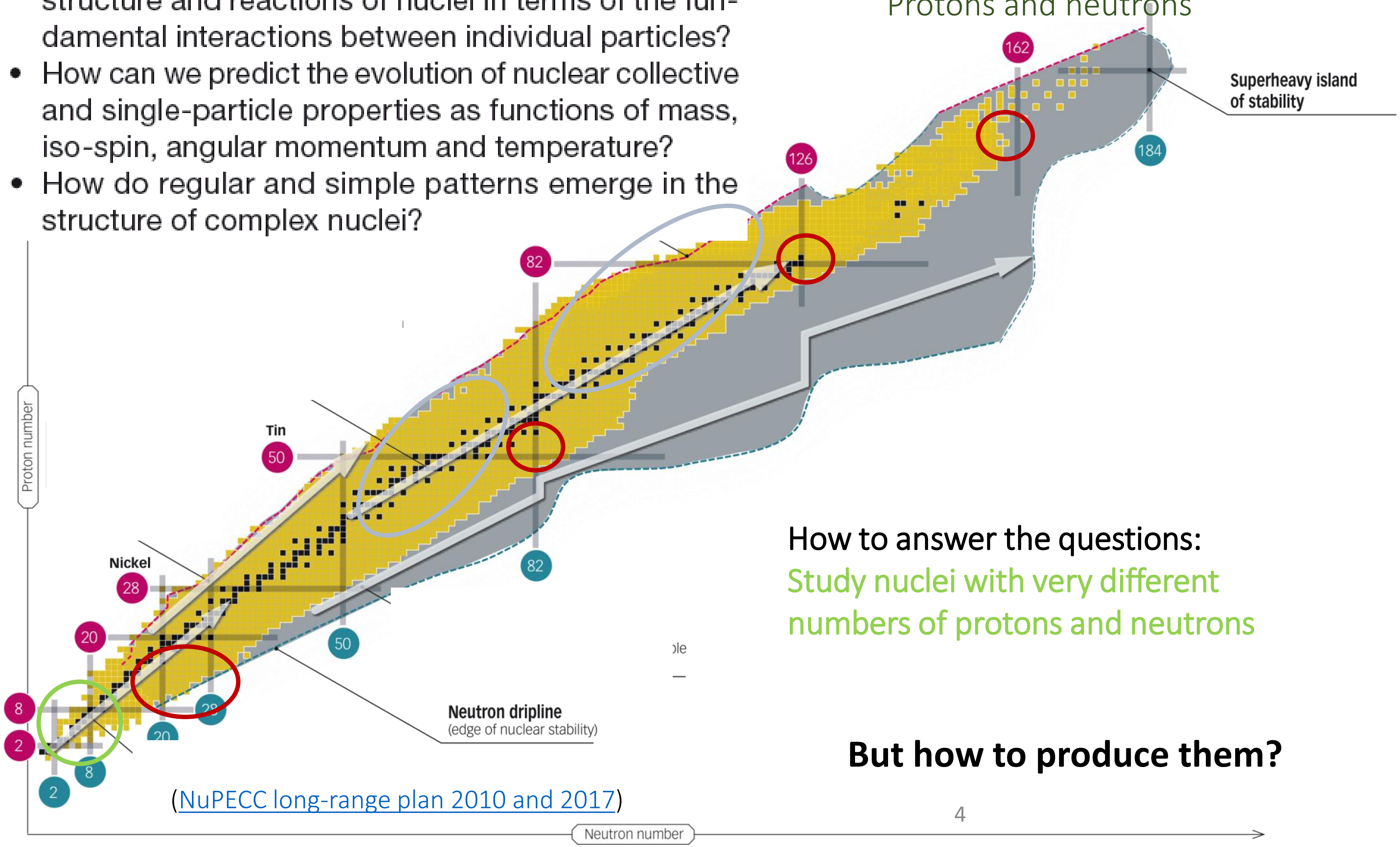
Radioactive Ion Beams

neutron-induced reactions

Open questions in low-energy nuclear physics

- How can we describe the rich variety of low-energy structure and reactions of nuclei in terms of the fundamental interactions between individual particles?
- How can we predict the evolution of nuclear collective and single-particle properties as functions of mass, iso-spin, angular momentum and temperature?
- How do regular and simple patterns emerge in the structure of complex nuclei?

2 kinds of interacting fermions:
Protons and neutrons



How to answer the questions:
Study nuclei with very different numbers of protons and neutrons

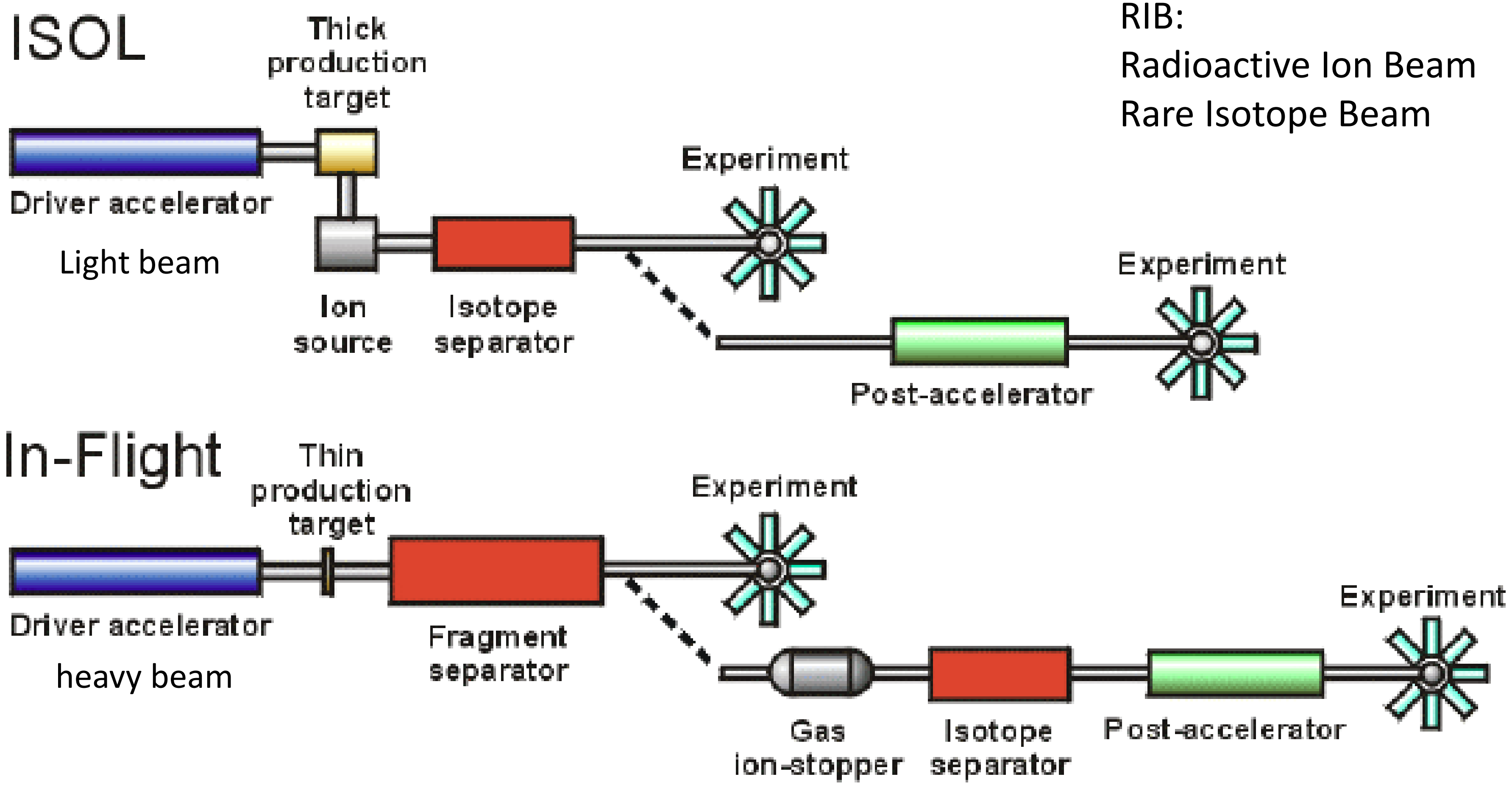
But how to produce them?

(NuPECC long-range plan 2010 and 2017)

RIB facilities

- Two main types of (complementary) RIB facilities:

RIB:
Radioactive Ion Beam
Rare Isotope Beam



Light beam

heavy beam

RIB facilities comparison

	ISOL	In-Flight
Projectile	light	heavy
Target	thick	thin
Ion beam energy	[redacted]	[redacted]
Beam intensity	[redacted]	[redacted]
Variety of nuclides	[redacted]	[redacted]
Release from target	[redacted]	[redacted]
Beam quality	[redacted]	[redacted]
Examples	ISOLDE@CERN, SPIRAL2@GANIL, ISAAC@TRIUMF	GANIL, GSI/FAIR, RIBF@RIKEN, FRIB@MSU

What is ISOLDE?

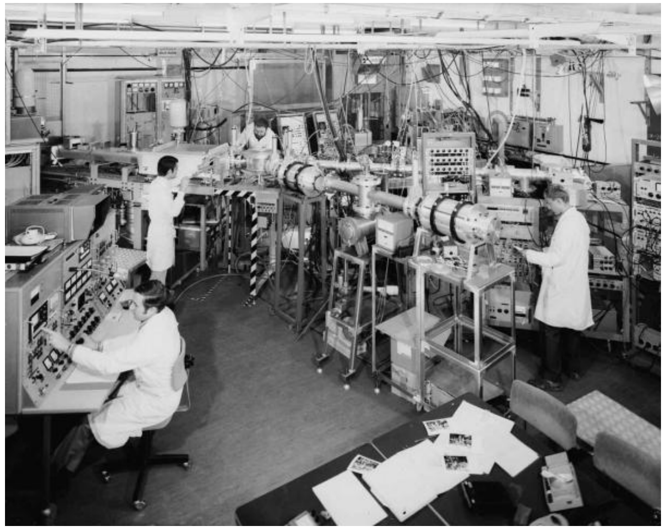
The On-Line Isotope Mass Separator ISOLDE is a facility dedicated to the production of a large variety of radioactive ion beams (RIBs)

Isolde history

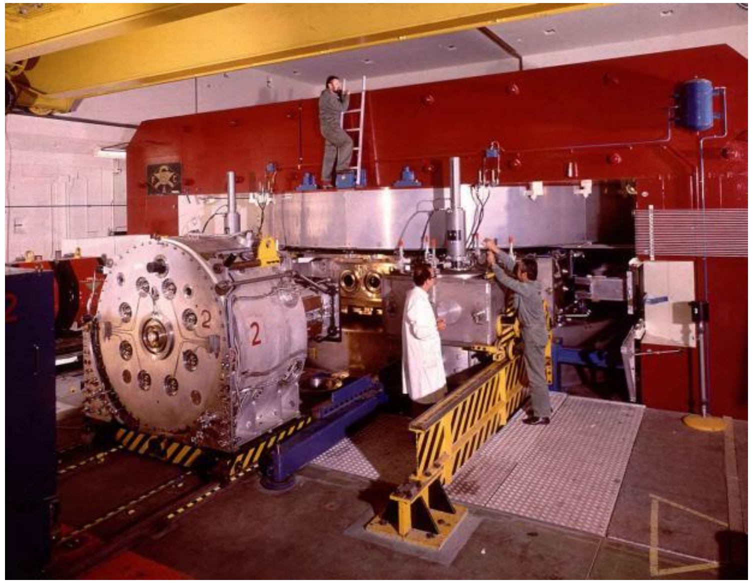
Dec 1964: CERN approves the online separator project

May 1966: SynchroCyclotron shuts down for the construction of ISOLDE

Oct 1967: First proton beams at ISOLDE



1972: SC Improvement Program – doubles the intensity
(now quite a nice museum)



1976: New experiments in ISOLDE II

June 1983: ISOLDE III approved – two-stage high resolution separation using two magnets

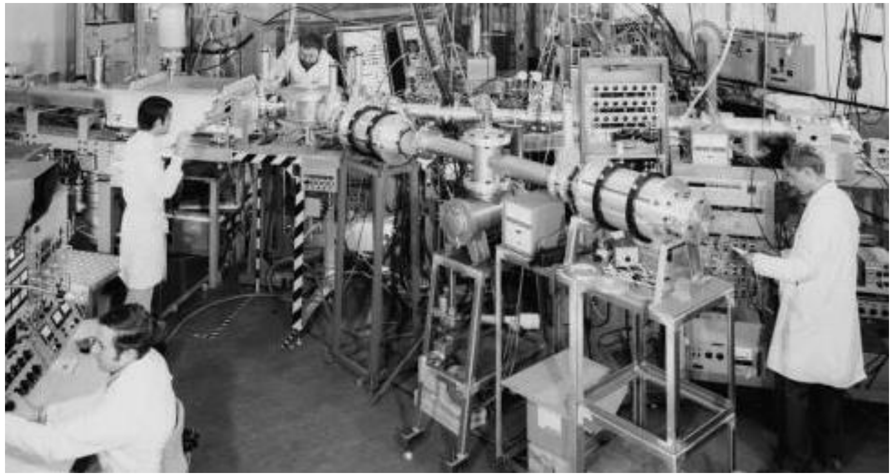
Dec 1990: The Synchrocyclotron beam ends
ISOLDE moves to PS booster to utilize CERN’s spare proton capacity…

ISOLDE at CERN

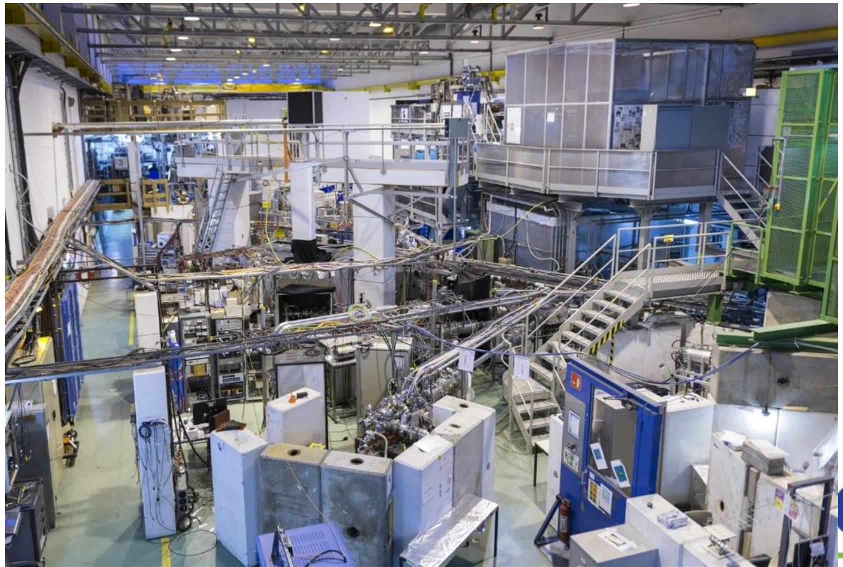
- Isotope Separator OnLine DEvice

- First ISOL facility worldwide!

- Produces Radioactive Ion Beams (RIBs)
- Approved by the CERN council in 1964
  - 1st used 600 MeV protons from SC
  - Then used 1.0 GeV (later 1.4 GeV) protons from the PSB

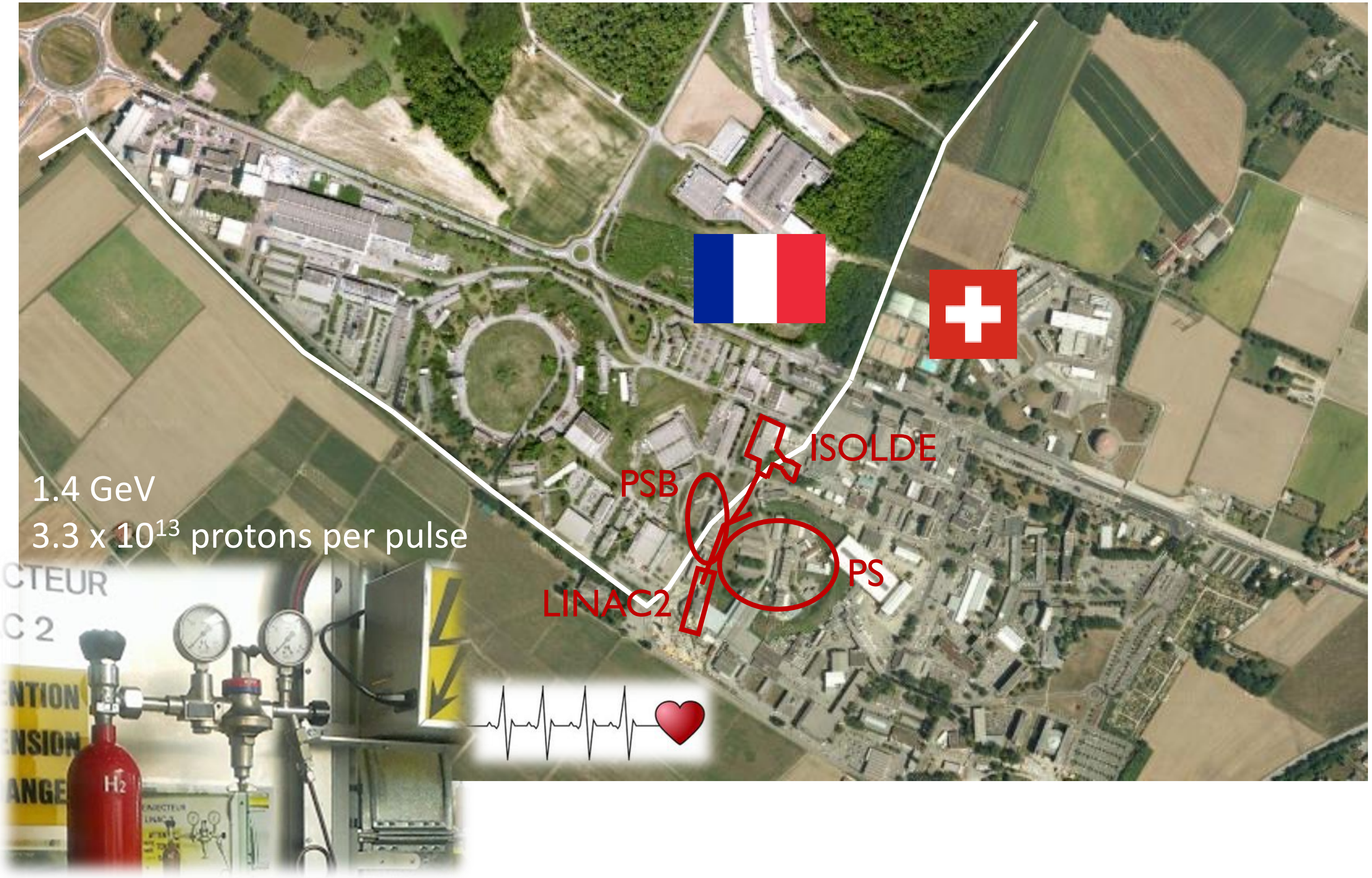


- A small facility with a big impact!
  - 0.1% of CERN budget
  - 7% of CERN scientists
  - 50% of CERN proton pulses
  - 80% of CERN protons



http://timeline.web.cern.ch/timelines/ISOLDE

Why at CERN?



1.4 GeV

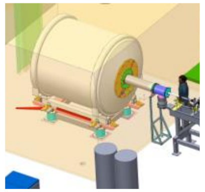
3.3×10^{13} protons per pulse

ISOLDE

Bulgaria Belgium CERN Denmark Spain Finland France Germany Greece Italy Norway Romania Sweden S. Africa Slovakia U. Kingdom Poland Switzerland

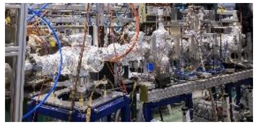

MINIBALL


SCATTERING EXPERIMENTS


ISS

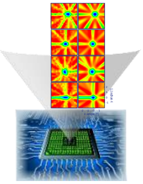

COLLAPS

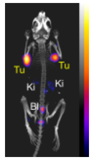

ISOLTRAP


CRIS

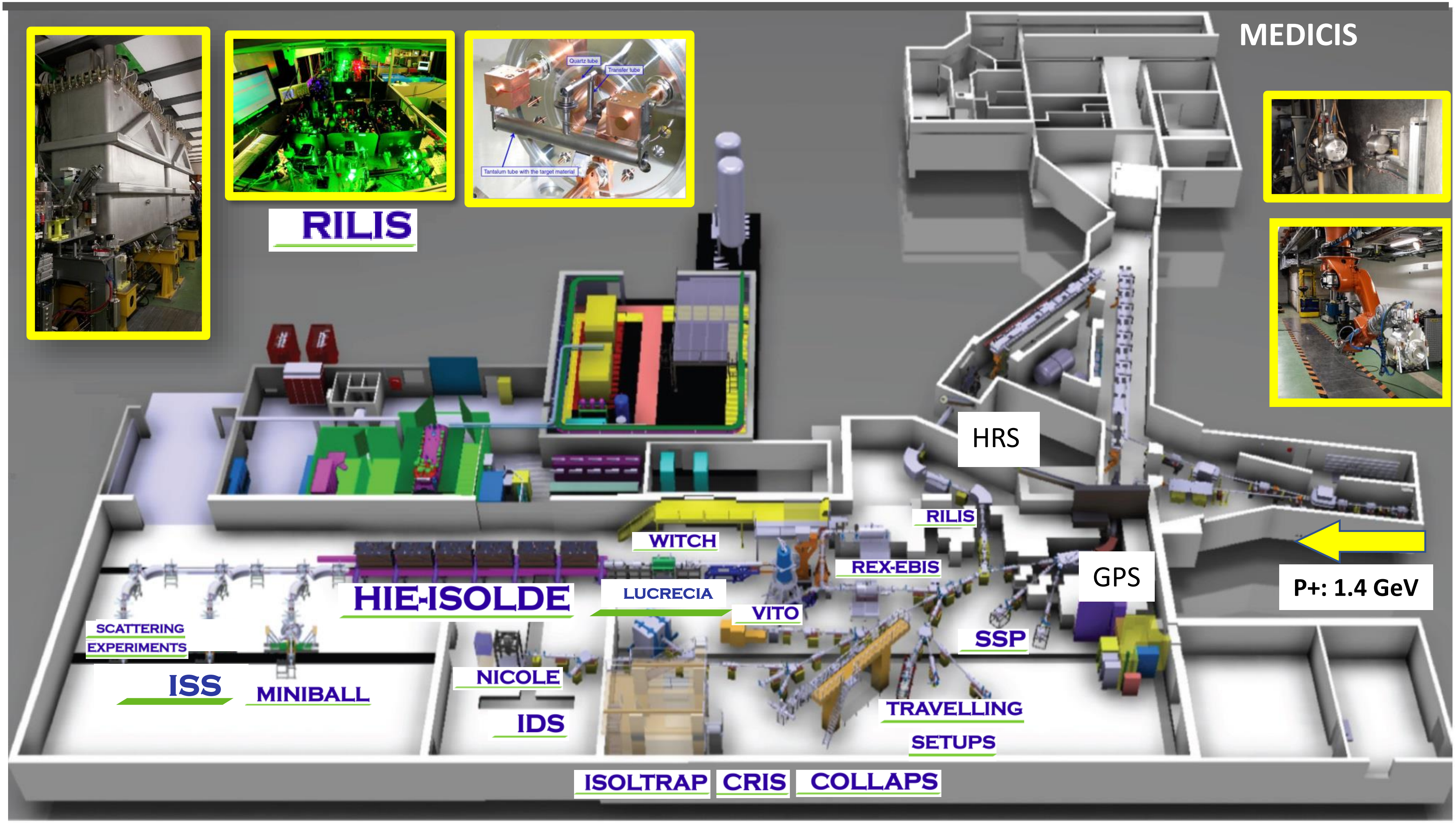

IDS


VITO


SSP



MEDICAL ISOTOPES



Production: Modern-day alchemy

◆High energy (1.4 GeV) protons are impacted onto a thick target e.g. ^{238}U

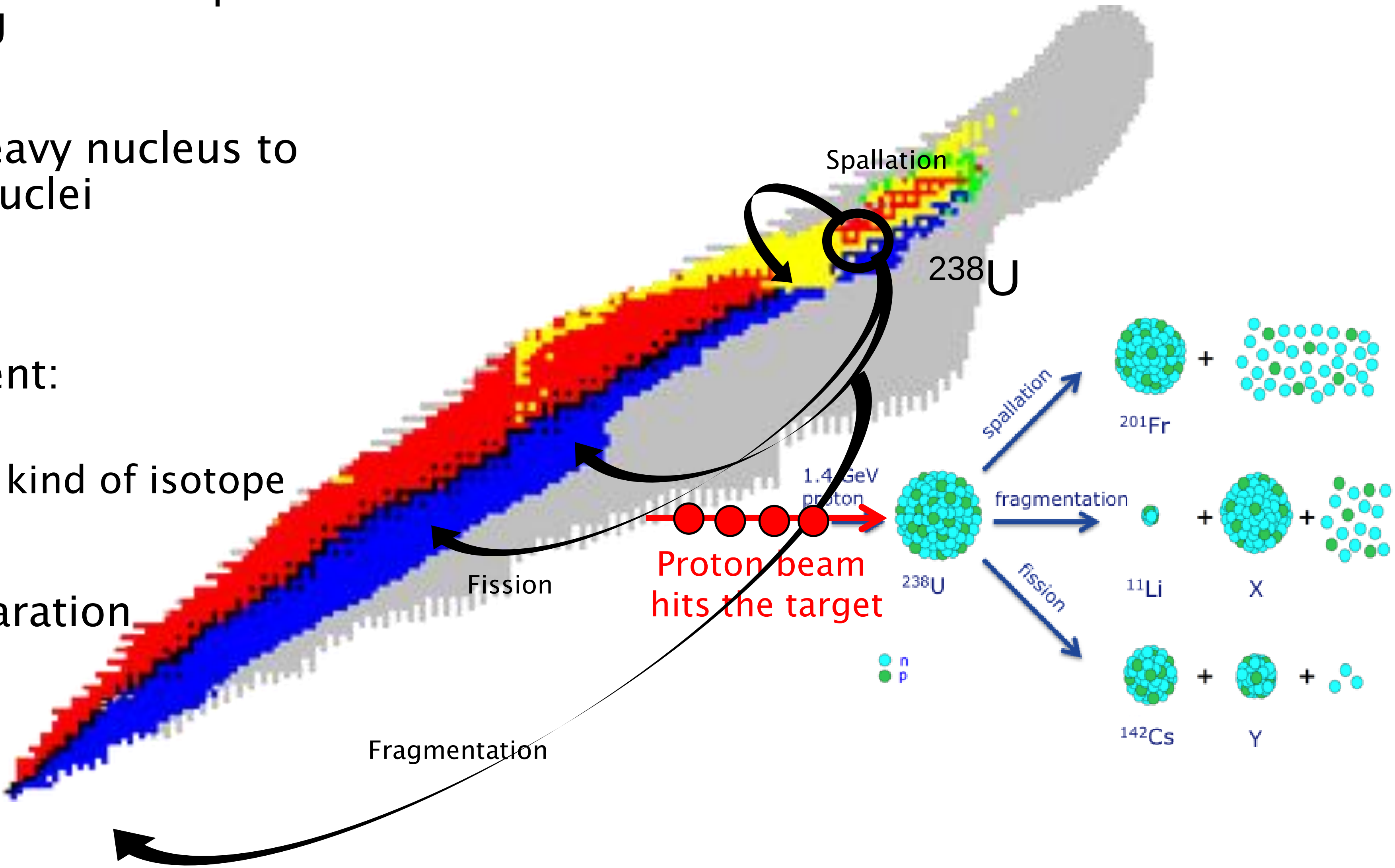
◆The protons split up the heavy nucleus to produce a wide variety of nuclei simultaneously

◆Requirements for experiment:

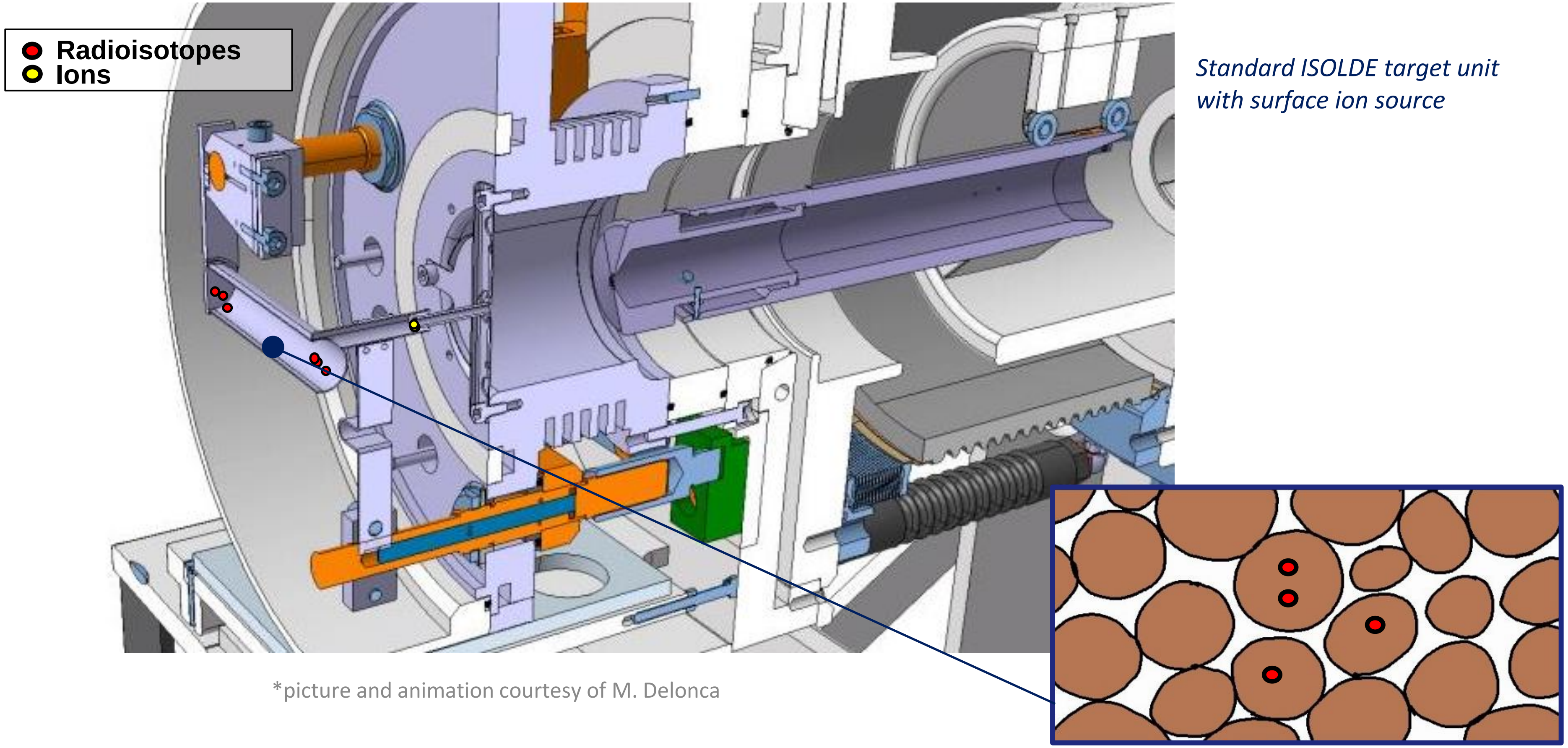
- ◆High production
- ◆Pure radioactive beams: 1 kind of isotope

◆There are 3 stages of preparation

- ◆Production
- ◆Ionization
- ◆Separation



Production: Targets



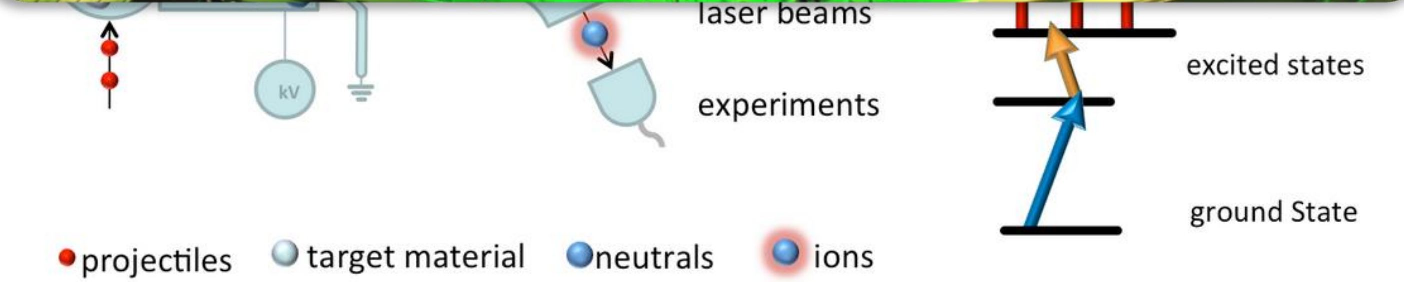
Standard ISOLDE target unit with surface ion source

*picture and animation courtesy of M. Delonca

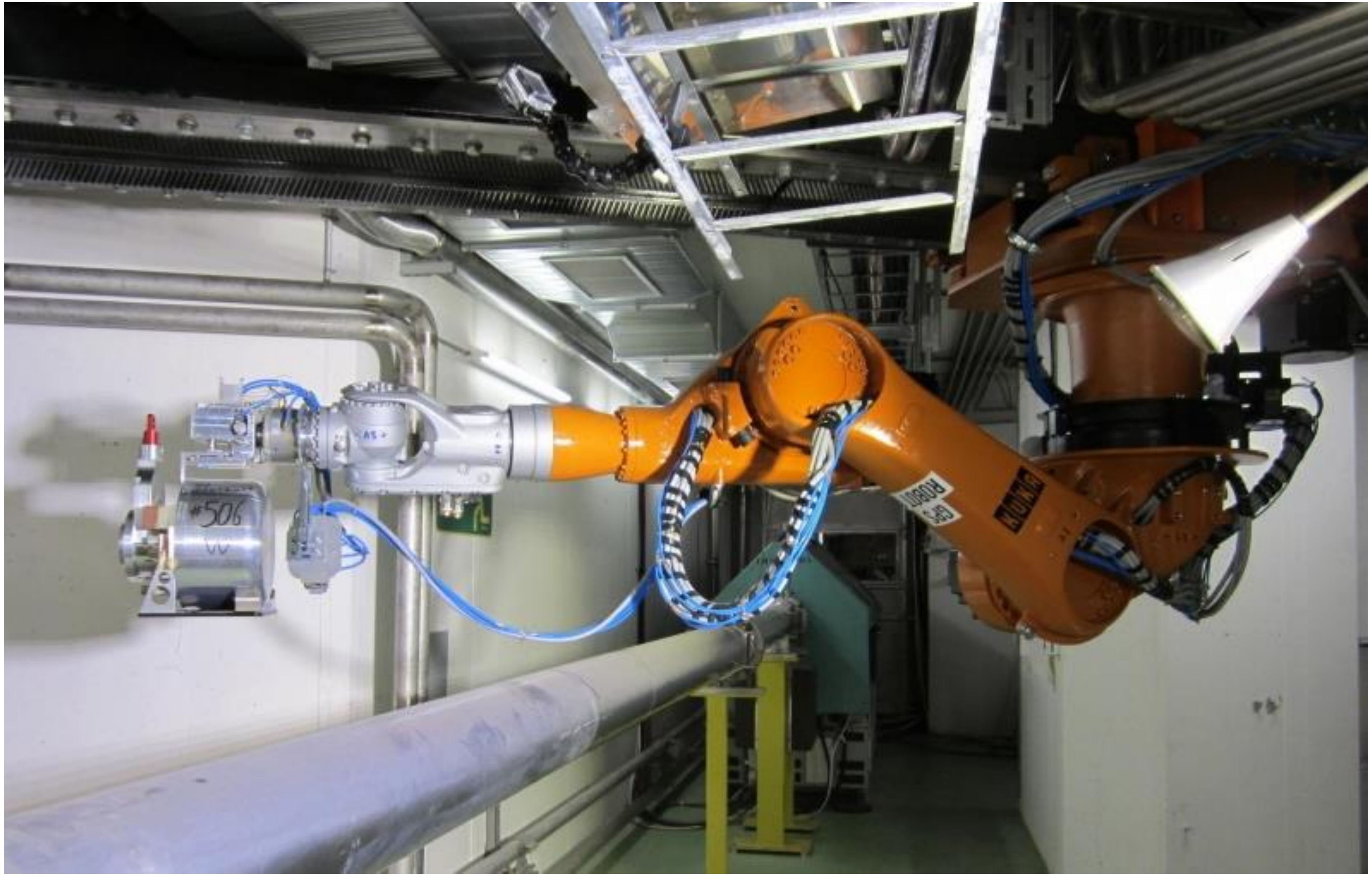
- Over 120 materials have been tested and/or used as ISOL targets
  - Choice of target material and ionizer dependent on radioactive beam of interest
- Target material and transfer tube heated to 1500 – 2000 degrees
- Operated by robots due to radiation

Ion Sources

- **Hot-cavity**
  - W heated at > 2000 C
  - High ionization efficiencies for some nuclei
- **Plasma**



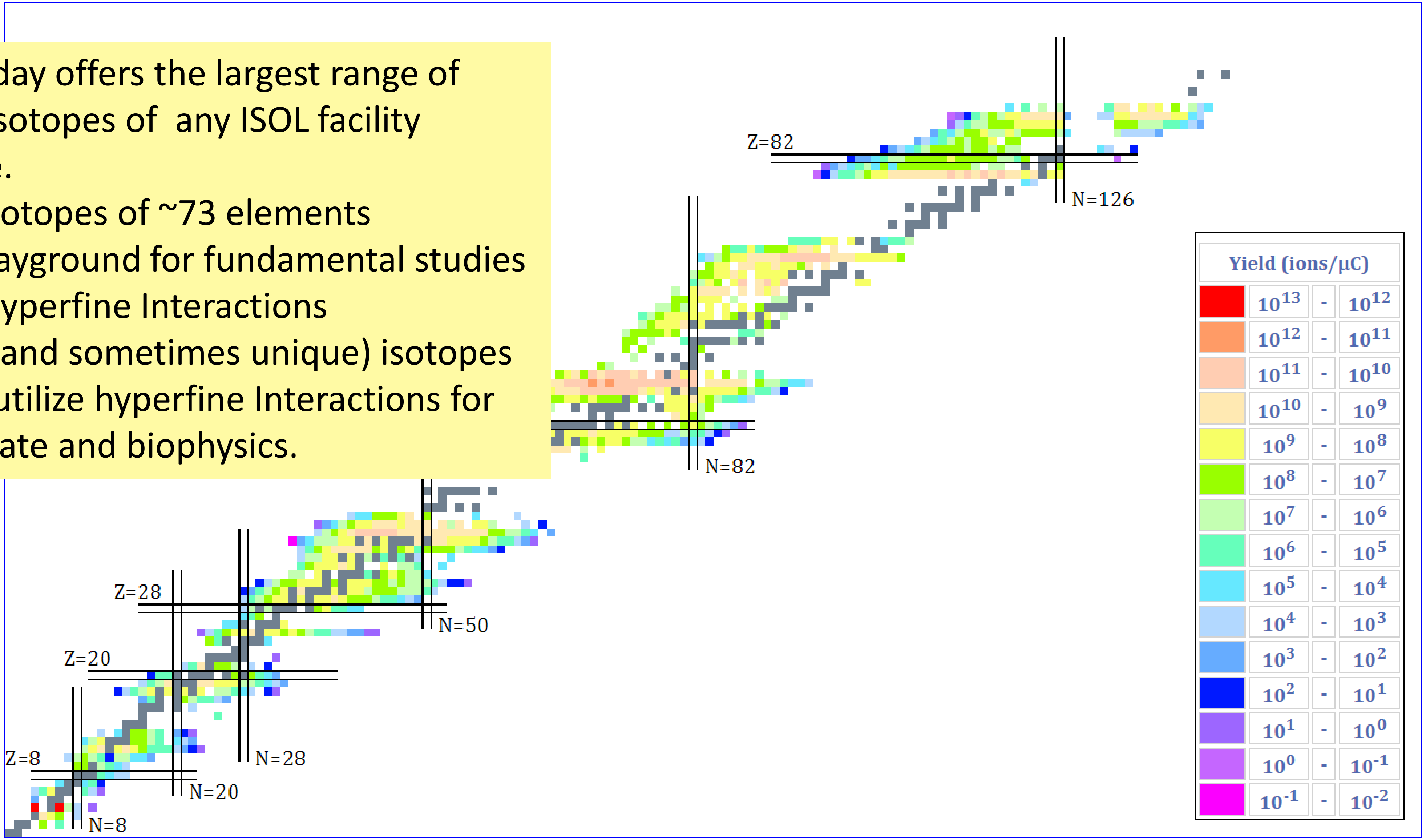
ISOLDE Robots

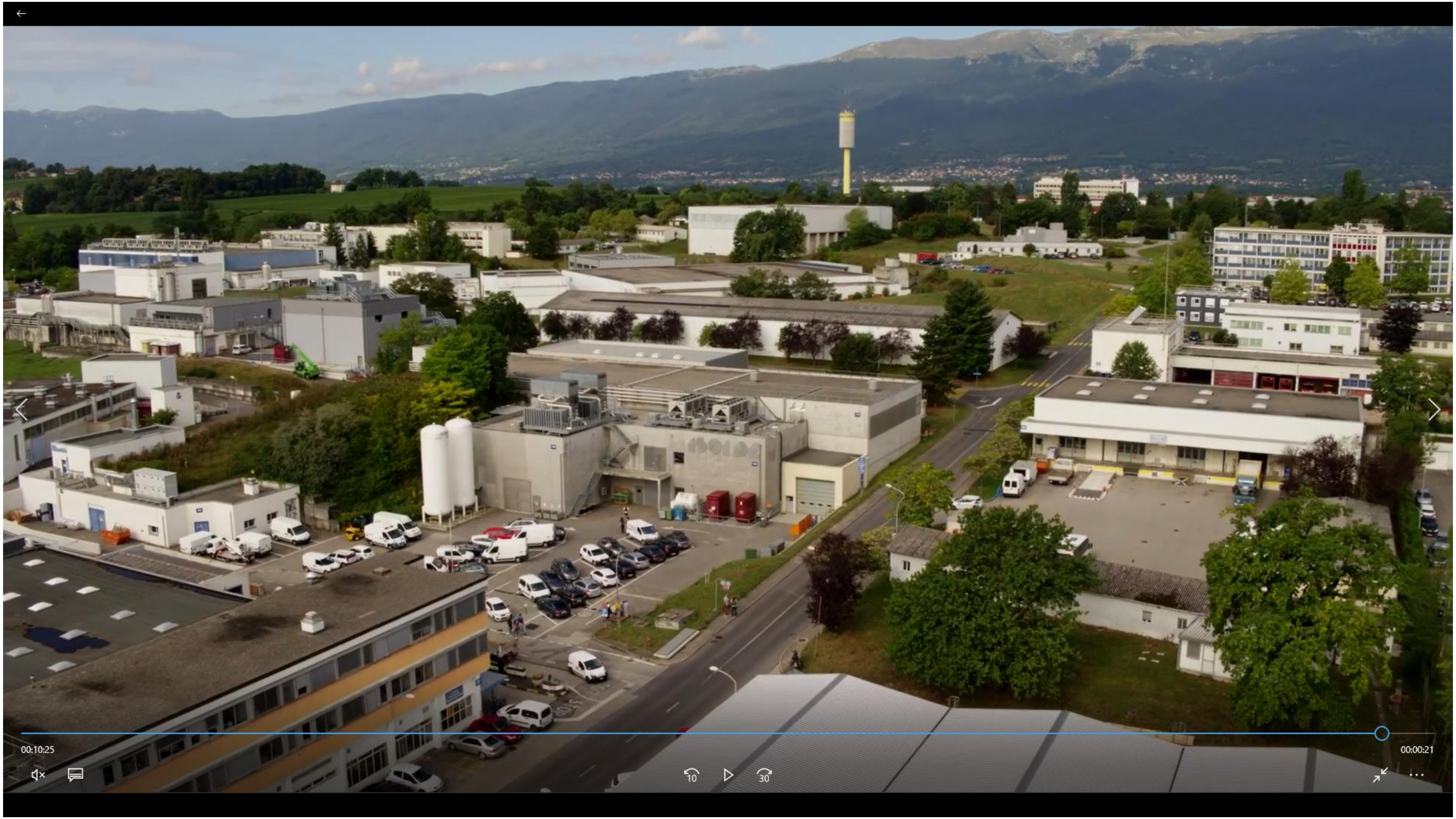


Nuclear chart for ISOLDE

ISOLDE today offers the largest range of available isotopes of any ISOL facility worldwide.

- 1200 isotopes of ~73 elements
- Rich playground for fundamental studies using hyperfine Interactions
- Novel (and sometimes unique) isotopes which utilize hyperfine Interactions for solid state and biophysics.

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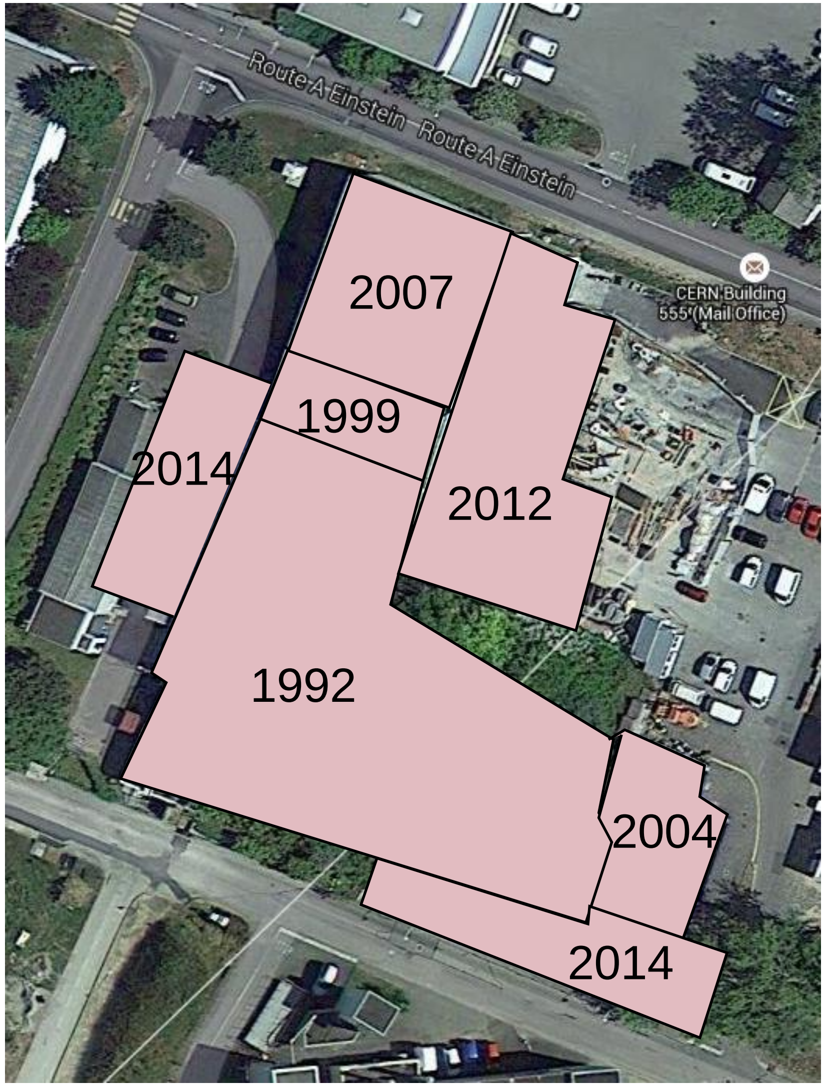
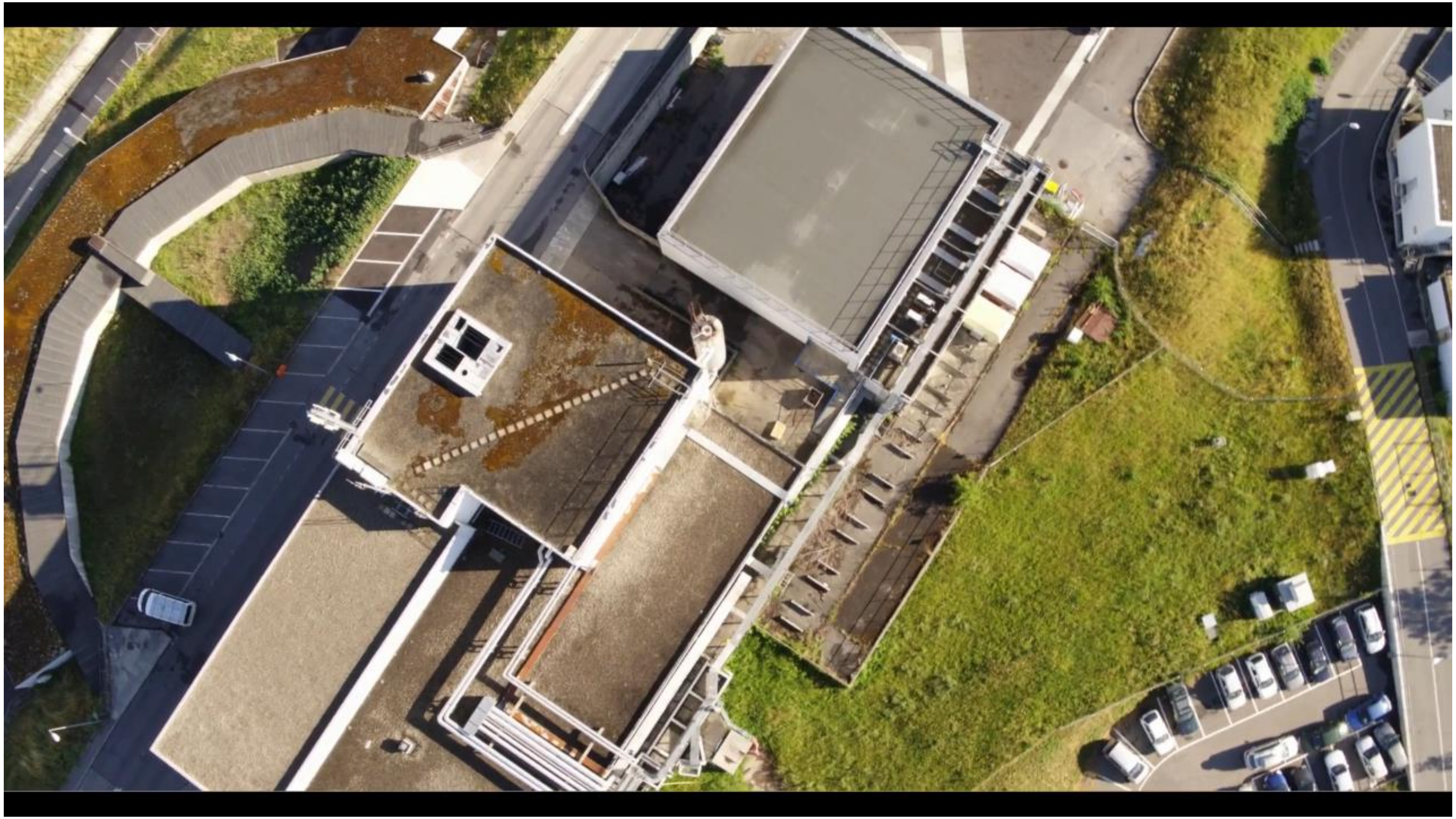
00:00:21
10
30



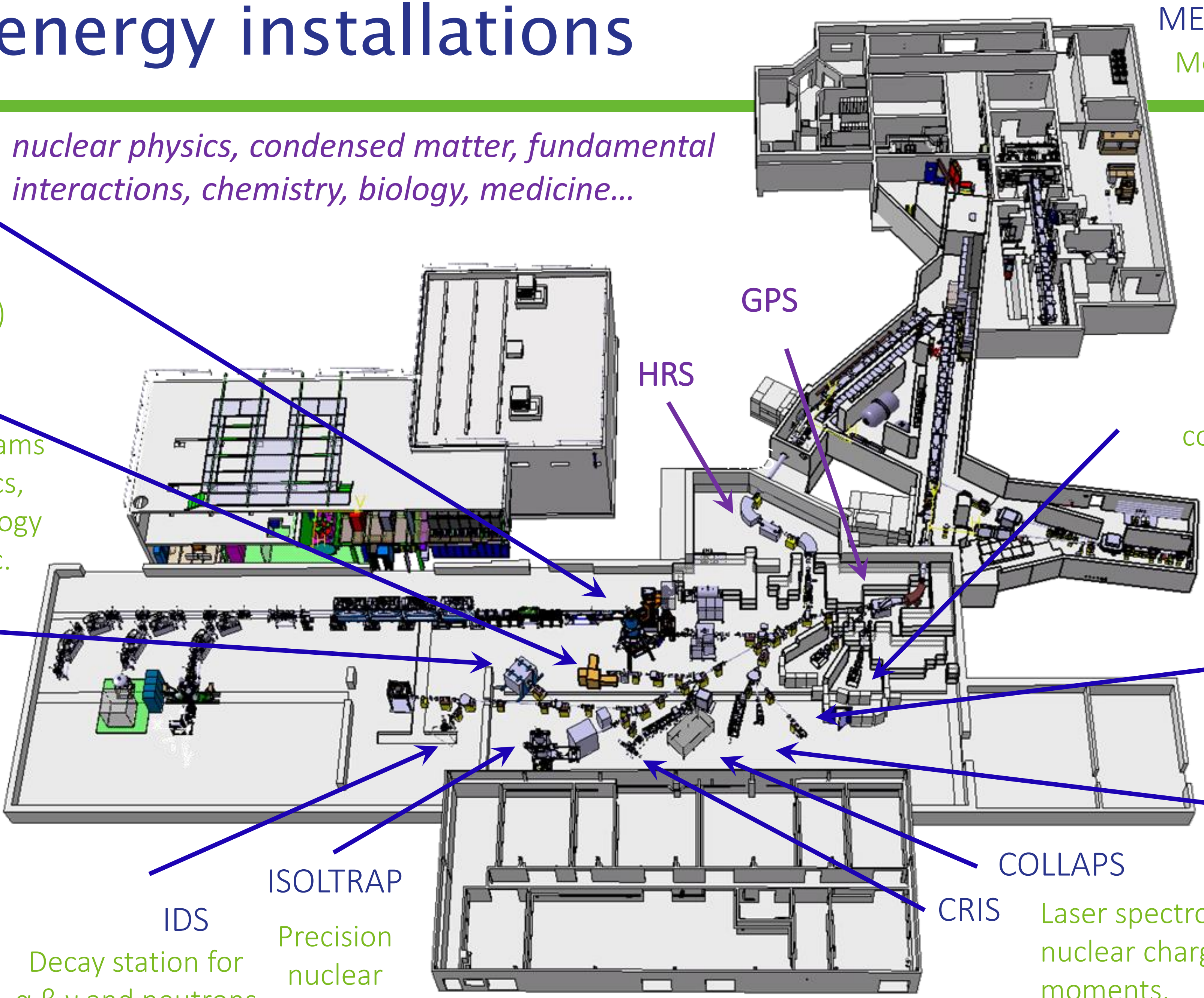
User and Operations facility building

Groundbreaking MEDICIS building



Low-energy installations

nuclear physics, condensed matter, fundamental interactions, chemistry, biology, medicine…



WISArD

Scalar and tensor currents in weak interactions: $\beta\nu(\theta)$

VITO

Laser-polarised beams for nuclear physics, chemistry and biology using β-NMR etc.

TAS

Total absorption spectrometer for β-decay feeding

IDS

Decay station for α,β,γ and neutrons

ISOLTRAP

Precision nuclear masses

CRIS

COLLAPS

MIRACLS
MR-TOF

Laser spectroscopy: nuclear charge radii and moments.

Travelling setups

Condensed-matter physics

Emission channeling, perturbed angular correlations, Mössbauer, isotope collections….

MEDICIS

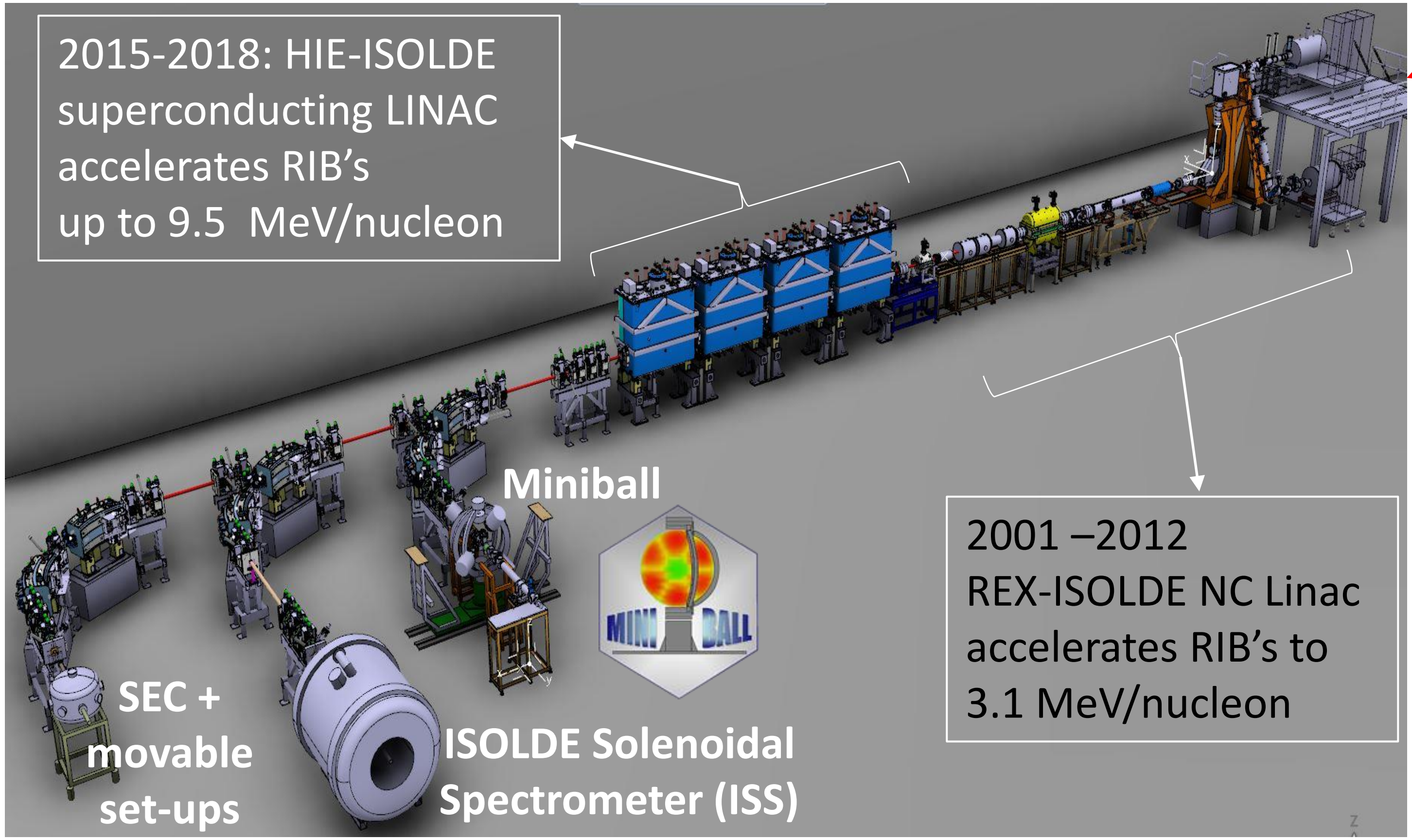
Medical isotopes research

High-energy installations

An accelerator of Radioactive Ion Beams (RIB’s)

Now 3 experimental set-ups available

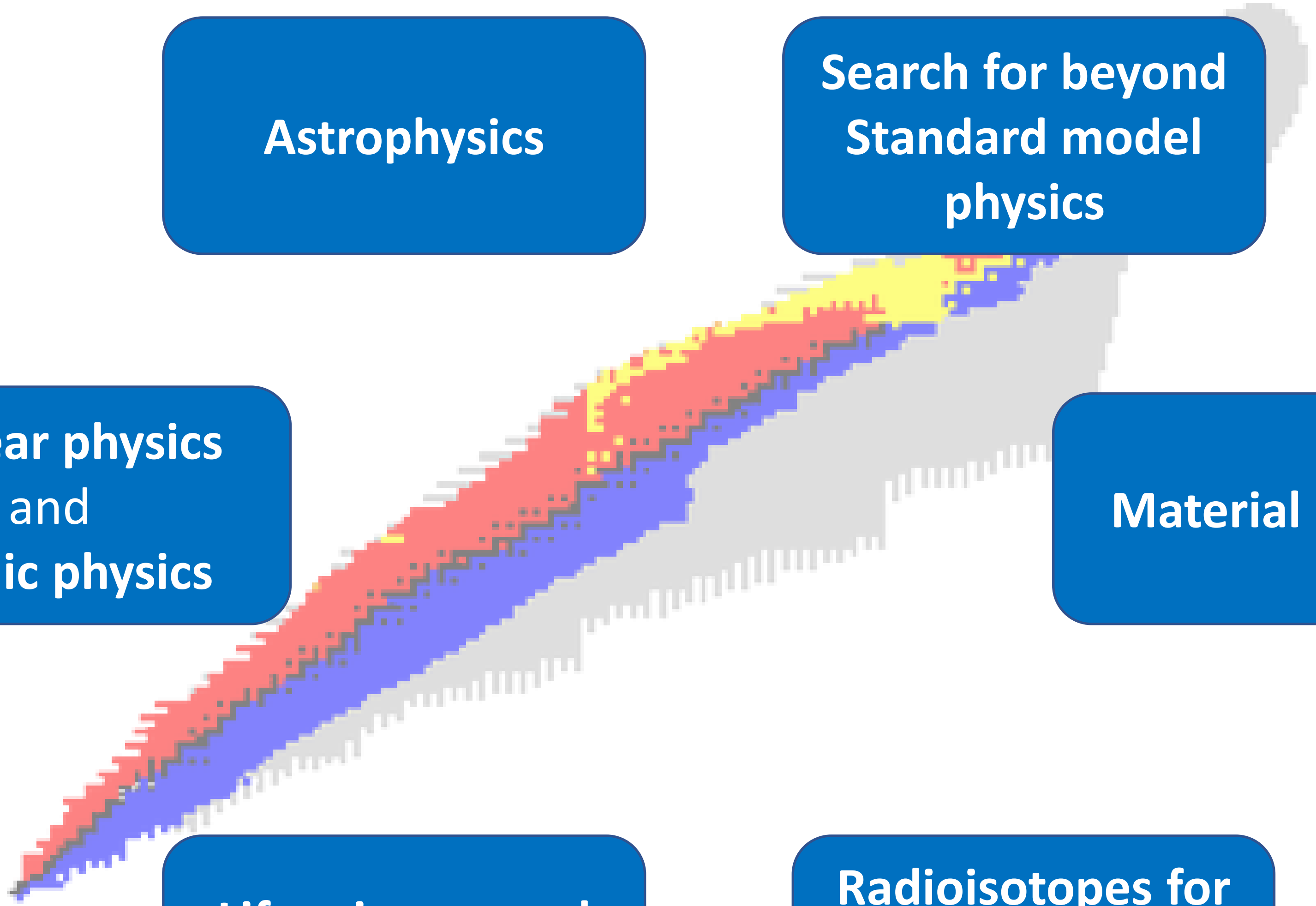
40-60 keV
RIB from ISOLDE



2015-2018: HIE-ISOLDE
superconducting LINAC
accelerates RIB’s
up to 9.5 MeV/nucleon

2001 –2012
REX-ISOLDE NC Linac
accelerates RIB’s to
3.1 MeV/nucleon

Research with radioactive beams at ISOLDE



Astrophysics

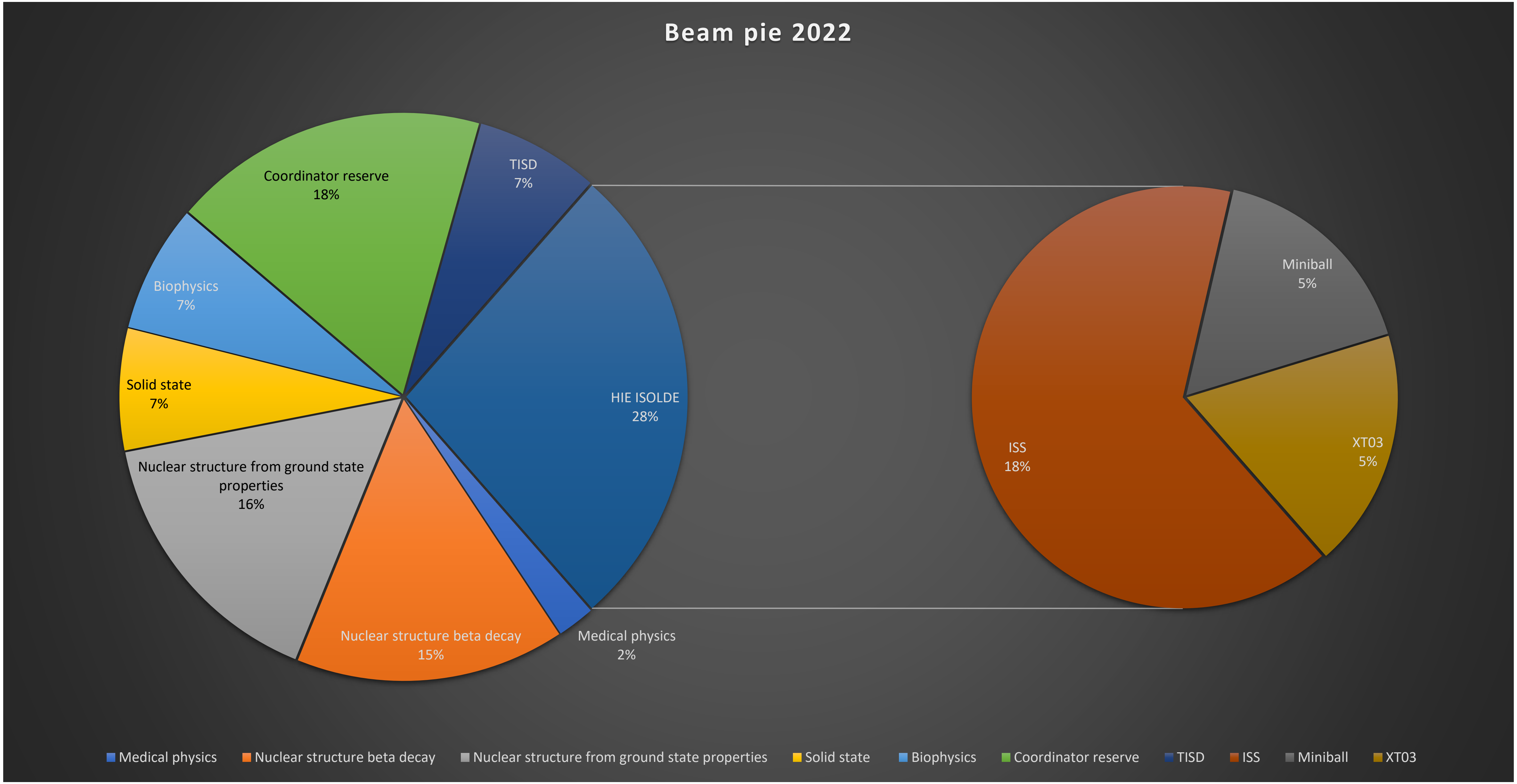
Search for beyond Standard model physics

Nuclear physics and atomic physics

Material science

Life sciences and biophysics

Radioisotopes for medical applications


Beam pie 2022
Coordinator reserve
18%
TISD
7%
Biophysics
7%
Solid state
7%
HIE ISOLDE
28%
Nuclear structure from ground state properties
16%
Nuclear structure beta decay
15%
Medical physics
2%
Miniball
5%
ISS
18%
XT03
5%
Medical physics
Nuclear structure beta decay
Nuclear structure from ground state properties
Solid state
Biophysics
Coordinator reserve
TISD
ISS
Miniball
XT03

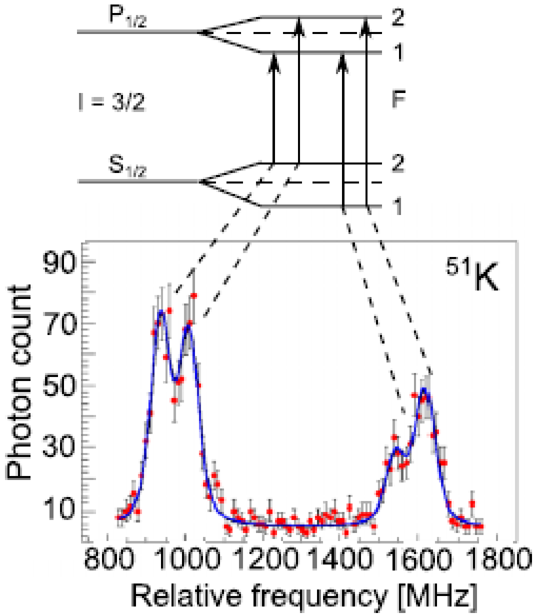
Laser spectroscopy and nuclear properties

Lasers allow studying **ground-state (and isomeric) properties of nuclei,** based on:

Atomic **hyperfine structure (HFS)**

(interaction of nuclear and atomic spins)

- HFS details depend on:
  - Spin -> orbit of last proton&neutron
  - Magnetic dipole moment -> orbits occupied by protons&neutrons
  - Electric quadrupole moment -> deformations

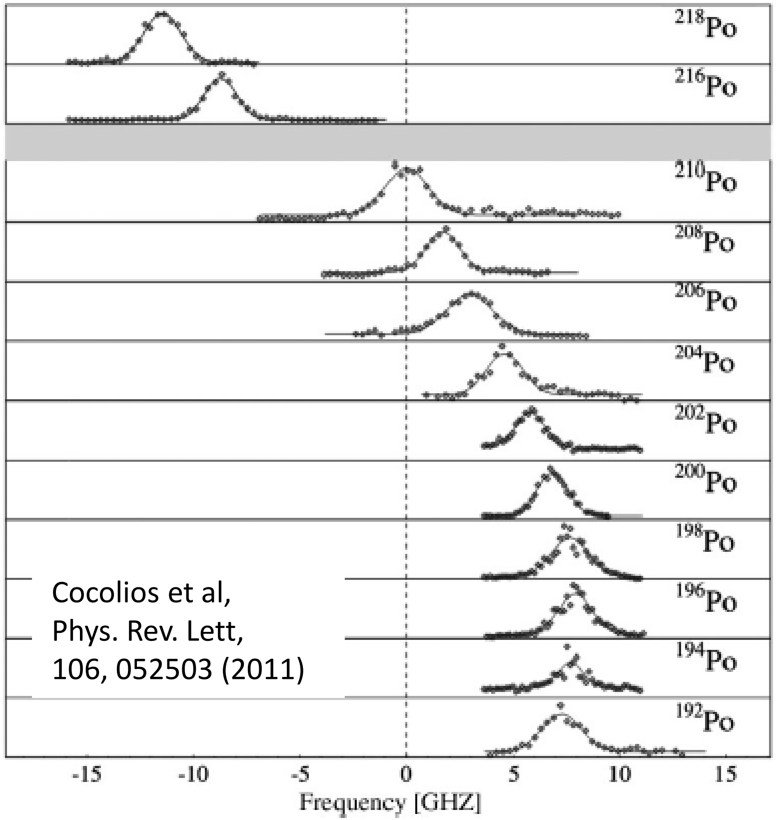


Yordanov et al,
Phys. Rev. Lett.,
110, 172503 (2013)

Isotope shifts (IS) in atomic transitions

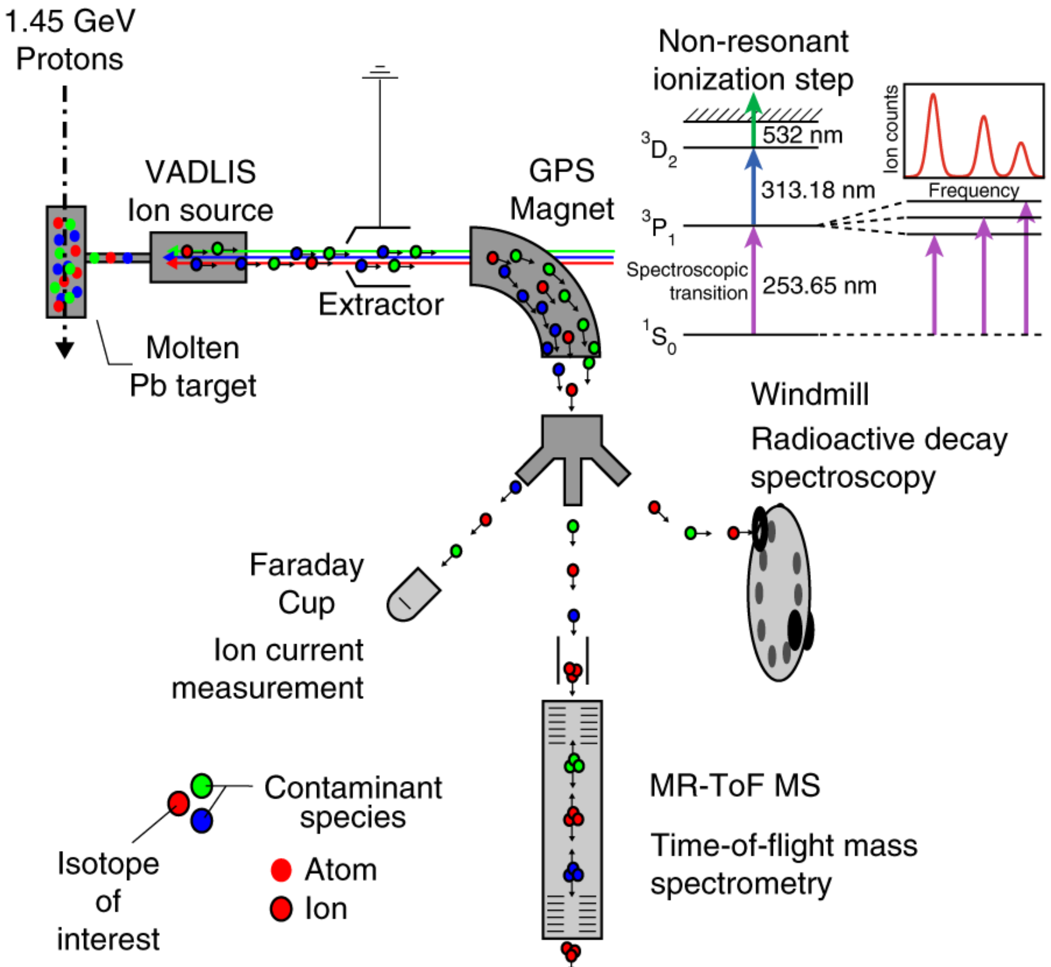
(change in mass and size of different isotopes of the same chemical element)

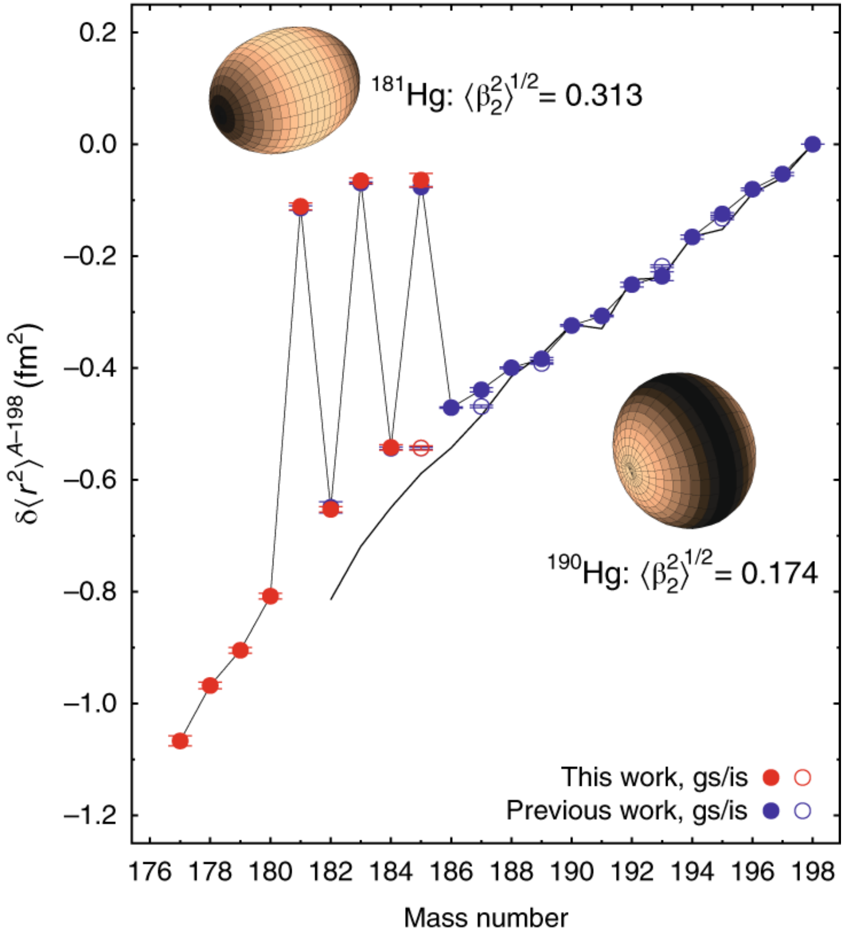
- IS between 2 isotopes depends on:
  - difference in their masses & charge radii

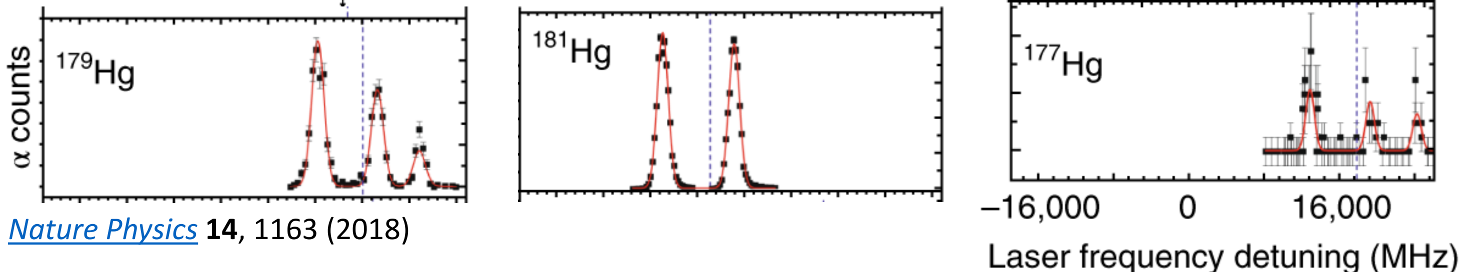


Cocolios et al,
Phys. Rev. Lett,
106, 052503 (2011)

Shape staggering of mercury isotopes with RILIS



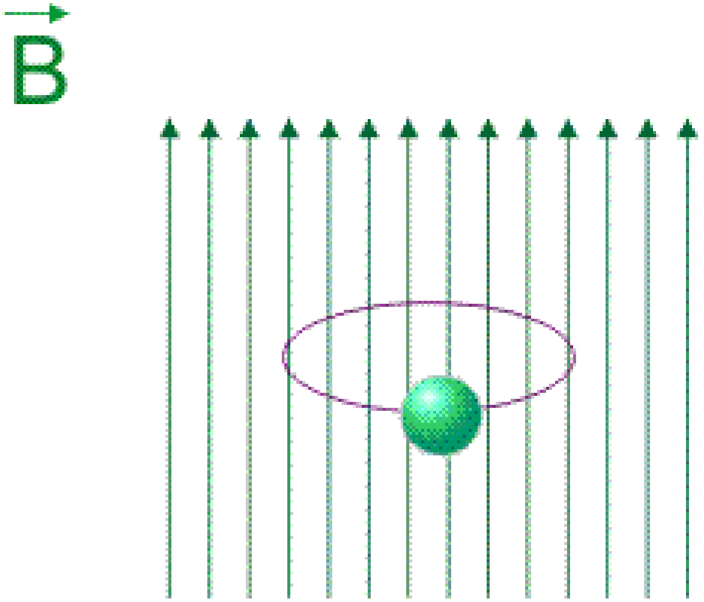




Nature Physics **14**, 1163 (2018)

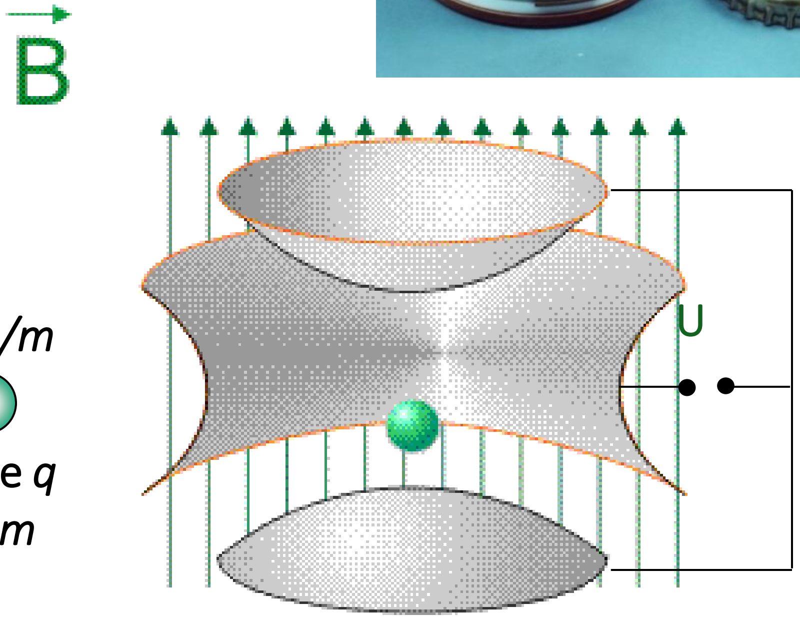
Penning-trap mass spectrometry

- Penning trap
  - superposition of static magnetic and electric field
  - Ion manipulation with radiofrequencies



Ion q/m

Charge q
Mass m

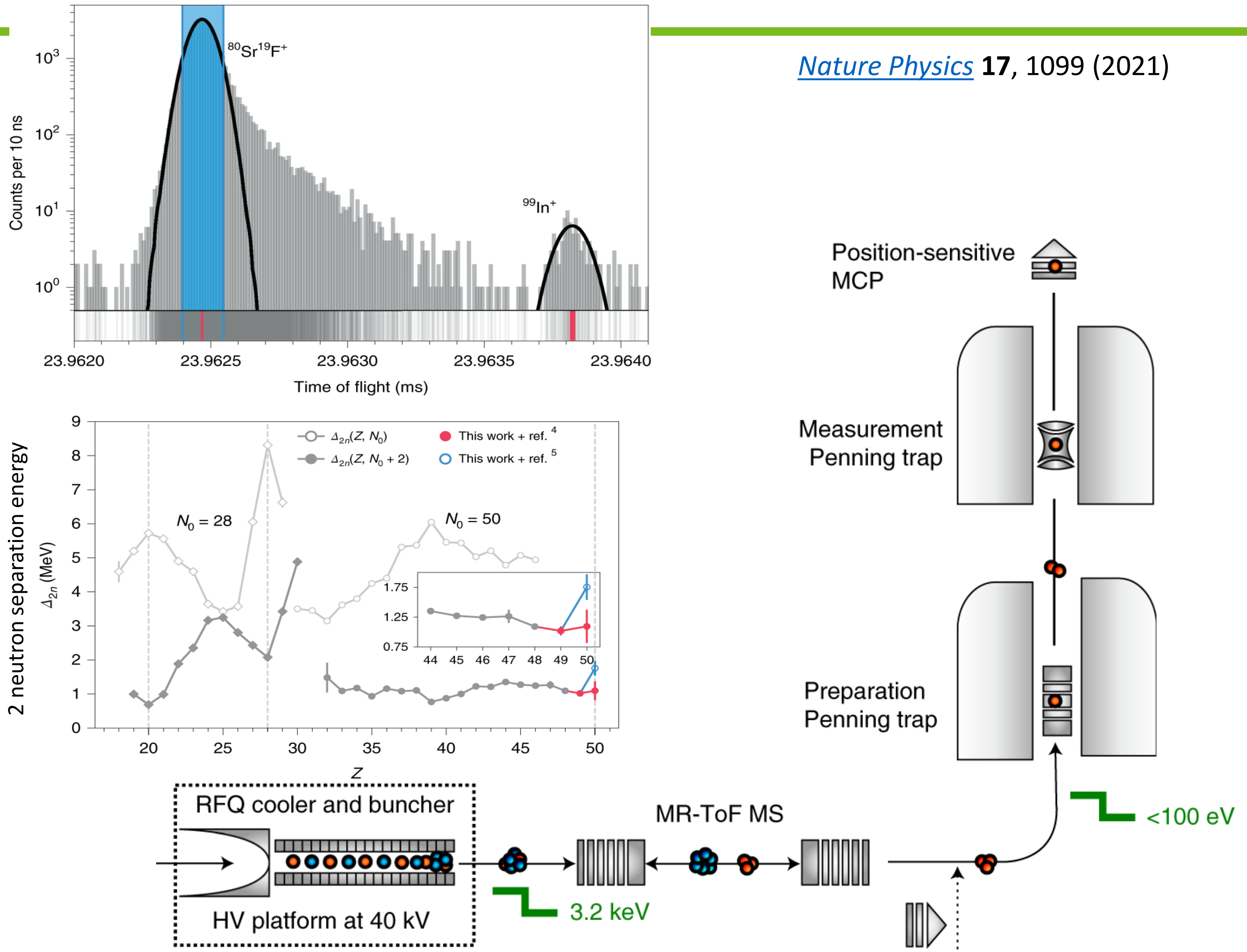


Free cyclotron frequency is inversely proportional to the mass of the ions!

$$\omega_c = qB/m$$

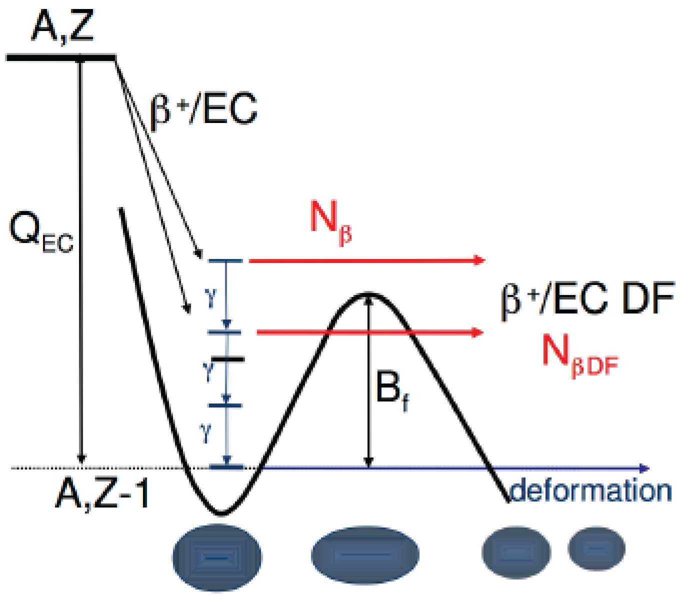
Masses around ^{100}Sn with ISOLTRAP

Nature Physics **17**, 1099 (2021)

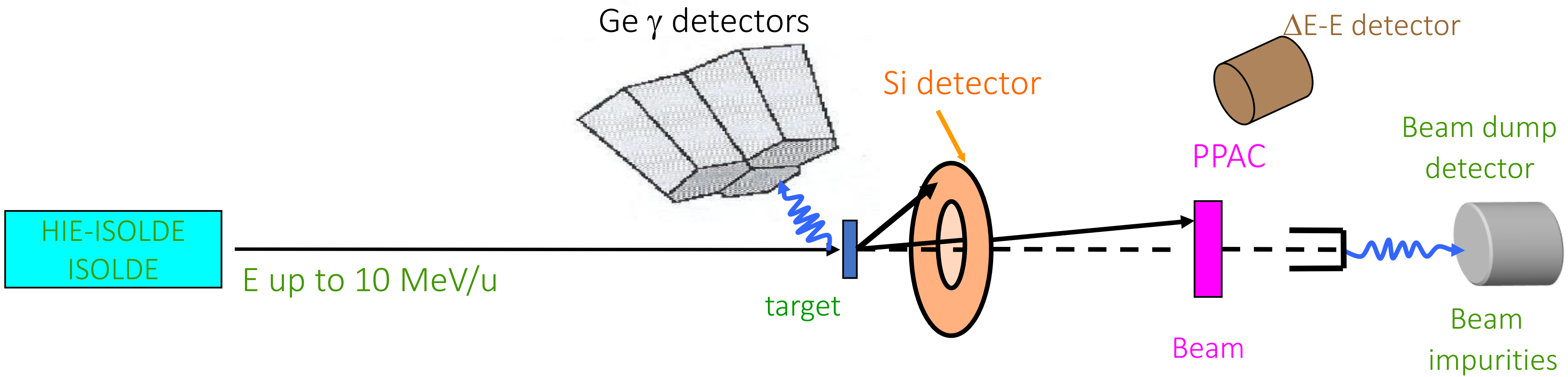


Decay spectroscopy

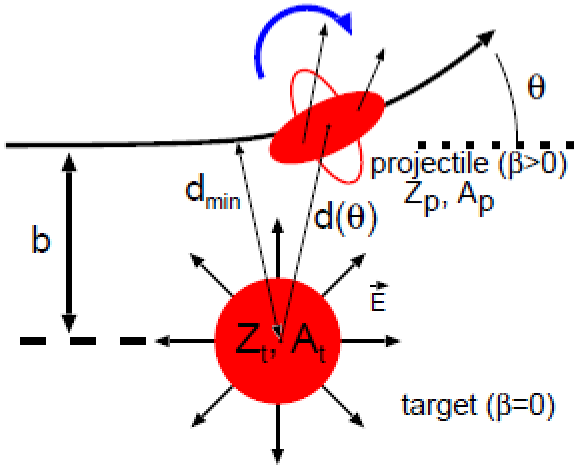
- Different detectors to sensitive to emitted:
  - Alpha particles
  - Beta particles
  - Gamma rays
  - Protons or neutrons
- Isolde Decay Station
- soon: polarised beams at VITO

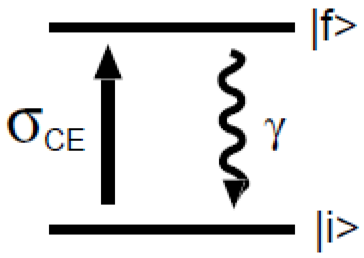


Coulomb excitation



Excitation of a projectile nucleus (radioactive) by the electromagnetic field of the target (made of stable nuclei)

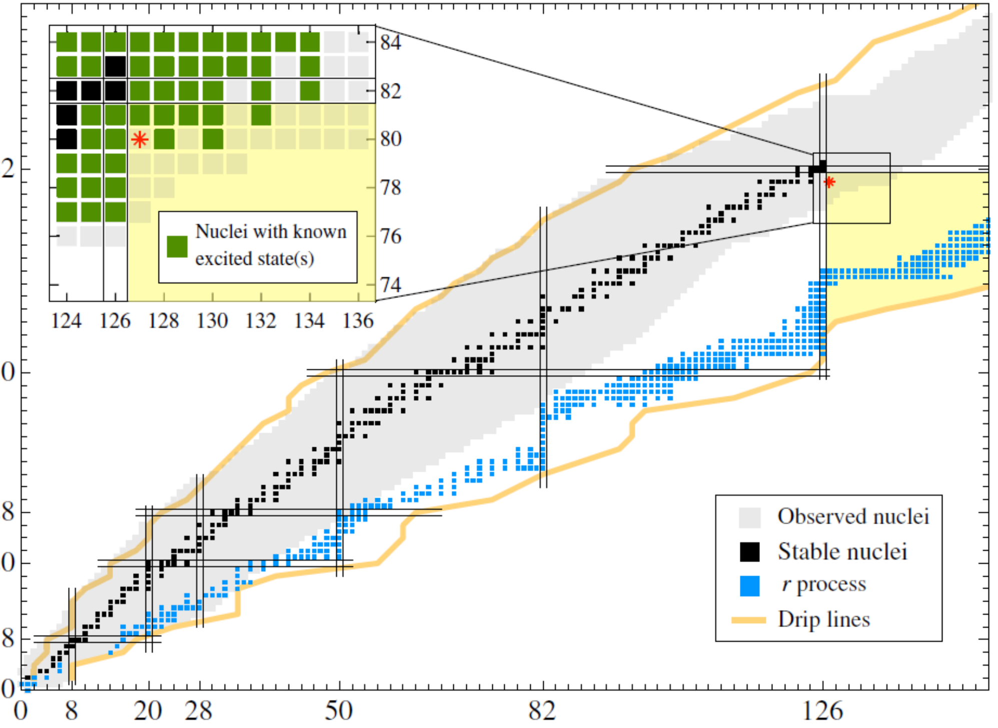




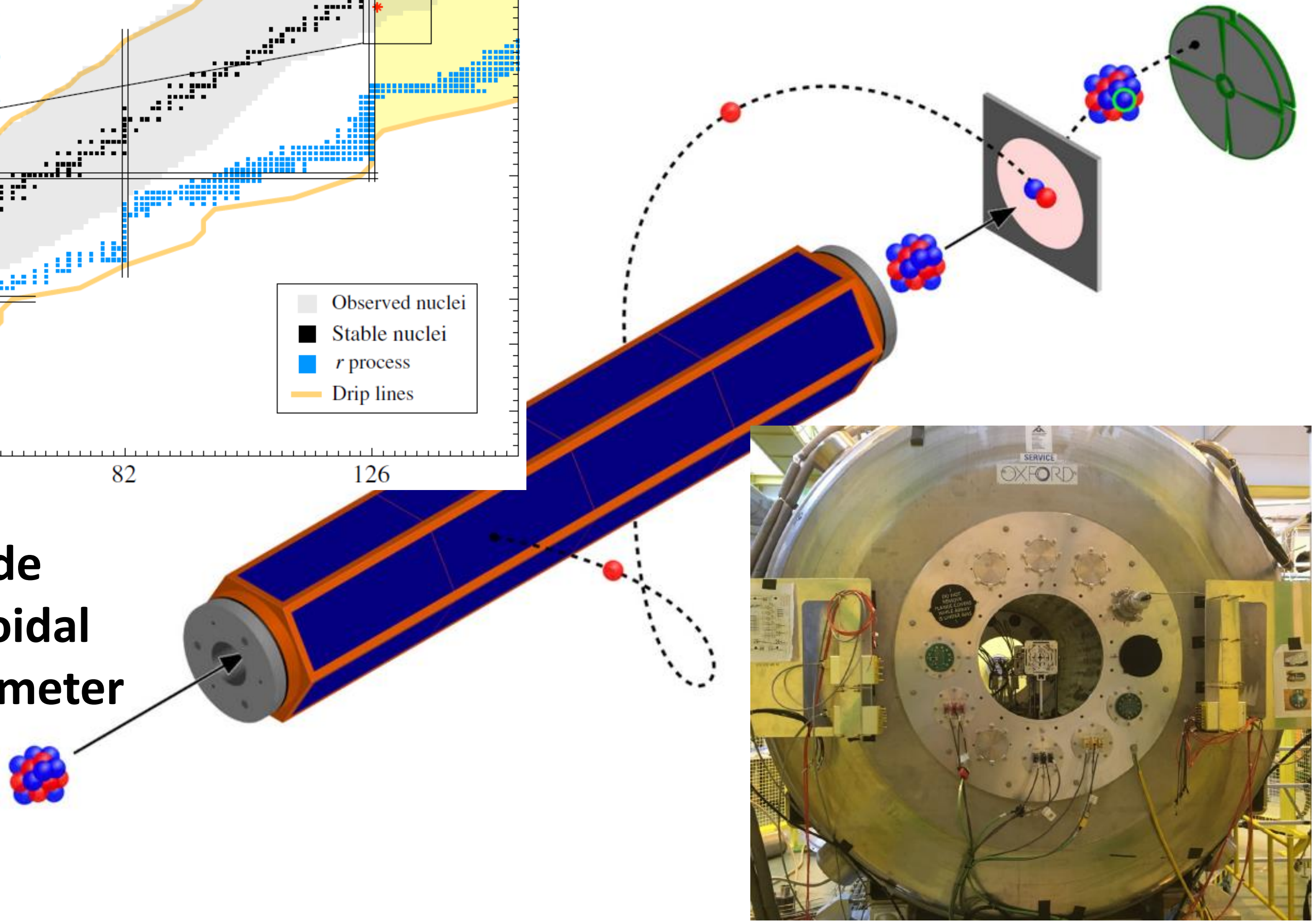
Observables: Transition energies and intensities

=> Determine new excited levels and study deformations

Nuclear astrophysics at HIE-ISOLDE



neutron excitations in ^{207}Hg by neutron-adding (d,p) reaction in inverse kinematics

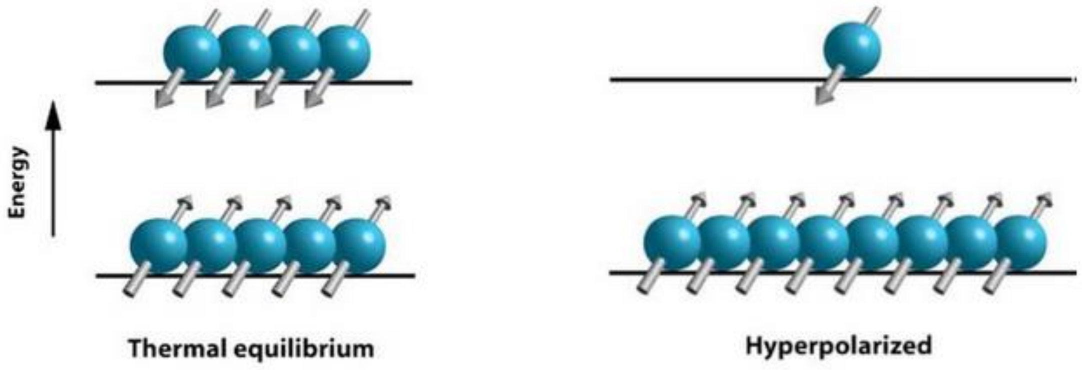


Isolde Solenoidal Spectrometer

Beta-NMR in organic samples

Unstable probe nuclei with spin > 0 in magnetic field

Spin hyperpolarisation

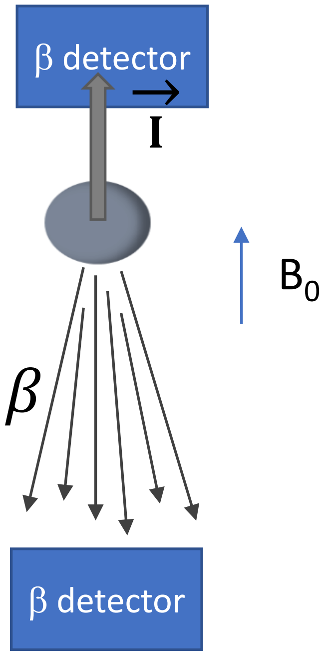


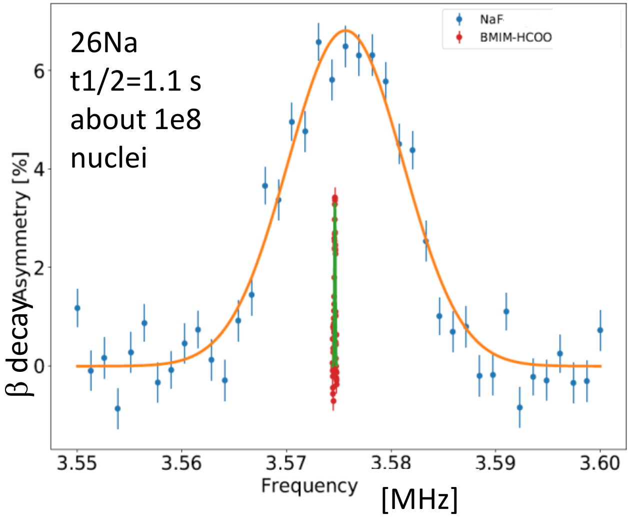
$P \approx 10^{-5} = \frac{1}{100{,}000}$ at 3T

$P \approx 50\% = \frac{50{,}000}{100{,}000}$

+ beta decay anisotropy

Beta decay, I>0





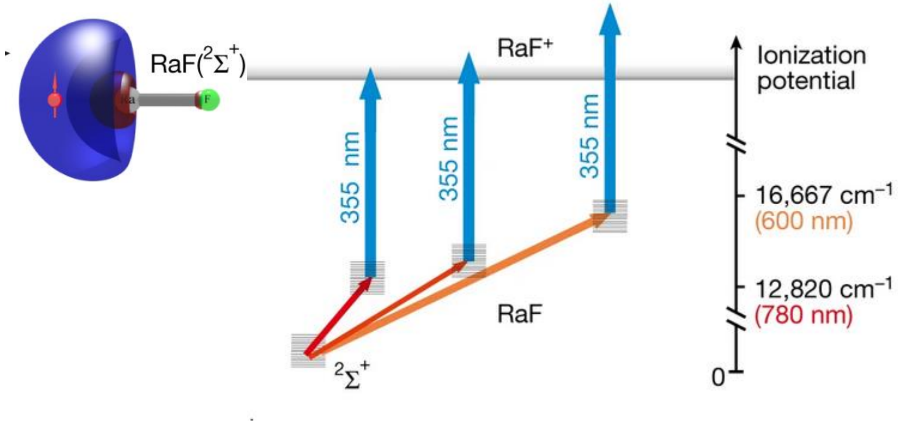
Up to 10 orders of magnitude more sensitive than conventional NMR,

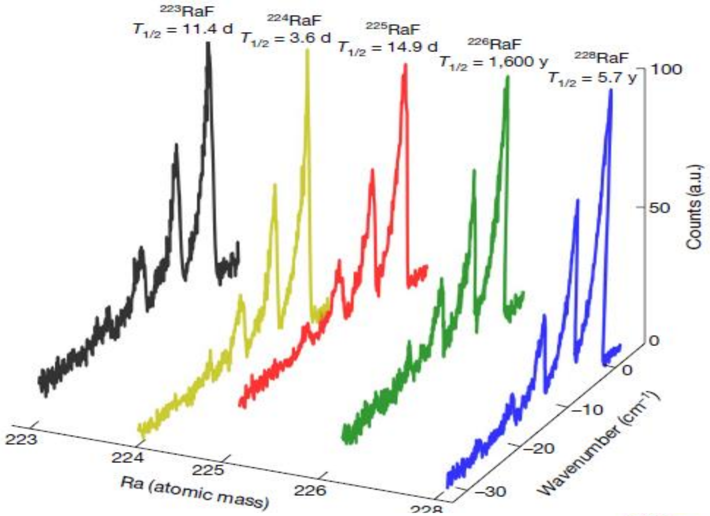
100 x more precise than solid state NMR

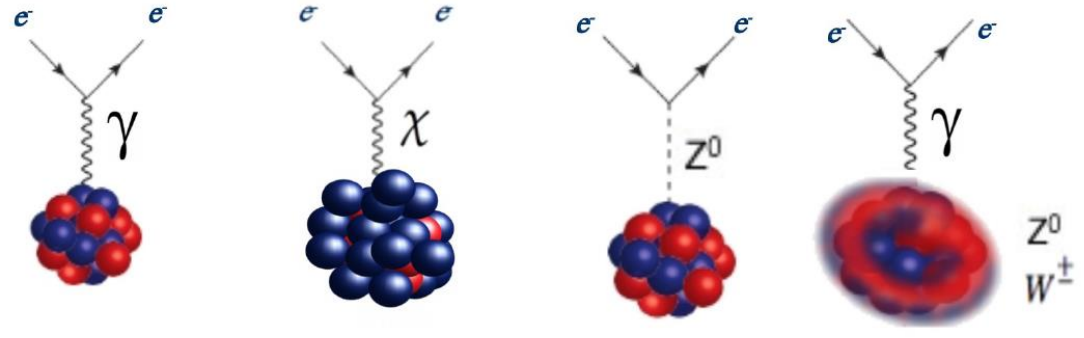
Phys. Rev. X 10, 041061 (2020)

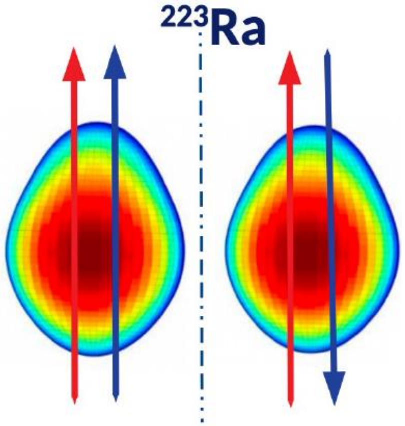
Applications in biology (metal ion interactions)
And nuclear physics: distribution of magnetisation

Radioactive molecules & Beyond SM









Low-energy SM tests

New e-N interactions?

P-violation

T-violation

- Nuclear matter
- Nuclear structure
- BSM searches

- Dark Matter properties?
- New forces?

- Baryogenesis

Nature 581, 396 (2020)

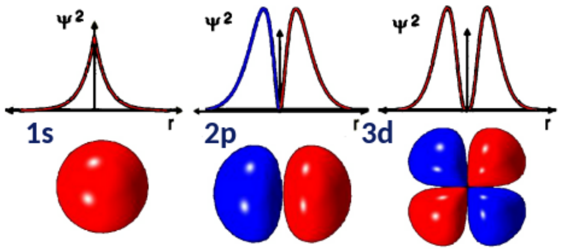
From M. Udrescu

Why Molecules?

→ New windows into the study of the atomic nucleus, and the fundamental particles and interactions of nature!

Atoms

Molecules



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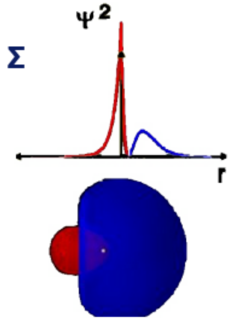
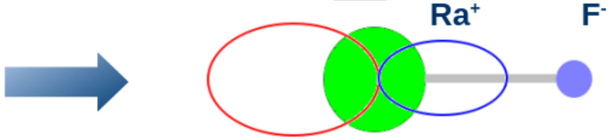
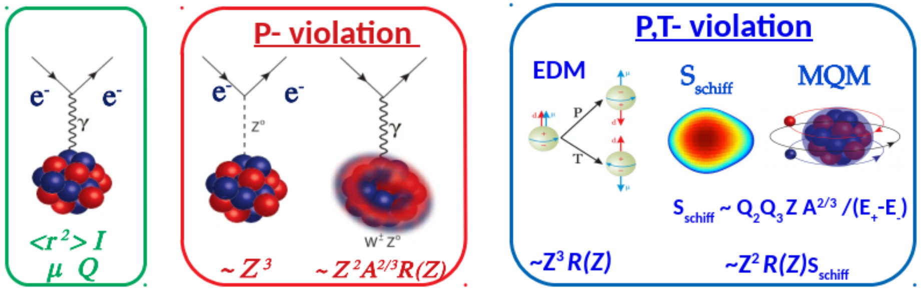




- Parity violation > 10^{10}
- Parity and Time reversal violation > 10^{3}

[ACME, Nature 562, 355 (2018)]

Why Molecules?



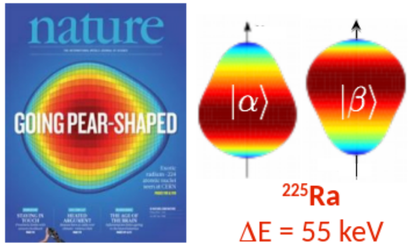
Molecules → x 10^{N} >10^{5} > 10^{3} (x 10^{5})

Exotic nuclei → Nuclear amplification (>10^{3})

→ Large Z, A

→ Max. Q_2Q_3

→ Min. (E_+-E_-)



[Gaffney et al. Nature 497, 199 (2013)]

Exotic molecules → Best of all worlds

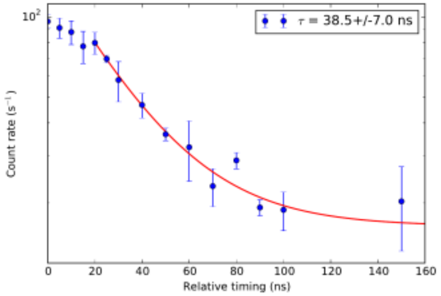
... BUT, are experimentally unknown!

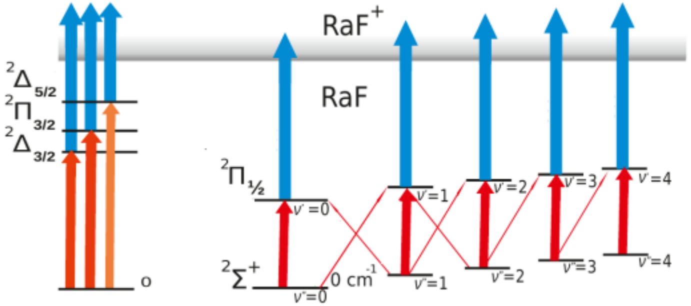
Recent results

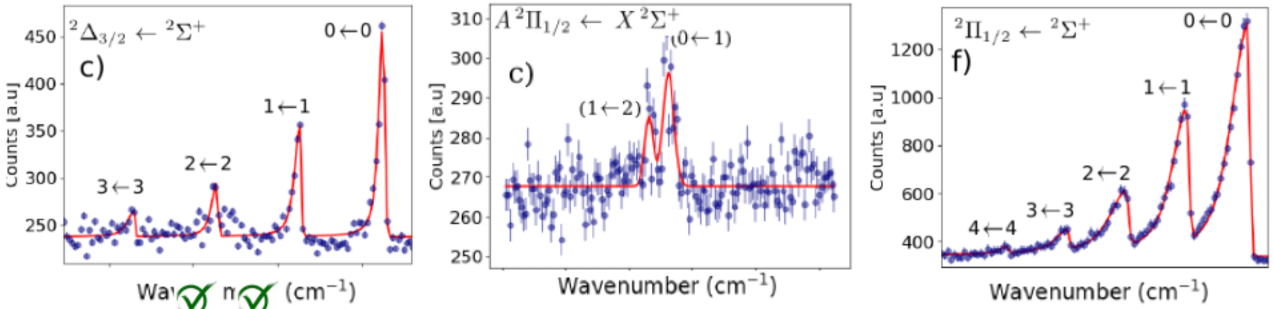
I. Low-lying structure ✓

II. Feasibility of laser cooling?

1. Dominant f_{00}? → $f_{00}/f_{ij} > 0.97$ ✓
2. Short-lived excited state ($T_{1/2}$)? → $T_{1/2} < 50$ ns ✓
3. Electronic states of lower energy (E)? → 2000 cm^{-1} above ✓







✓ ✓

$H_{mol} = H_e + H_{vib} + H_{rot} + H_{sr} + H_{hfs} + H_{PV} + H_{PTV}$

[Garcia Ruiz et al. Nature 581, 396 (2020)]

"Hot" molecules can be super cool!

nature

Article | Open Access | Published: 27 May 2020

Spectroscopy of short-lived radioactive molecules

R. F. Garcia Ruiz, R. Berger, […] X. F. Yang

Nature **581**, 396–400(2020) | Cite this article

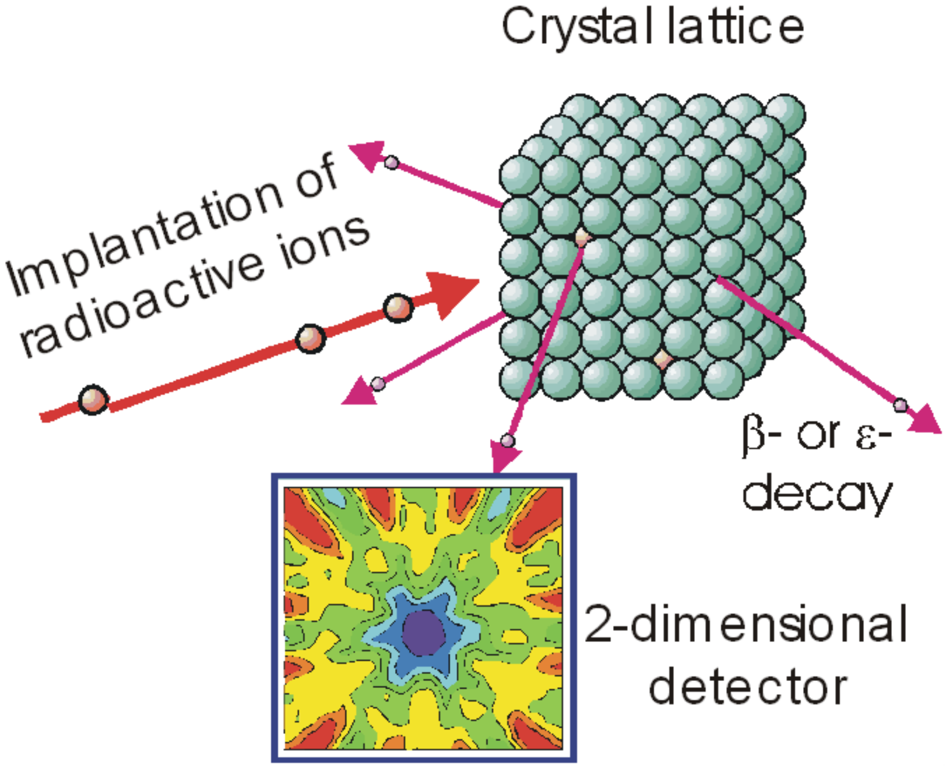
8120 Accesses | **145** Altmetric | Metrics

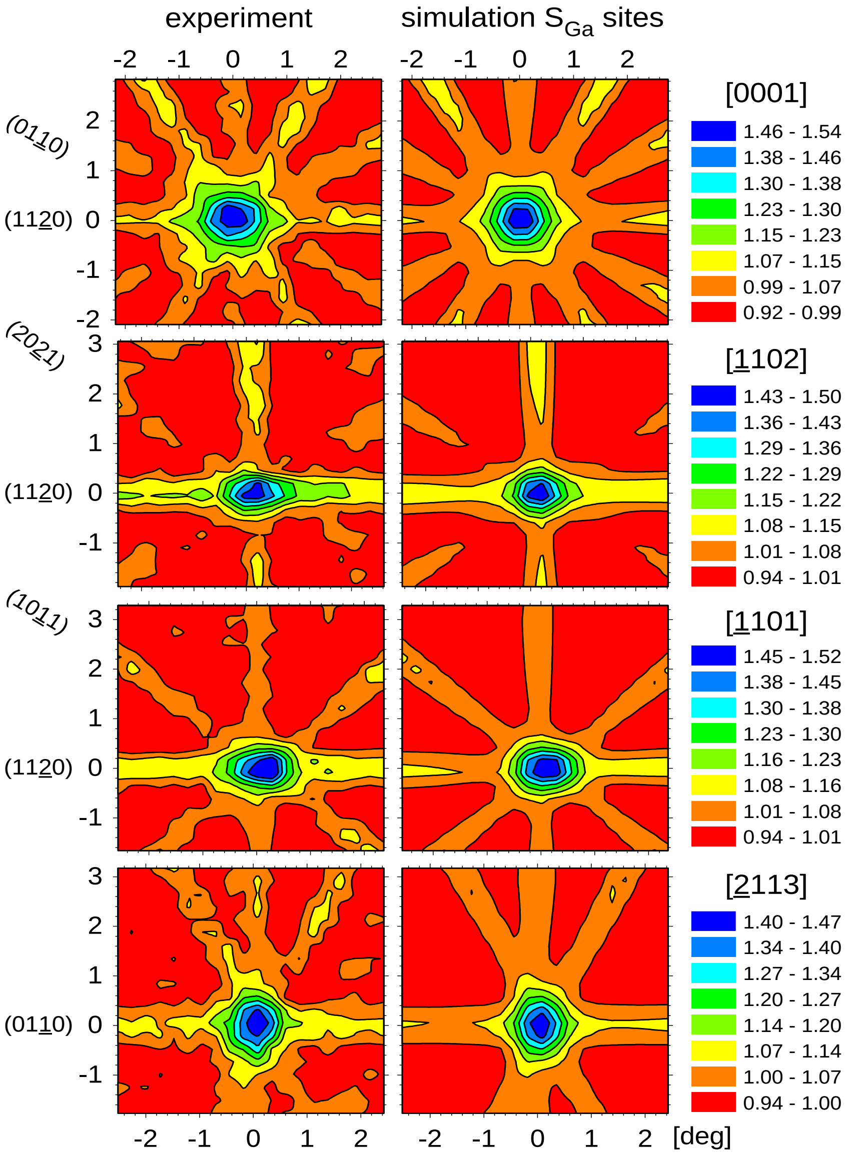
✓ ✓

$H_{mol} = H_e + H_{vib} + H_{rot} + H_{sr} + H_{hfs} + H_{PV} + H_{PTV}$

Material science

- Emission channeling
  - ➢ Position of implanted ions

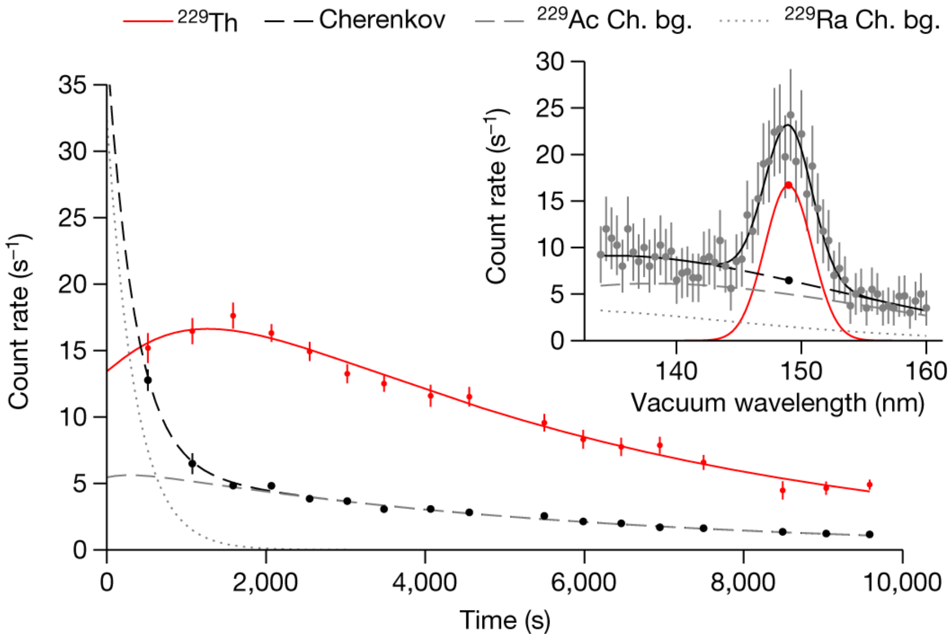


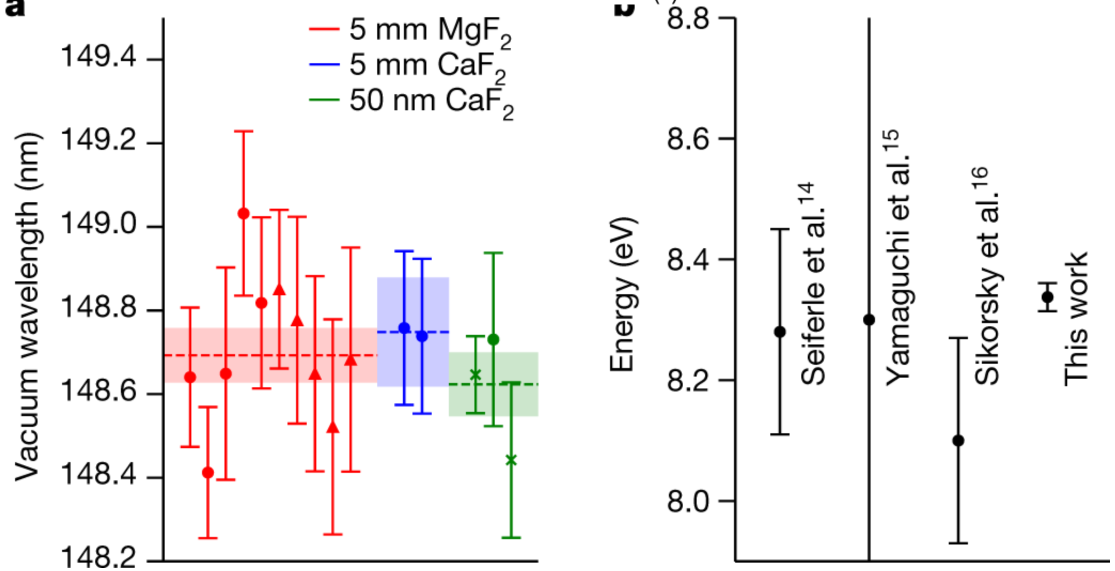


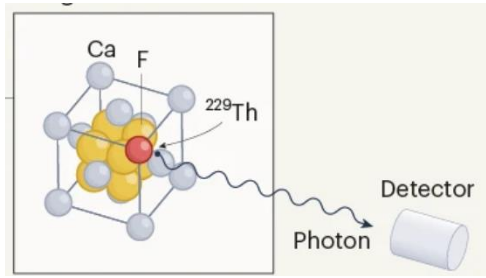
Emission channelling pattern

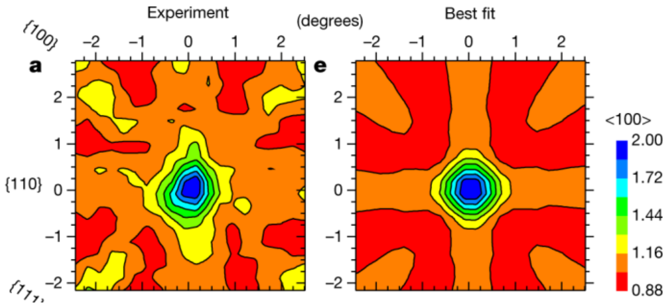
^{229m}Th: towards a nuclear clock with VUV and EC

- Determination of isomer energy with vacuum UV spectroscopy:
  - 229Ac decay to 229mTh
  - Internal conversion decay branch removed via study in a crystal
  - CaF as host (wide band gap material)
  - Implantation site verified with emission channeling



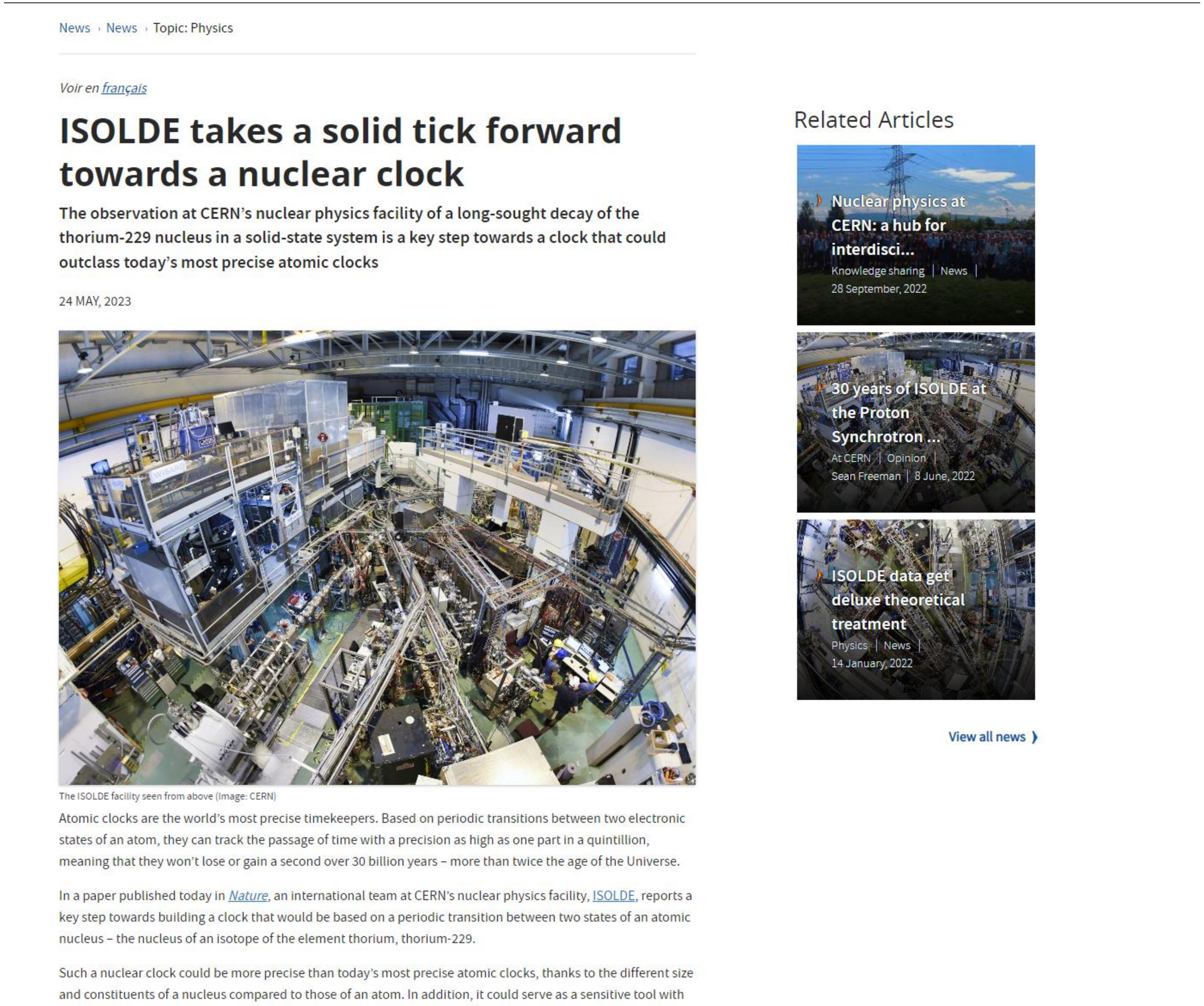






S Kraemer et al, *Nature* **617**, 706 (2023)

Video: https://videos.cern.ch/record/2297990



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Voir en français

ISOLDE takes a solid tick forward towards a nuclear clock

The observation at CERN's nuclear physics facility of a long-sought decay of the thorium-229 nucleus in a solid-state system is a key step towards a clock that could outclass today's most precise atomic clocks

24 MAY, 2023

The ISOLDE facility seen from above (Image: CERN)

Atomic clocks are the world's most precise timekeepers. Based on periodic transitions between two electronic states of an atom, they can track the passage of time with a precision as high as one part in a quintillion, meaning that they won't lose or gain a second over 30 billion years – more than twice the age of the Universe.

In a paper published today in *Nature*, an international team at CERN's nuclear physics facility, ISOLDE, reports a key step towards building a clock that would be based on a periodic transition between two states of an atomic nucleus – the nucleus of an isotope of the element thorium, thorium-229.

Such a nuclear clock could be more precise than today's most precise atomic clocks, thanks to the different size and constituents of a nucleus compared to those of an atom. In addition, it could serve as a sensitive tool with

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Article

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

https://doi.org/10.1038/s41586-023-05894-z

Received: 20 September 2022

Accepted: 28 February 2023

Published online: 24 May 2023

Check for updates

Sandro Kraemer[1,2,✉], Janni Moens[3], Michail Athanasakis-Kaklamanakis[1,4], Silvia Bara[1], Kjeld Beeks[5], Premaditya Chhetri[1], Katerina Chrysalidis[4], Arno Claessens[1], Thomas E. Cocolios[1], João G. M. Correia[6], Hilde De Witte[1], Rafael Ferrer[1], Sarina Geldhof[1], Reinhard Heinke[4], Niyusha Hosseini[5], Mark Huyse[1], Ulli Köster[7], Yuri Kudryavtsev[1], Mustapha Laatiaoui[8,9,10], Razvan Lica[4,11], Goele Magchiels[3], Vladimir Manea[1], Clement Merckling[12], Lino M. C. Pereira[3], Sebastian Raeder[9,10], Thorsten Schumm[5], Simon Sels[1], Peter G. Thirolf[2], Shandirai Malven Tunhuma[3], Paul Van Den Bergh[1], Piet Van Duppen[1], André Vantomme[3], Matthias Verlinde[1], Renan Villarreal[3] & Ulrich Wahl[6]

The radionuclide thorium-229 features an isomer with an exceptionally low excitation energy that enables direct laser manipulation of nuclear states. It constitutes one of the leading candidates for use in next-generation optical clocks[1–3]. This nuclear clock will be a unique tool for precise tests of fundamental physics[4–9]. Whereas indirect experimental evidence for the existence of such an extraordinary nuclear state is substantially older[10], the proof of existence has been delivered only recently by observing the isomer's electron conversion decay[11]. The isomer's excitation energy, nuclear spin and electromagnetic moments, the electron conversion lifetime and a refined energy of the isomer have been measured[12–16]. In spite of recent progress, the isomer's radiative decay, a key ingredient for the development of a nuclear clock, remained unobserved. Here, we report the detection of the radiative decay of this low-energy isomer in thorium-229 (^{229m}Th). By performing vacuum-ultraviolet spectroscopy of ^{229m}Th incorporated into large-bandgap CaF_2 and MgF_2 crystals at the ISOLDE facility at CERN, photons of 8.338(24) eV are measured, in agreement with recent measurements[14–16] and the uncertainty is decreased by a factor of seven. The half-life of ^{229m}Th embedded in MgF_2 is determined to be 670(102) s. The observation of the radiative decay in a large-bandgap crystal has important consequences for the design of a future nuclear clock and the improved uncertainty of the energy eases the search for direct laser excitation of the atomic nucleus.

The ^{229}Th isotope and its low-energy isomer have inspired research for decades and the prospect of developing an optical clock using a nuclear transition has intensified efforts[5]. A particular focus lies on the precise measurement of properties relevant for an optical clock involving the direct laser manipulation of nuclear states[17]. Values of the isomer's excitation energy reported in the literature have changed substantially over time[18]. Recent measurements using conversion-electron spectroscopy of electrically neutral thorium-229 atoms ($^{229}Th^0$) resulted in an excitation energy of 8.28(17) eV, corresponding, for radiative decay, to photons of a vacuum wavelength of 149.7(31) nm (ref. 14). Measurements of gamma (γ) ray energy differences of nuclear transitions feeding the isomer and the ground state, using a magnetic microcalorimeter, revealed energies of 8.30(92) and 8.10(17) eV, with an associated vacuum wavelength of 149(17) and 153.1(32) nm, respectively[15,16].

A half-life of 7(1) μs has been reported for $^{229m}Th^0$ deposited onto a microchannel plate detector, an environment in which electron conversion is expected to constitute the dominant decay path[13]. Theoretical estimates for the radiative decay half-life vary by an order of magnitude between about 10^3 and 10^4 s (refs. 19–21). For a dominating radiative decay, which is required for the clock application, the non-radiative decay channels, for example, by means of electron conversion decay, need to be sufficiently suppressed. The last requires charged ^{229m}Th ions to have an electron binding energy larger than the isomer's decay energy.

At present, two different routes towards a nuclear clock are being pursued. These consist of an approach with triply charged thorium ions stored in a radio-frequency ion trap and a solid-state approach with a thorium-doped large-bandgap crystal[1,5,22–24]. For the latter, theoretical studies suggest that, at specific lattice positions, the conversion-electron decay channel of the isomer is suppressed and the radiative decay channel becomes dominant[25,26]. Despite various attempts, the observation of the radiative decay of ^{229m}Th following the

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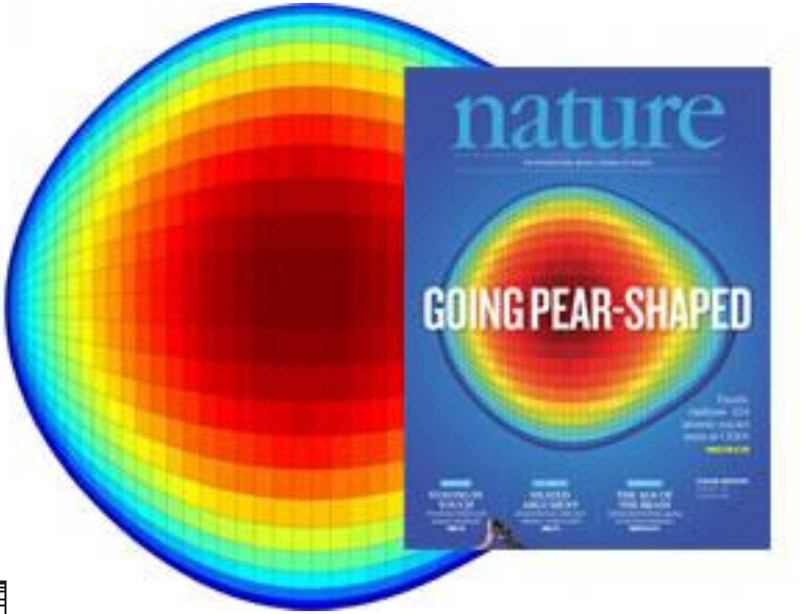
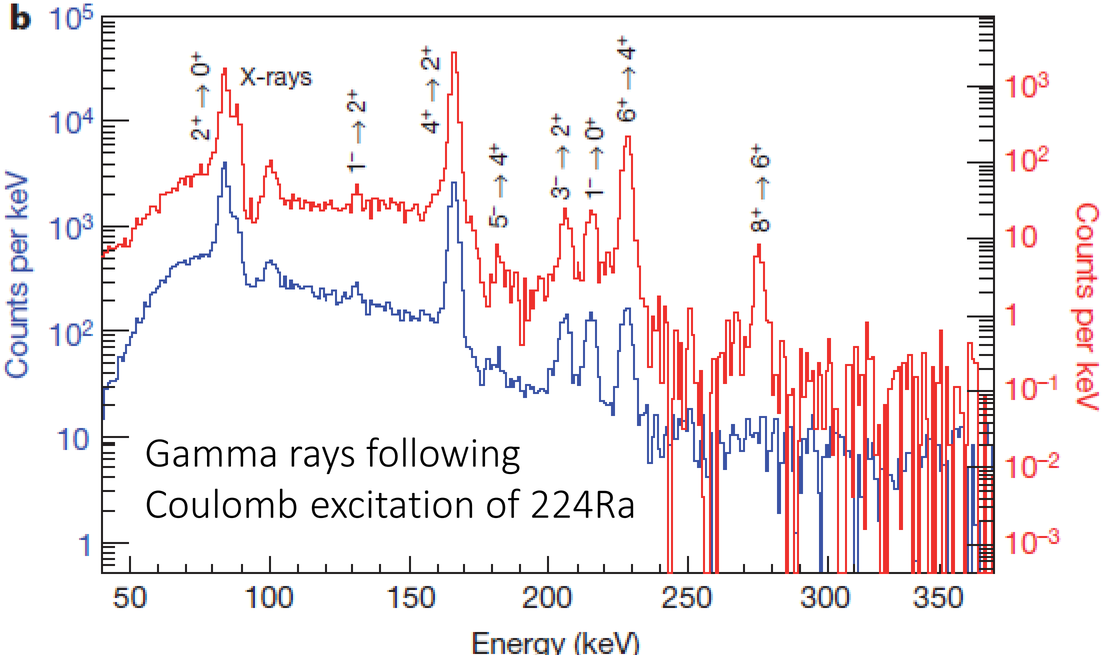
[1]KU Leuven, Instituut voor Kern- en Stralingsfysica, Leuven, Belgium. [2]Ludwig-Maximilians-Universität München, Garching, Germany. [3]KU Leuven, Quantum Solid State Physics, Leuven, Belgium. [4]CERN, Geneva, Switzerland. [5]Institute for Atomic and Subatomic Physics, TU Wien, Vienna, Austria. [6]Centro de Ciências e Tecnologias Nucleares, Departamento de Engenharia e Ciências Nucleares, Instituto Superior Técnico, Universidade de Lisboa, Bobadela, Portugal. [7]Institut Laue-Langevin, Grenoble, France. [8]Department Chemie, Johannes-Gutenberg-Universität, Mainz, Germany. [9]Helmholtz-Institut Mainz, Mainz, Germany. [10]GSI Helmholtzzentrum für Scherionenforschung, Darmstadt, Germany. [11]Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania. [12]imec, Leuven, Belgium. ✉e-mail: sandro.kraemer@kuleuven.be

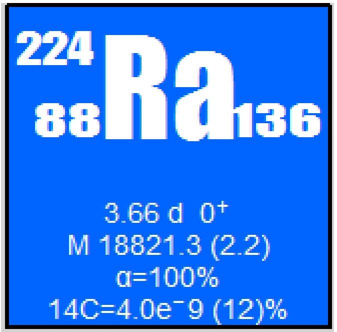
MINIBALL: Pear shape in ^{224}Ra

- Pear shape - octupole deformation
    - Very rare nuclear shape
- Coulomb excitation with MINIBALL
    - Determine electric octupole transition strengths (direct measure of octupole correlations)
- Pear shape shown for the 1st time experimentally
    - Test of nuclear models
    - Important in searches for permanent atomic





Gamma rays following Coulomb excitation of 224Ra



$^{224}_{88}\mathrm{Ra}_{136}$

3.66 d 0^+

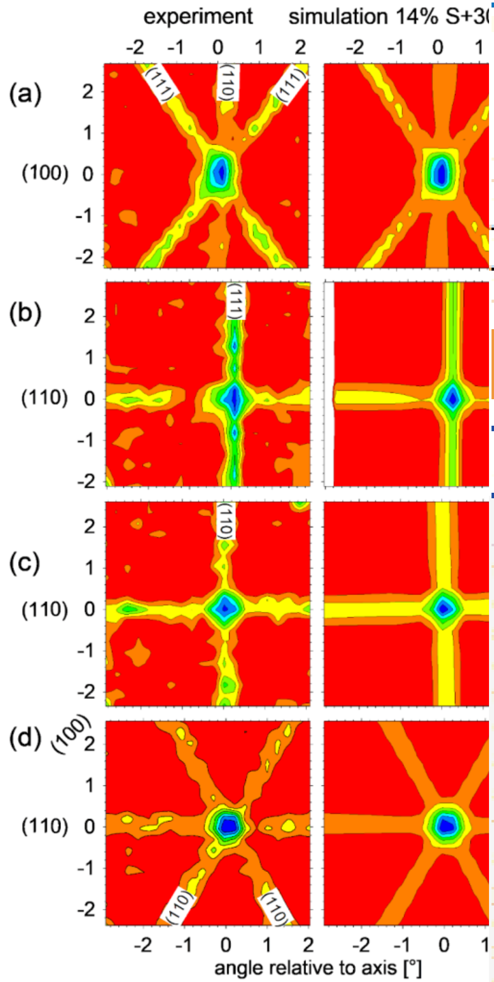
M 18821.3 (2.2)

α=100%

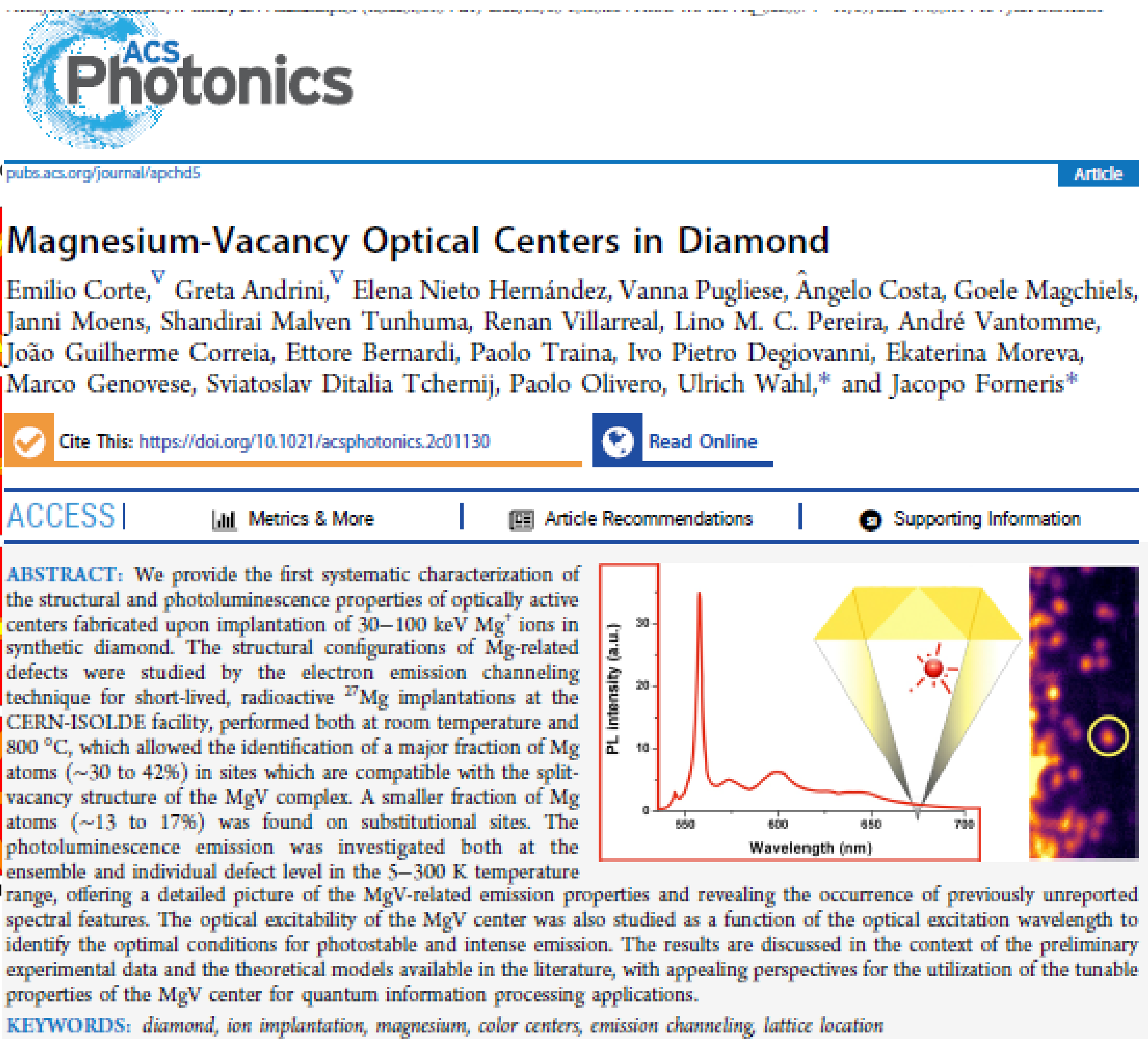
14C=4.0e⁻9 (12)%

P. Gaffney et al,

ature 497 (2013) 199



T_i=800°C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Article

Magnesium-Vacancy Optical Centers in Diamond

Emilio Corte,[∇] Greta Andrini,[∇] Elena Nieto Hernández, Vanna Pugliese, Ângelo Costa, Goele Magchiels, Janni Moens, Shandirai Malven Tunhuma, Renan Villarreal, Lino M. C. Pereira, André Vantomme, João Guilherme Correia, Ettore Bernardi, Paolo Traina, Ivo Pietro Degiovanni, Ekaterina Moreva, Marco Genovese, Sviatoslav Ditalia Tchernij, Paolo Olivero, Ulrich Wahl,* and Jacopo Forneris*

Cite This: https://doi.org/10.1021/acsphotonics.2c01130

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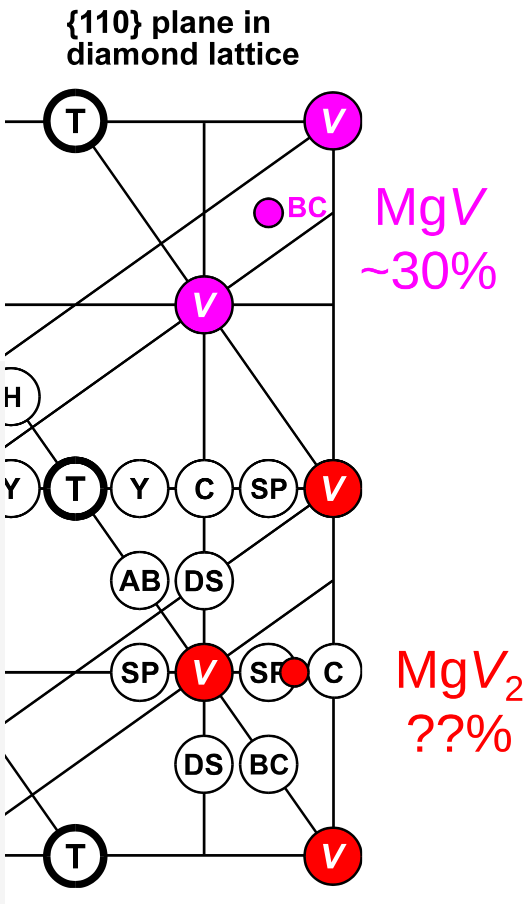
ABSTRACT: We provide the first systematic characterization of the structural and photoluminescence properties of optically active centers fabricated upon implantation of 30−100 keV Mg^+ ions in synthetic diamond. The structural configurations of Mg-related defects were studied by the electron emission channeling technique for short-lived, radioactive ^{27}Mg implantations at the CERN-ISOLDE facility, performed both at room temperature and 800 °C, which allowed the identification of a major fraction of Mg atoms (~30 to 42%) in sites which are compatible with the split-vacancy structure of the MgV complex. A smaller fraction of Mg atoms (~13 to 17%) was found on substitutional sites. The photoluminescence emission was investigated both at the ensemble and individual defect level in the 5−300 K temperature range, offering a detailed picture of the MgV-related emission properties and revealing the occurrence of previously unreported spectral features. The optical excitability of the MgV center was also studied as a function of the optical excitation wavelength to identify the optimal conditions for photostable and intense emission. The results are discussed in the context of the preliminary experimental data and the theoretical models available in the literature, with appealing perspectives for the utilization of the tunable properties of the MgV center for quantum information processing applications.

KEYWORDS: *diamond, ion implantation, magnesium, color centers, emission channeling, lattice location*

exes in diamond



Mg*V*
~30%

MgV_2
??%

Radioisotopes and Nuclear Medicine

NATURE | NEWS FEATURE

Radioisotopes: The medical testing crisis

With a serious shortage of medical isotopes looming, innovative companies are exploring ways to make them without nuclear reactors.

Richard Van Noorden

11 December 2013

1- Established isotopes: 'industrial' suppliers

99mTc, 18F, 123,125,131I,111In,90Y

2- Emerging isotopes: 'small' innovative suppliers

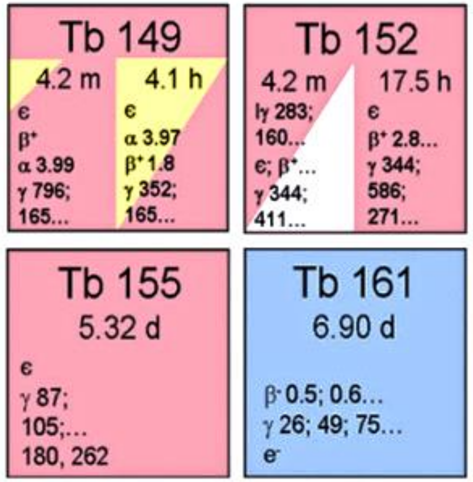
68Ga, 82Rb, 89Zr, 177Lu, 188Re

3- R&D isotopes: research labs

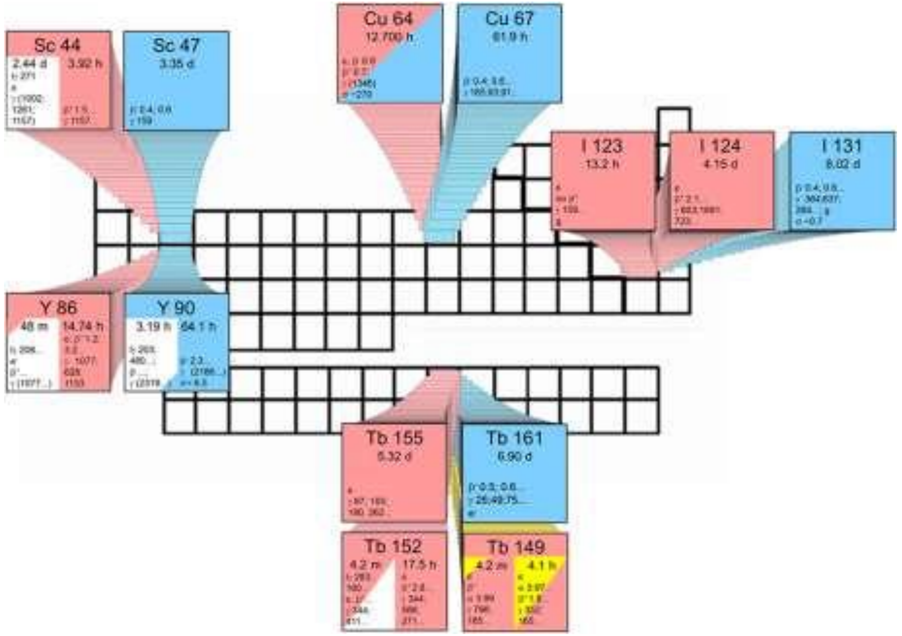
44,47Sc, 64,67Cu, 134Ce, 140Nd, 149,152,155,161Tb, 166Ho,195mPt, 211At, 212,213Bi, 223Ra,225Ac..

Medical Physics : ISOLDE and MEDICIS

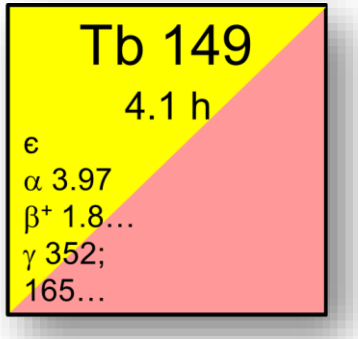
14 years ago – now :
Innovative radioisotopes

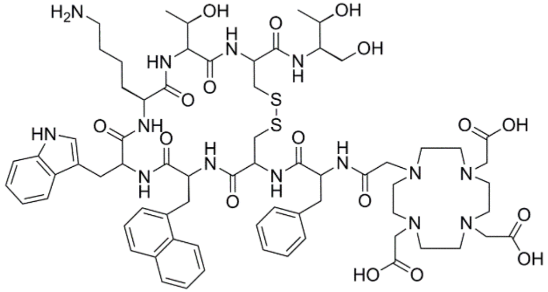


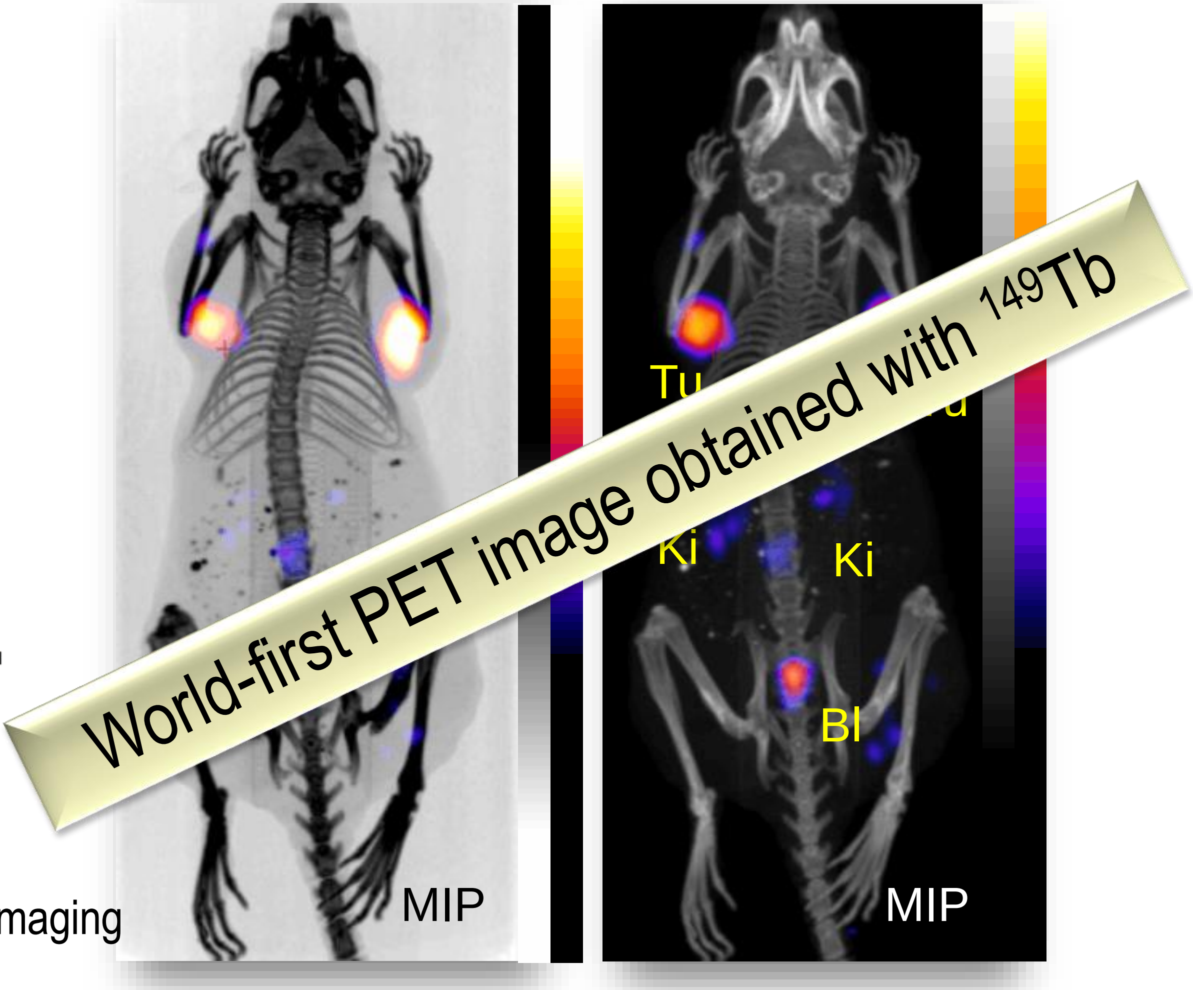
Matched pairs for theranostics



^{149}Tb







World-first PET image obtained with ^{149}Tb

Useful for α-Therapy and PET Imaging

PET/CT scan of a AR42J tumor-bearing mouse performed 2 h after injection of ^{149}Tb-DOTANOC

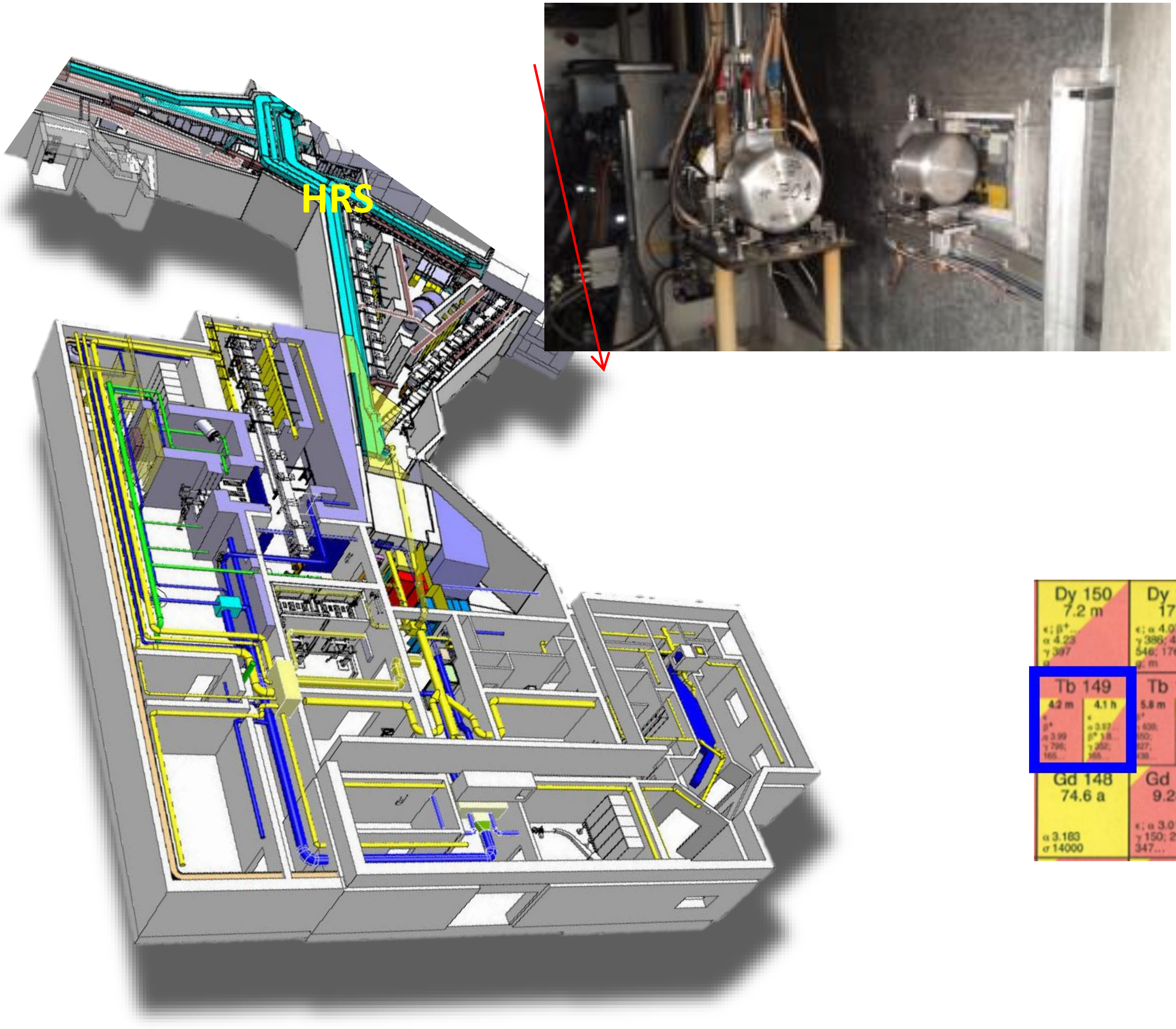
Muller et al., *EJNMMI Radiopharmacy and Chemistry*, (2016) 1:5.

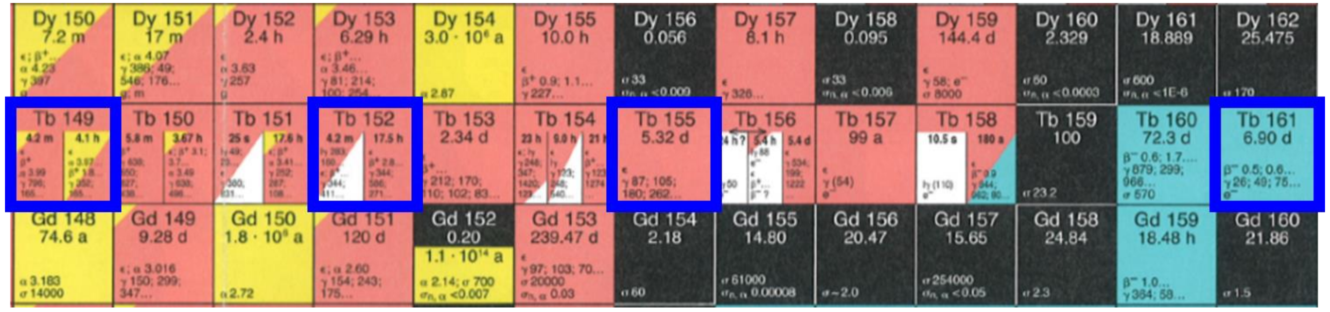
Logistics: The Travel Challenge : ^{149}Tb

200 MBq

110 MBq

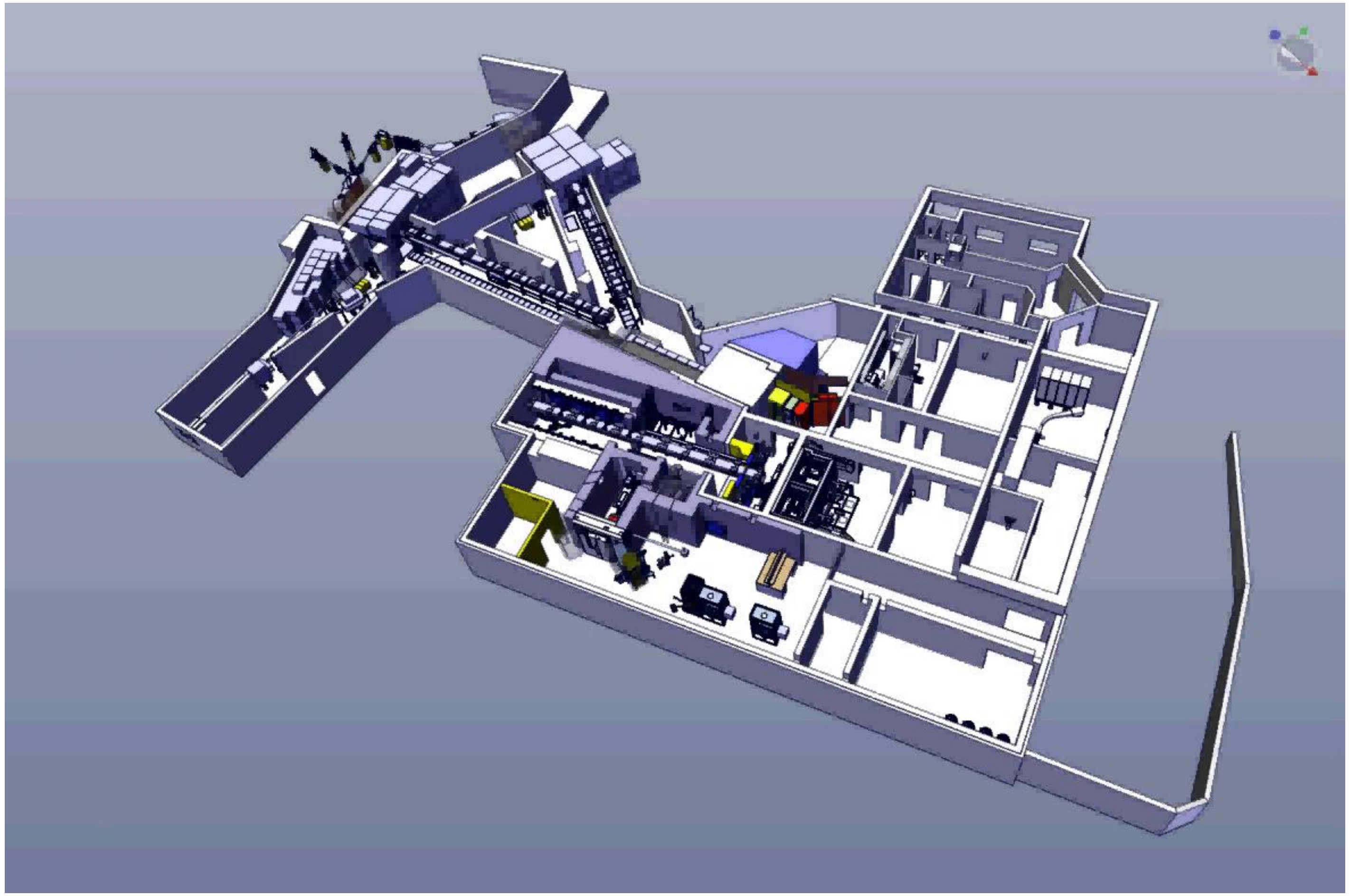
CERN-MEDICIS: new Facility for medical isotopes (and solid state/materials?)





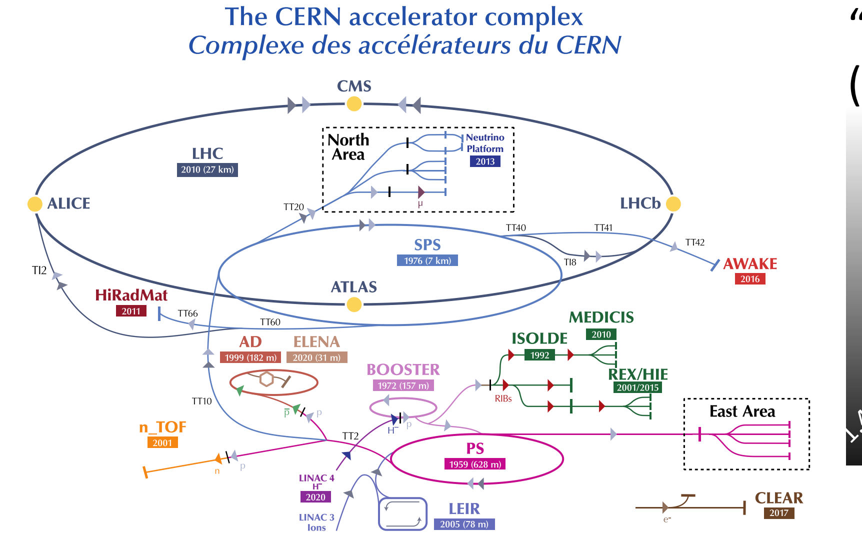
Dy 150 7.2 m	Dy 151 17 m	Dy 152 2.4 h	Dy 153 6.29 h	Dy 154 $3.0 \cdot 10^6$ a	Dy 155 10.0 h	Dy 156 0.056	Dy 157 8.1 h	Dy 158 0.095	Dy 159 144.4 d	Dy 160 2.329	Dy 161 18.889	Dy 162 25.475
Tb 149 4.2 m 4.1 h	Tb 150 5.8 m 3.67 h	Tb 151 25 s 17.6 h	Tb 152 4.2 m 17.5 h	Tb 153 2.34 d	Tb 154 23 h 9.0 h 21 h	Tb 155 5.32 d	Tb 156 24 h? 5.4 h 5.4 d	Tb 157 99 a	Tb 158 10.5 s 180 a	Tb 159 100	Tb 160 72.3 d	Tb 161 6.90 d
Gd 148 74.6 a	Gd 149 9.28 d	Gd 150 $1.8 \cdot 10^6$ a	Gd 151 120 d	Gd 152 0.20 $1.1 \cdot 10^{14}$ a	Gd 153 239.47 d	Gd 154 2.18	Gd 155 14.80	Gd 156 20.47	Gd 157 15.65	Gd 158 24.84	Gd 159 18.48 h	Gd 160 21.86

MEDICIS isotope production chain

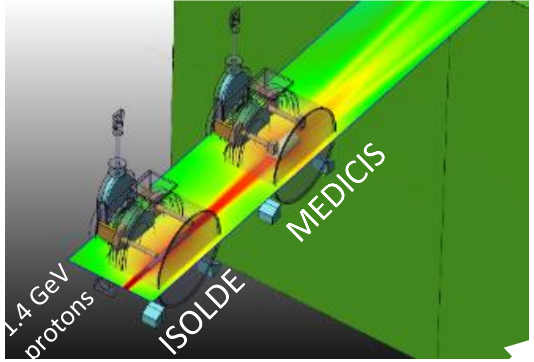


Animation: V. Barozier

Mass separation as applied in MEDICIS in a snapshot

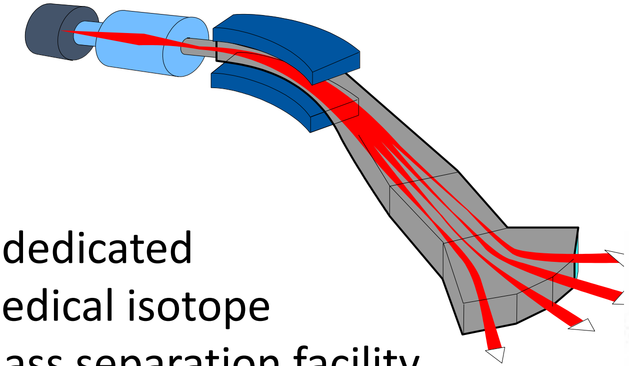


“Free” proton beam
(otherwise lost in the dump)



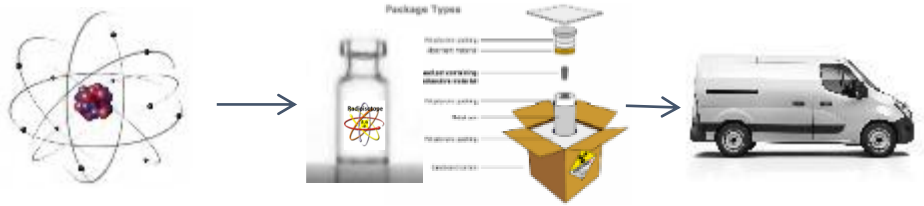
Some **MEDICIS isotopes** :

High activity Sm-153, Ba/Cs-128, Tm/Er-165



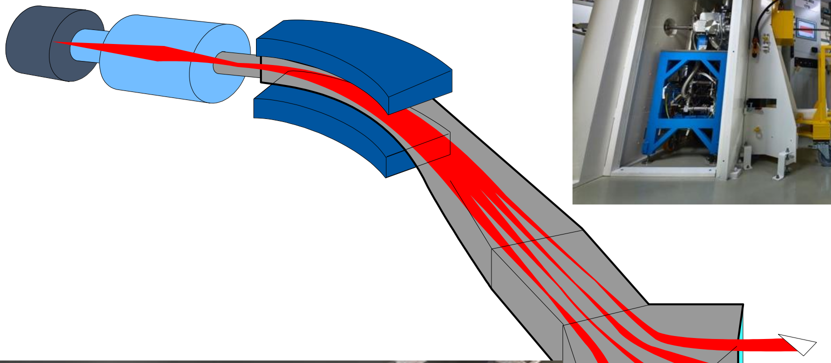
A dedicated medical isotope Mass separation facility in Europe.

120MBq Auger ^{165}Tm >99%
Produced/delivered in 24hr

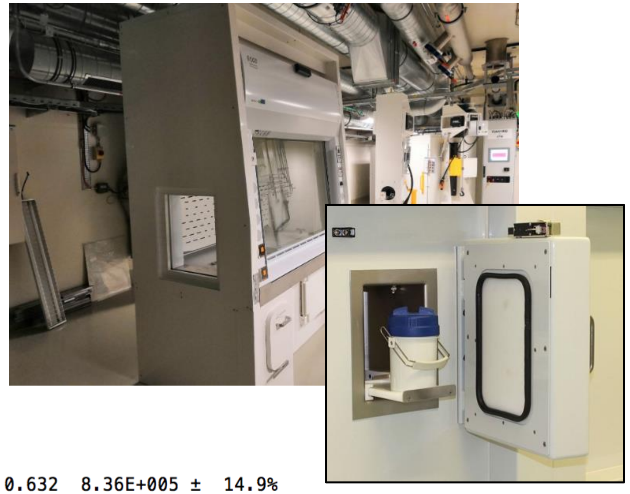


From CERN- MEDICIS to the lab/Hospital

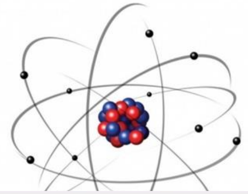
From CERN- MEDICIS to the lab/Hospital

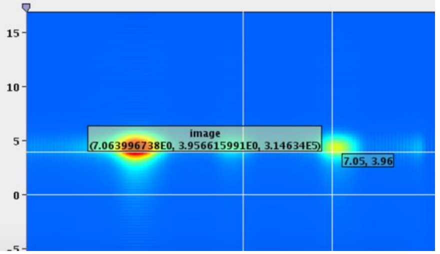


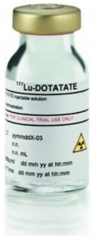
120MBq Auger ^{165}Tm >99%
Produced/delivered in 24hr



```
Gd-149  @  9.28E+000 D   0.632  8.36E+005 ±  14.9%
Tb-149  @  4.12E+000 H   0.964  1.71E+006 ±   9.4%
Er-165     1.04E+001 H   0.894
Tm-165  @  1.25E+000 D   0.979  1.21E+008 ±   6.3%
```







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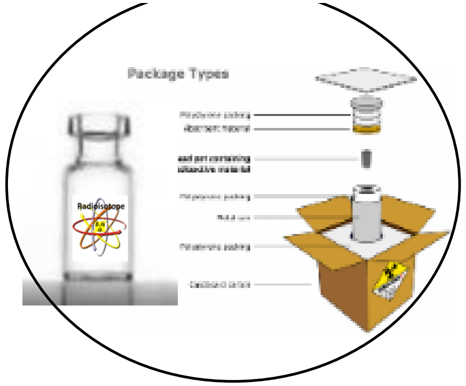


→

Isotope separation for experiment MED011
from external 168/169Er source

From CERN- MEDICIS to the lab/Hospital
(Countries: BE, CH, FR, PK, PT, LV, UK)

How to supply “novel” radionuclides with mass separation

- **PRISMAP** proposes to federate a consortium of high energy cyclotrons, research reactors, and isotope mass separation facilities in Europe.

Accelerator

Isotope mass separation

Research reactor

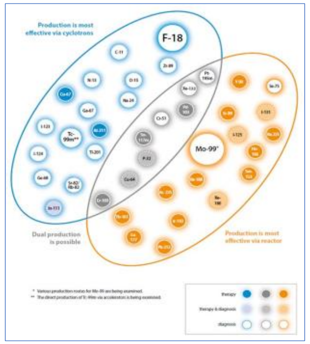
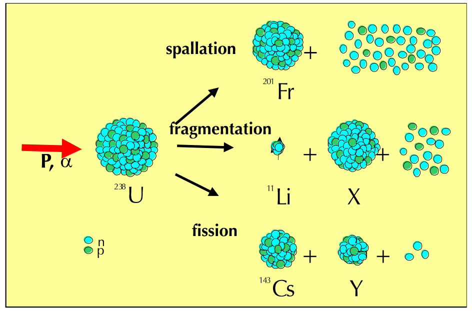
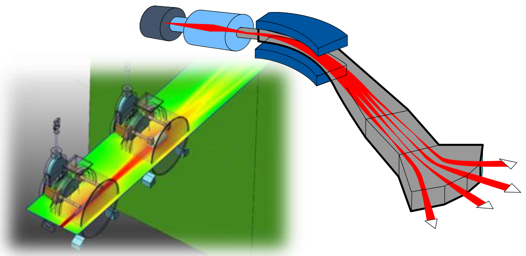
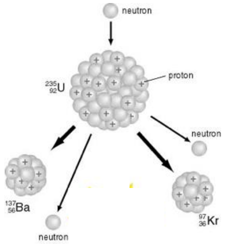


Figure 31 : Main medical radioisotopes production process

European Commission ENER/17/NUCL/SI2.755660 (2018)



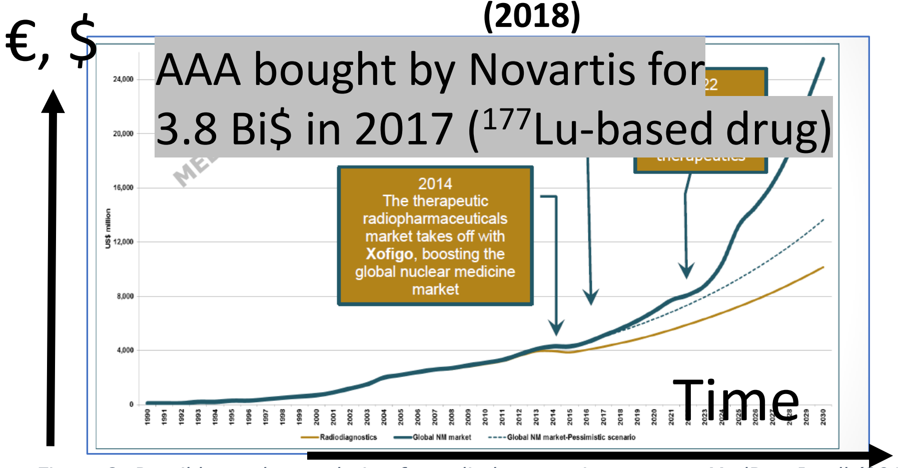




$I_{[pps]}$ ~ $F_{[pps]}$ $S_{[barn]}$ $N_{[g/cm2]}$ production rate
10^{10}pps 100∝A (6.10^{14}) 1mbarn 1g/cm² for A_{target}=30g/mol

$I_{[pps]}$ ~ $F_{[pps]}$ $S_{[barn]}$ $N_{[g/cm2]}$ $e_{[\%]}$

$$\frac{dN'}{dt} = n v \sigma_{act} N_T$$



AAA bought by Novartis for 3.8 Bi$ in 2017 (^{177}Lu-based drug)

Figure 8: Possible market evolution for radiotherapeutics – source MedRaysIntell (2016

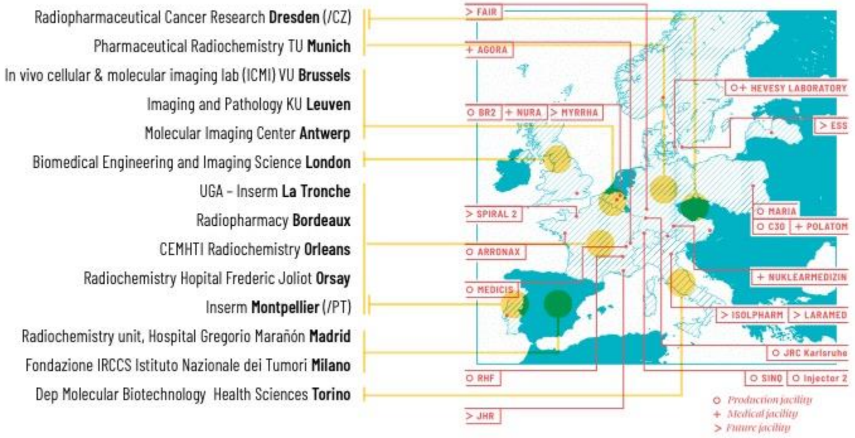
Economics, Innovators

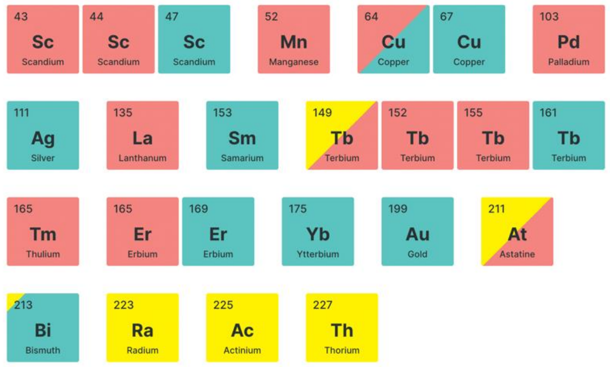
PRISMAP – The European medical radionuclides programme (2021-2025)

https://medical-radionuclides.eu

- Achievements in 2022:
  - 15 projects for biomedical research with novel radionuclides were selected for services across Europe

    www.prismap.eu/access/user-projects (BE, CZ, DE, ES, FR, IT, PT, UK)




43 Sc Scandium | 44 Sc Scandium | 47 Sc Scandium | 52 Mn Manganese | 64 Cu Copper | 67 Cu Copper | 103 Pd Palladium

111 Ag Silver | 135 La Lanthanum | 153 Sm Samarium | 149 Tb Terbium | 152 Tb Terbium | 155 Tb Terbium | 161 Tb Terbium

165 Tm Thulium | 165 Er Erbium | 169 Er Erbium | 175 Yb Ytterbium | 199 Au Gold | 211 At Astatine

213 Bi Bismuth | 223 Ra Radium | 225 Ac Actinium | 227 Th Thorium

  - PRISMAP is invited to present research needs in the field of novel biomedical radionuclides to the EU Commissioner for research and education Mariya Gabriel

MEDICIS
European organization for nuclear research - CERN

PSI
Paul Scherrer Institut – PSI

Hevesy Laboratory
Danmarks Tekniske Universitet – DTU

BR2
Belgian Nuclear Research Centre — SCK CEN

ARRONAX
Groupement interet public ARRONAX — ARRONAX

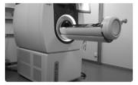
RHF
Institut Max von Laue - Paul Langevin – ILL

JRC Karlsruhe
Joint Research Centre - European Commission – JRC

NCBJ
Narodowe Centrum Badań Jądrowych — NCBJ

Hevesy Laboratory
Danmarks Tekniske Universitet – DTU

AGORA
Centre hospitalier universitaire vaudois — CHUV



NURA
Studiecentrum voor Kernenergie / Centre d'étude de l'énergie nucleaire — SCK CEN

Nuklearmedizin
Klinikum rechts der Isar der Technischen Universität München — TUM

POLATOM
Narodowe Centrum Badań Jądrowych – NCBJ