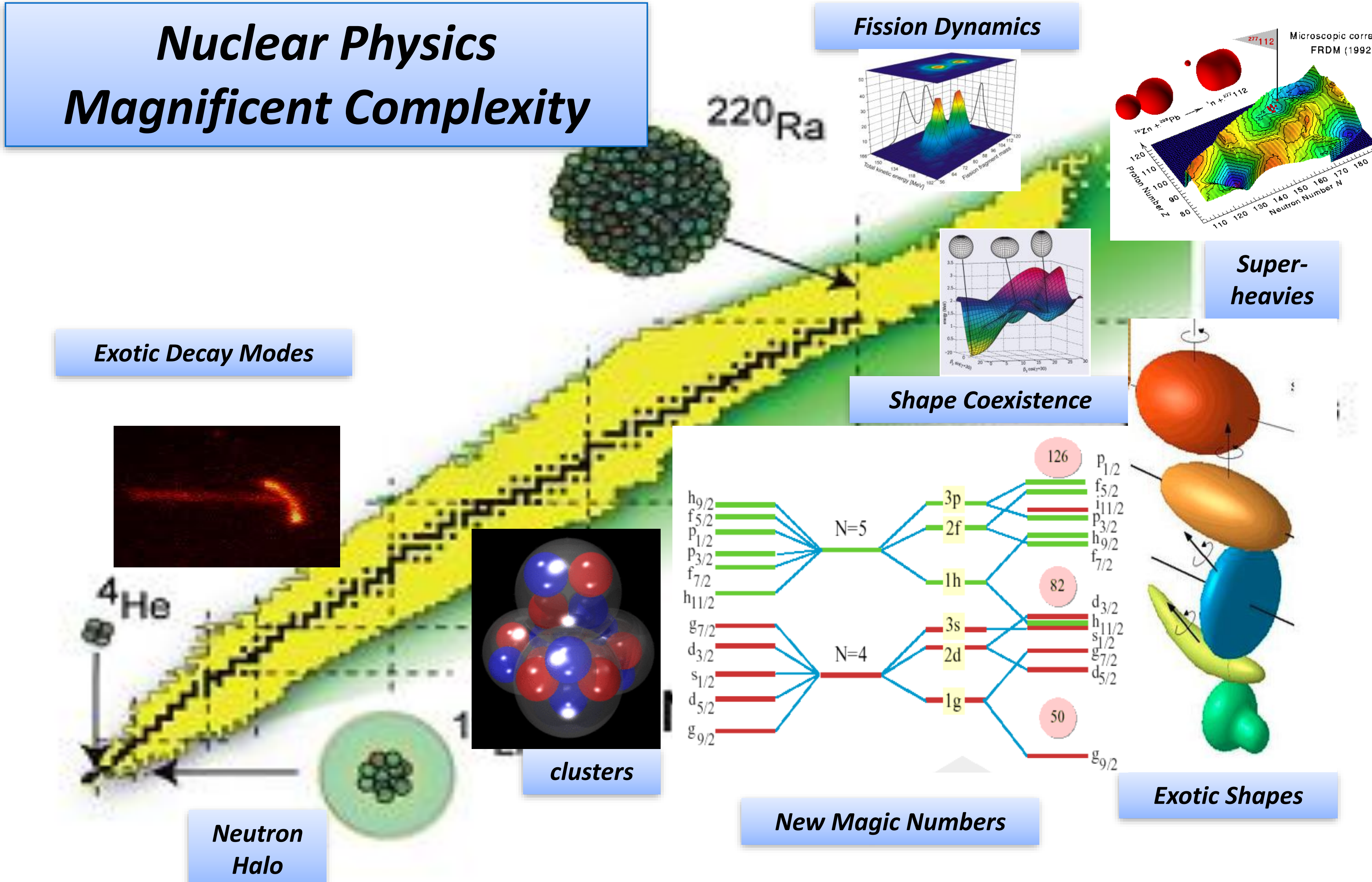
# The ISOL Method for Nuclear Physics and Medical applications

Maria J. G. Borge
IEM-CSIC, Madrid Spain
Former ISOLDE leader and Spokeperson, CERN

# Hot subjects in Nuclear Physics

***Nuclear Physics***
***Magnificent Complexity***



***Fission Dynamics***

***Super-heavies***

***Shape Coexistence***

***Exotic Decay Modes***

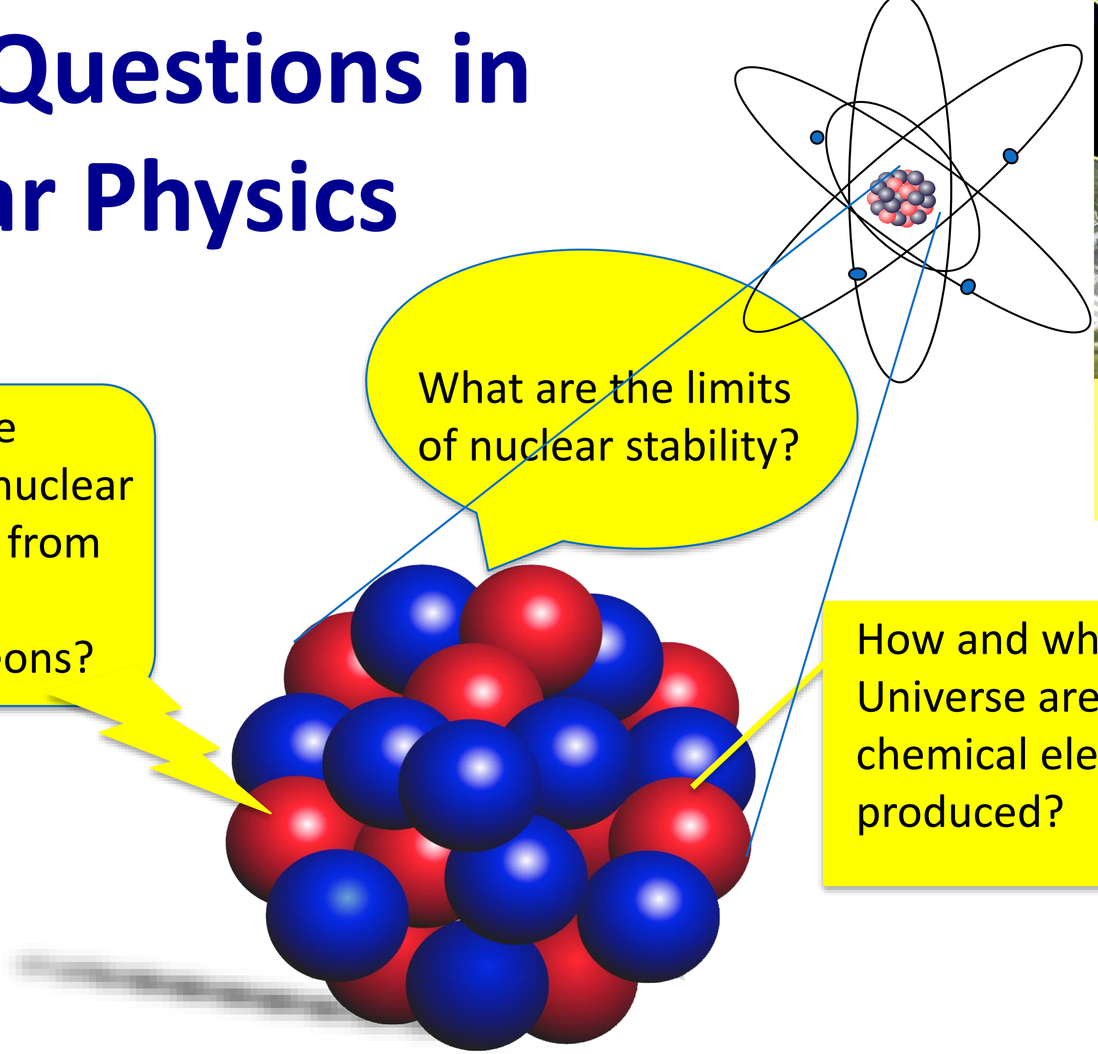
***clusters***

***Neutron Halo***

***New Magic Numbers***

***Exotic Shapes***

# Open Questions in Nuclear Physics



¿ How does the complexity of nuclear structure arise from the interaction between nucleons?

What are the limits of nuclear stability?

How and where in the Universe are the chemical elements produced?

NuPECC
Long Range Plan 2017
Perspectives
in Nuclear Physics

2017

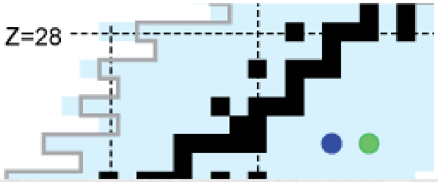
***Observables***:
Basic ground state properties:
mass, radius, moments J, μ, Q
Half-life y decay process
Transition probabilities
Cross sections

**Theoretical Models:**
Shell Model (magic numbers)
Mean field Calculations (collective properties)
*Ab Initio Calculations* (light nuclei)

# The Nuclear Shell Model: Universal Magic Numbers ?

Mayer & Jensen (1949)

- Nuclei exhibit shell structure
  - Filled orbitals = « magic nuclei »
  - Valence nucleons are crucial
  - We rely on the Shell Model, with magic nuclei as the building blocks, to predict the structure of exotic nuclei



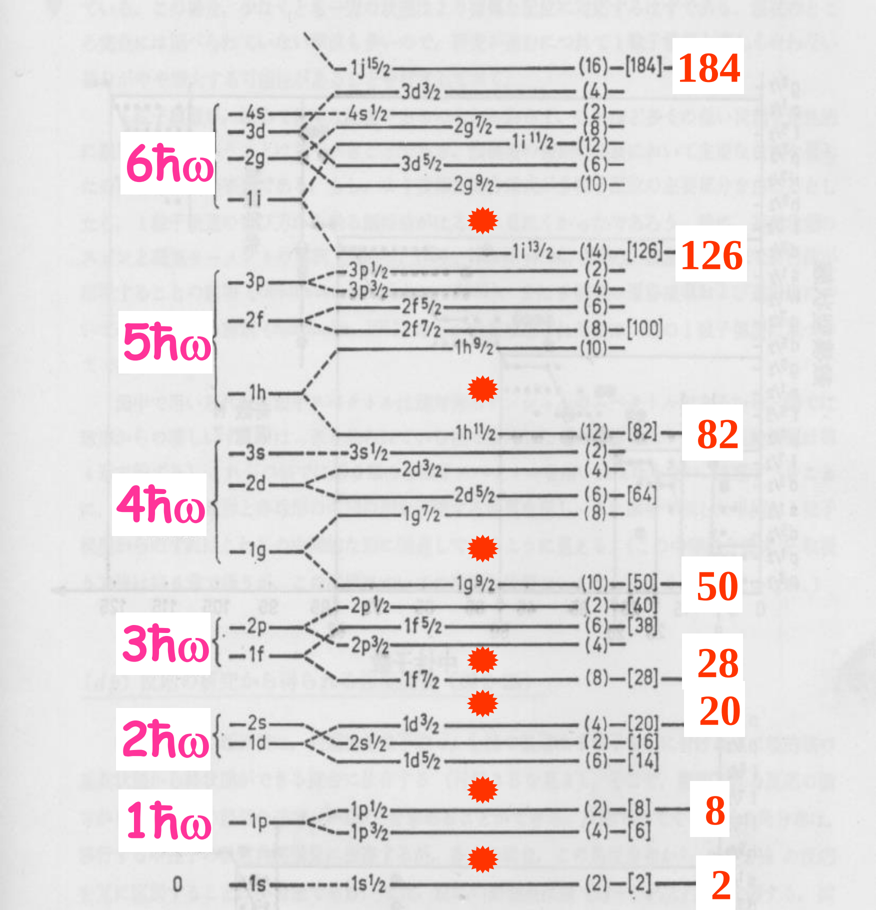
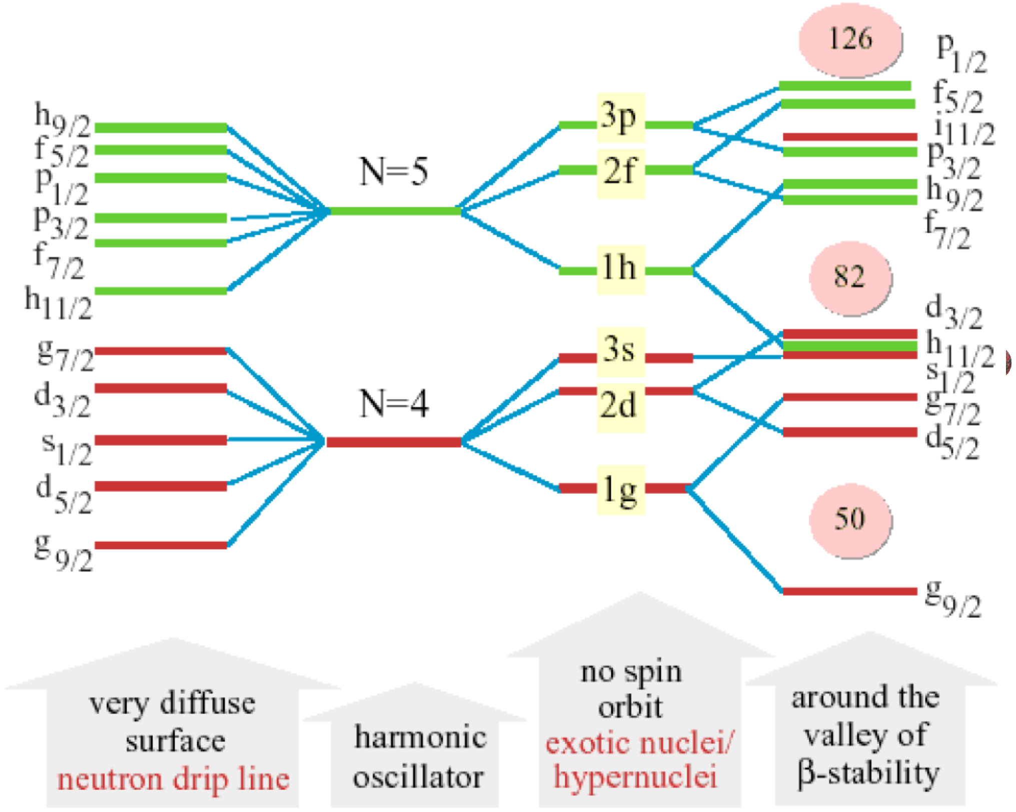
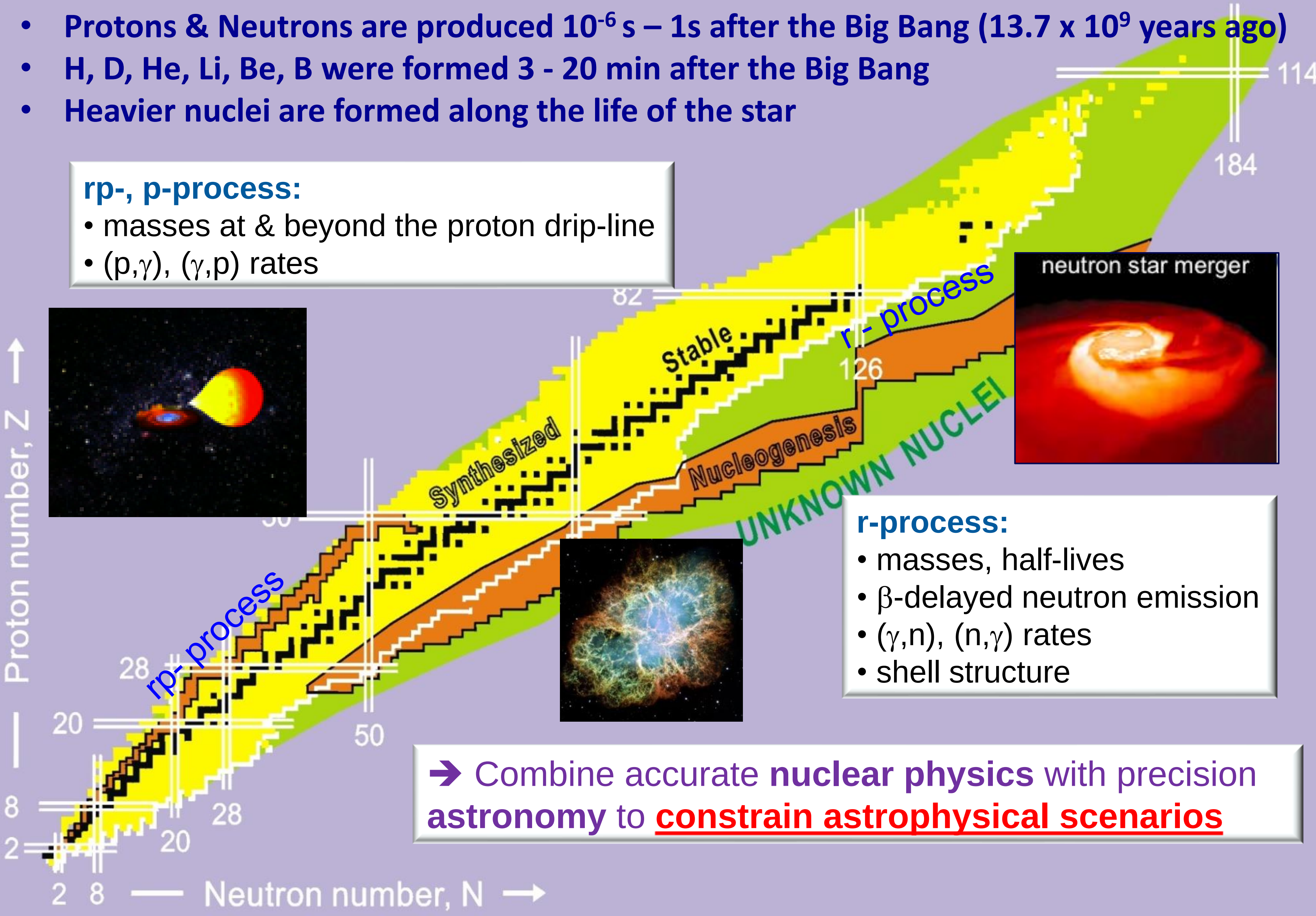


図2-23 1粒子軌道の順序. 図は M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure*, p. 58, Wiley, New York, 1955 からとった.



# Nucleo-synthesis: Stellar scenario

- **Protons & Neutrons are produced $10^{-6}$ s – 1s after the Big Bang ($13.7 \times 10^9$ years ago)**
- **H, D, He, Li, Be, B were formed 3 - 20 min after the Big Bang**
- **Heavier nuclei are formed along the life of the star**



**rp-, p-process:**
- masses at & beyond the proton drip-line
- $(p,\gamma)$, $(\gamma,p)$ rates

**r-process:**
- masses, half-lives
- $\beta$-delayed neutron emission
- $(\gamma,n)$, $(n,\gamma)$ rates
- shell structure

➔ Combine accurate **nuclear physics** with precision **astronomy** to **constrain astrophysical scenarios**

# Production of Radioactive Beams

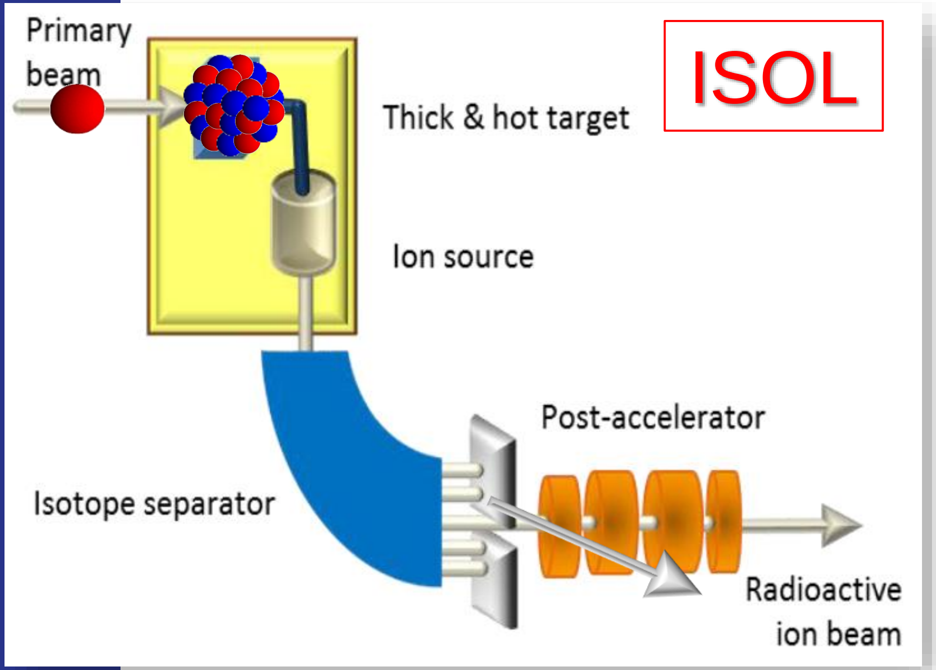
- Radioactive Ion Beams are produced using two complementary ways

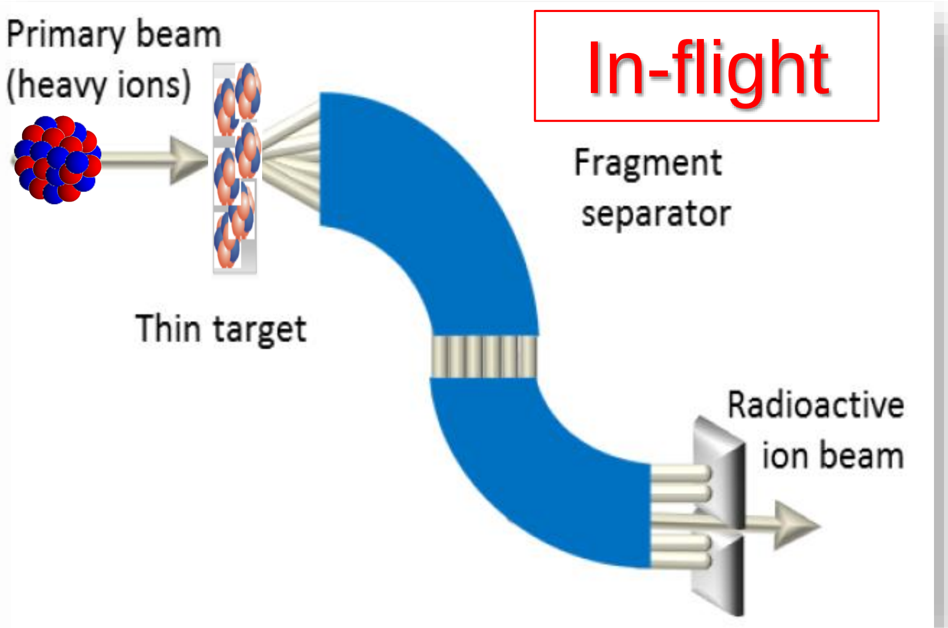
Isotope Separator On Line method (ISOL):

✓ low/medium energy, high quality beams (phase space)

In-flight method:

✓ high energy, short lived (μs)

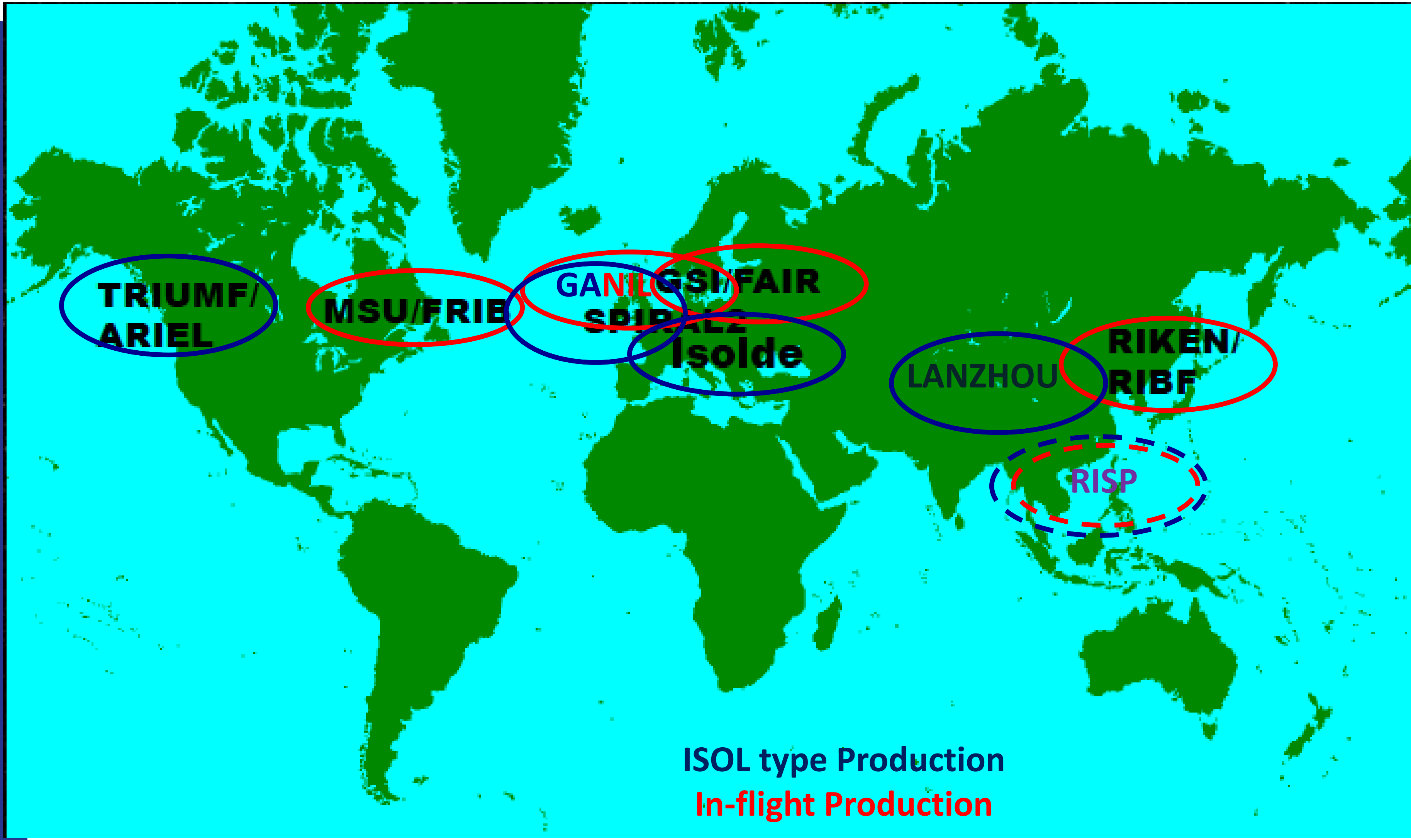




**Tailored made nuclei**
**Extraction time: ms – s**
**Well defined beam optics**

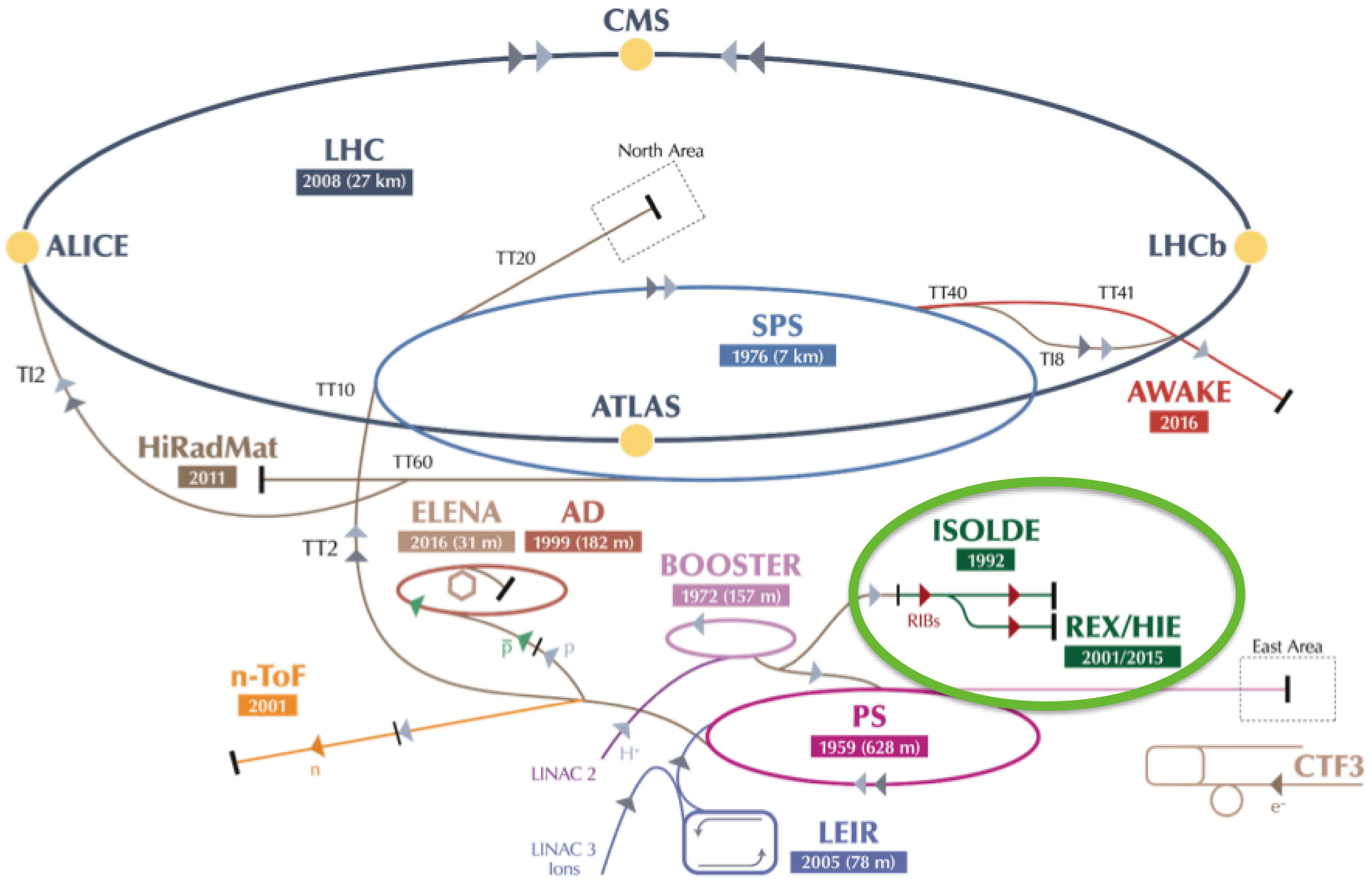
**Fast production**
**Many nuclei at the same time**
**Mapping region**

# RIB Facilities in the World



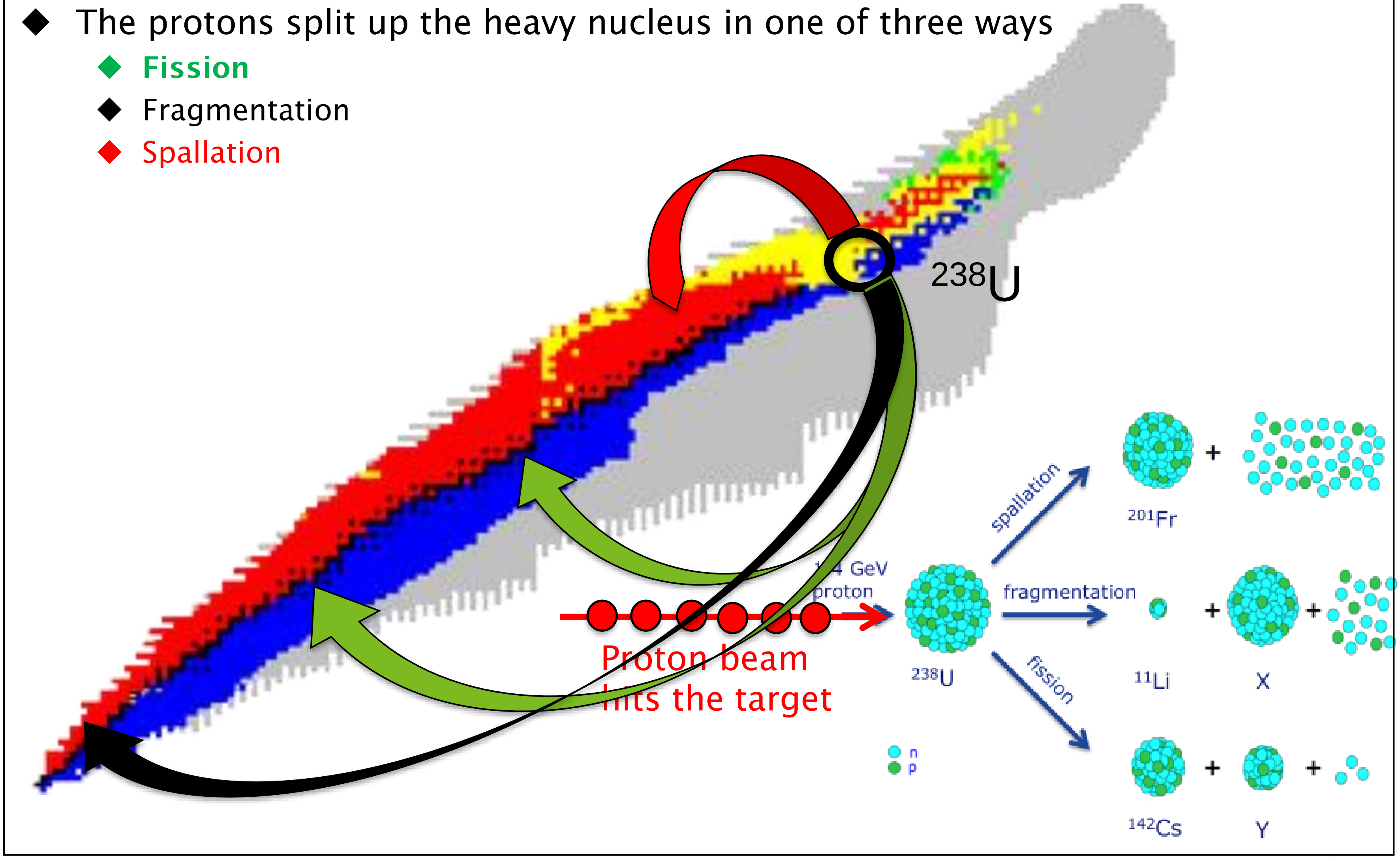
RISP will enjoy both production methods

# ISOLDE at CERN

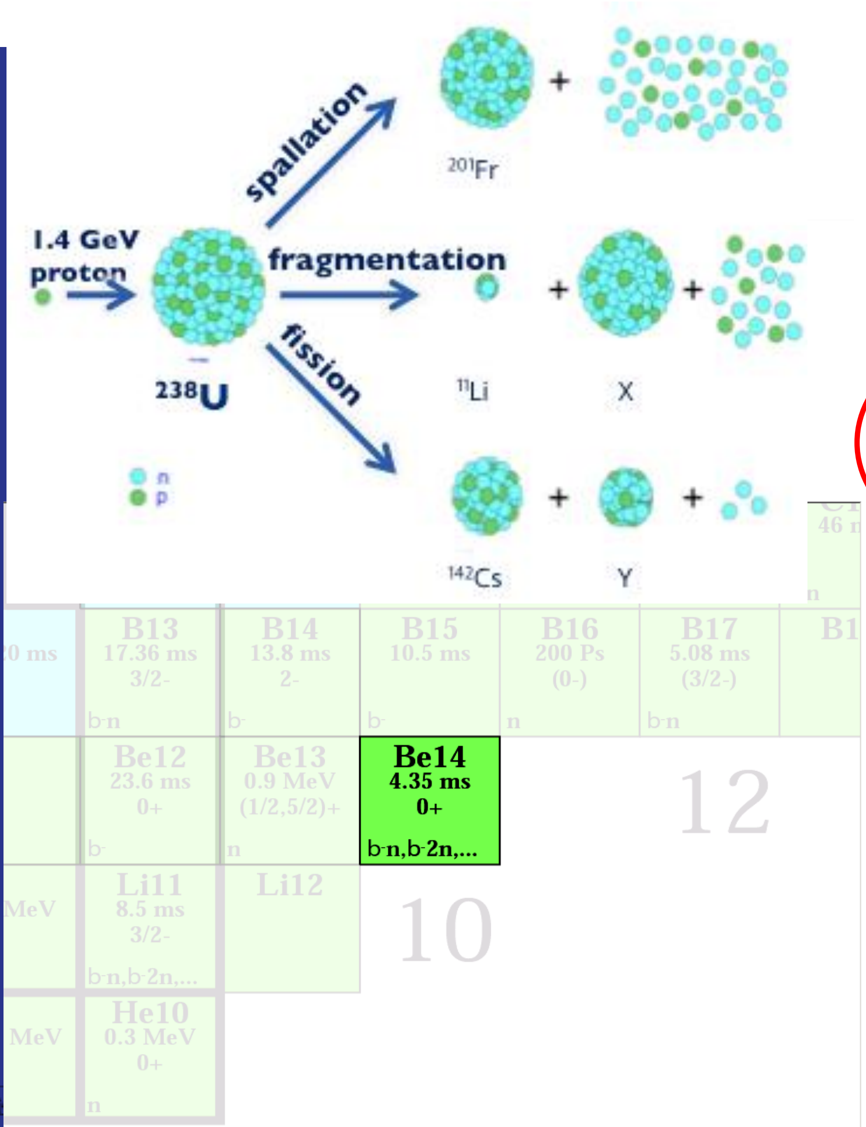


# Production: Modern-day alchemy

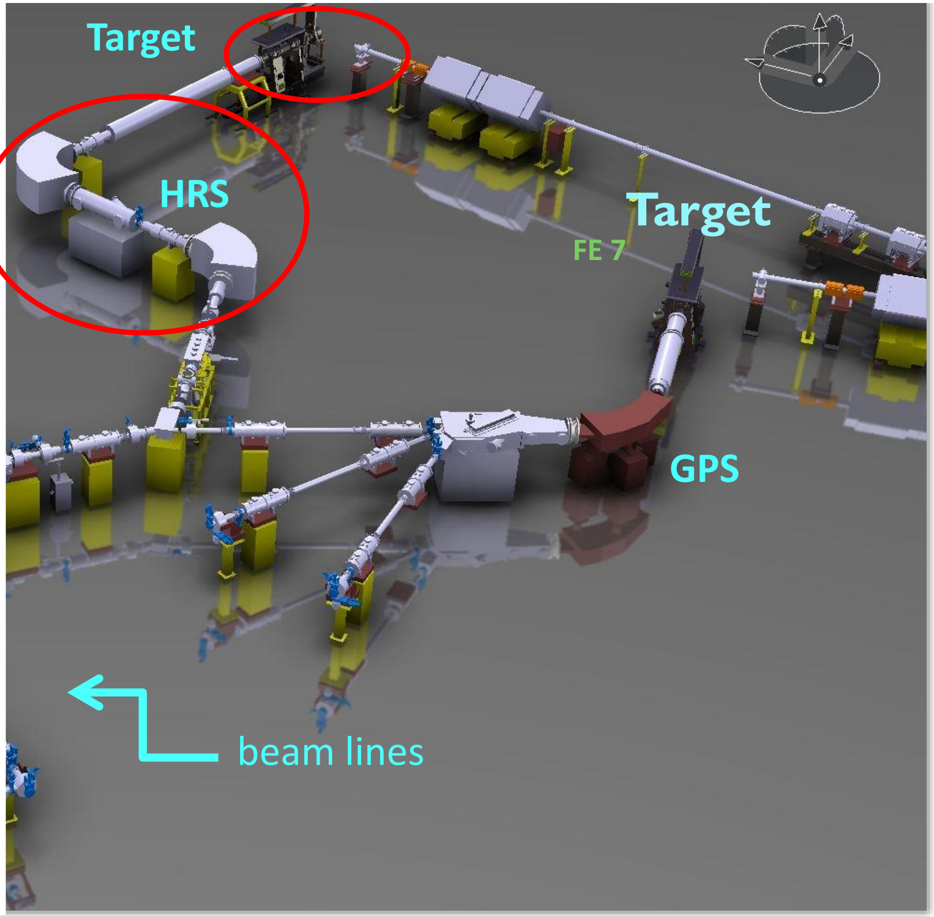
- High energy (1.4 GeV) protons are impacted onto a thick target e.g. $^{238}U$
- The protons split up the heavy nucleus in one of three ways
  - **Fission**
  - Fragmentation
  - Spallation



# Production Mechanism

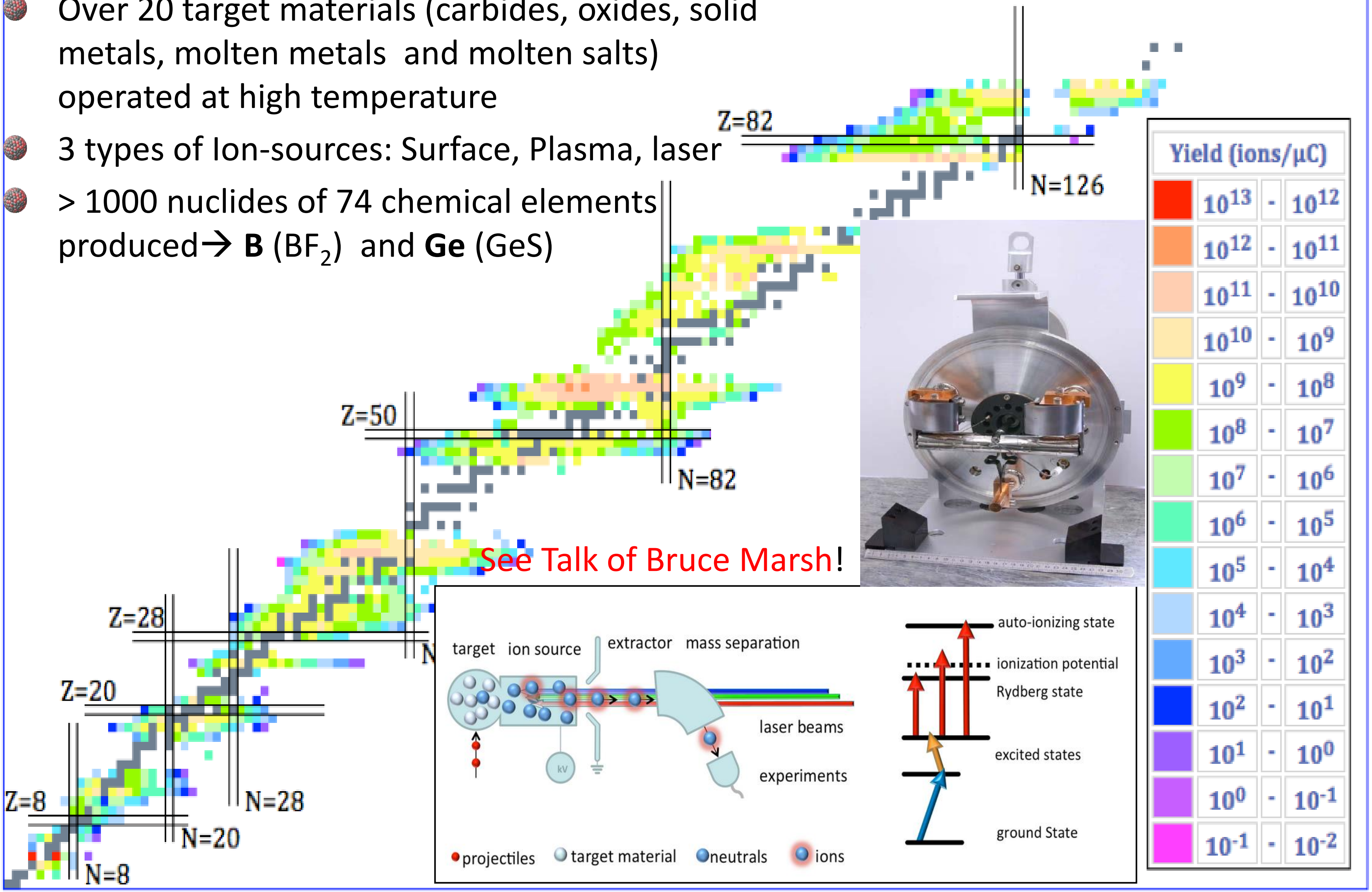


$$Y = I \; X \; \sigma \overbrace{\varepsilon_{rel} \; \varepsilon_{ion}}^{10^{-3} - 10^{-8}} \; \overbrace{\varepsilon_{sep} \; \varepsilon_{transp}}^{5 - 90\ \%}$$



# Produced Nuclei: 50 y Experience

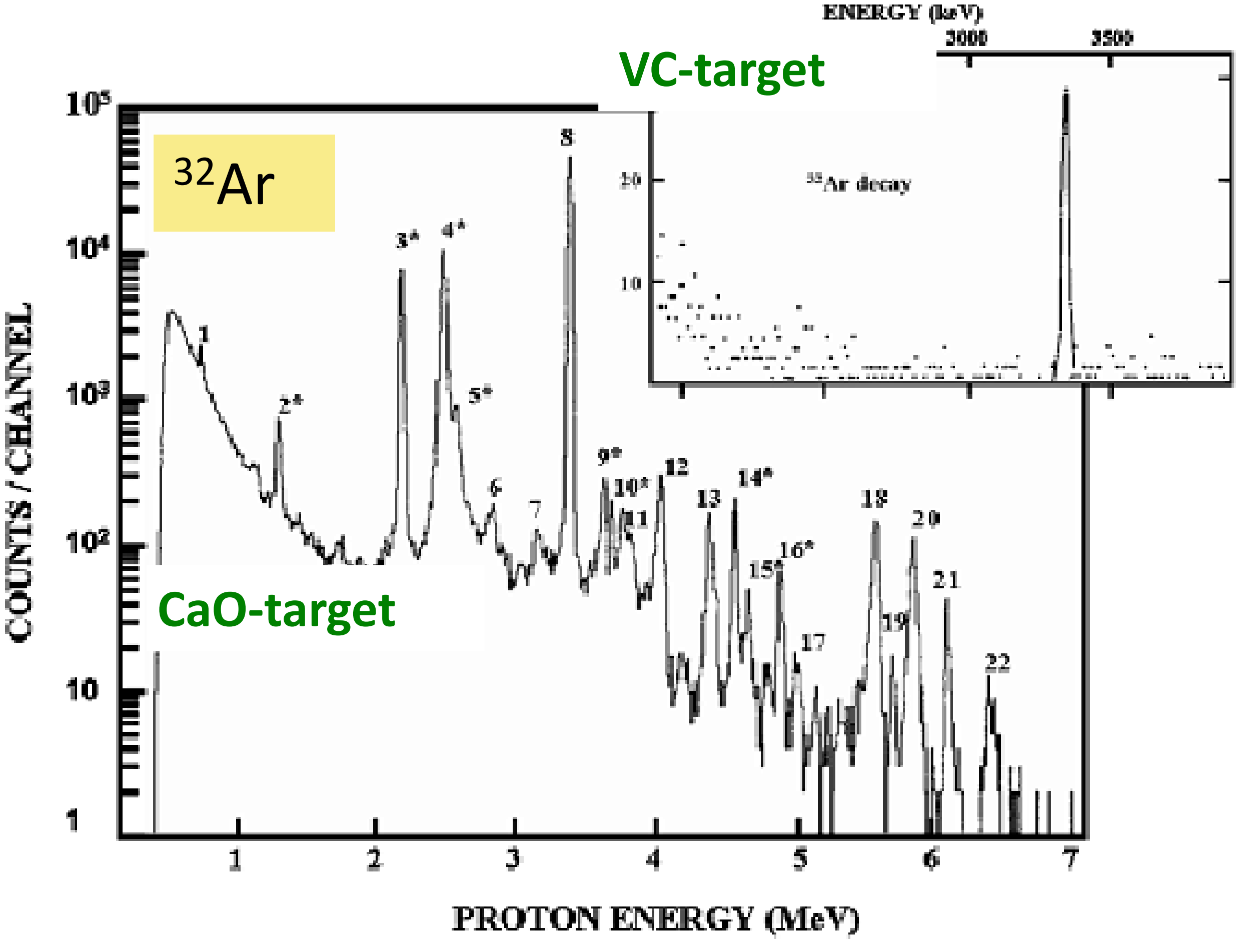
- Over 20 target materials (carbides, oxides, solid metals, molten metals and molten salts) operated at high temperature
- 3 types of Ion-sources: Surface, Plasma, laser
- > 1000 nuclides of 74 chemical elements produced→ **B** ($BF_2$) and **Ge** (GeS)



See Talk of Bruce Marsh!

# The type of Material matters!

The new target material allowed for spectroscopic studies

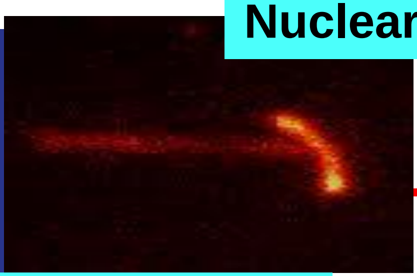


mgb@cern.ch

# Research with radioactive nuclides @ ISOLDE

ISOLDE today offers the largest range of available nuclei ( >1000 of 74 elements) of any ISOL facility worldwide.

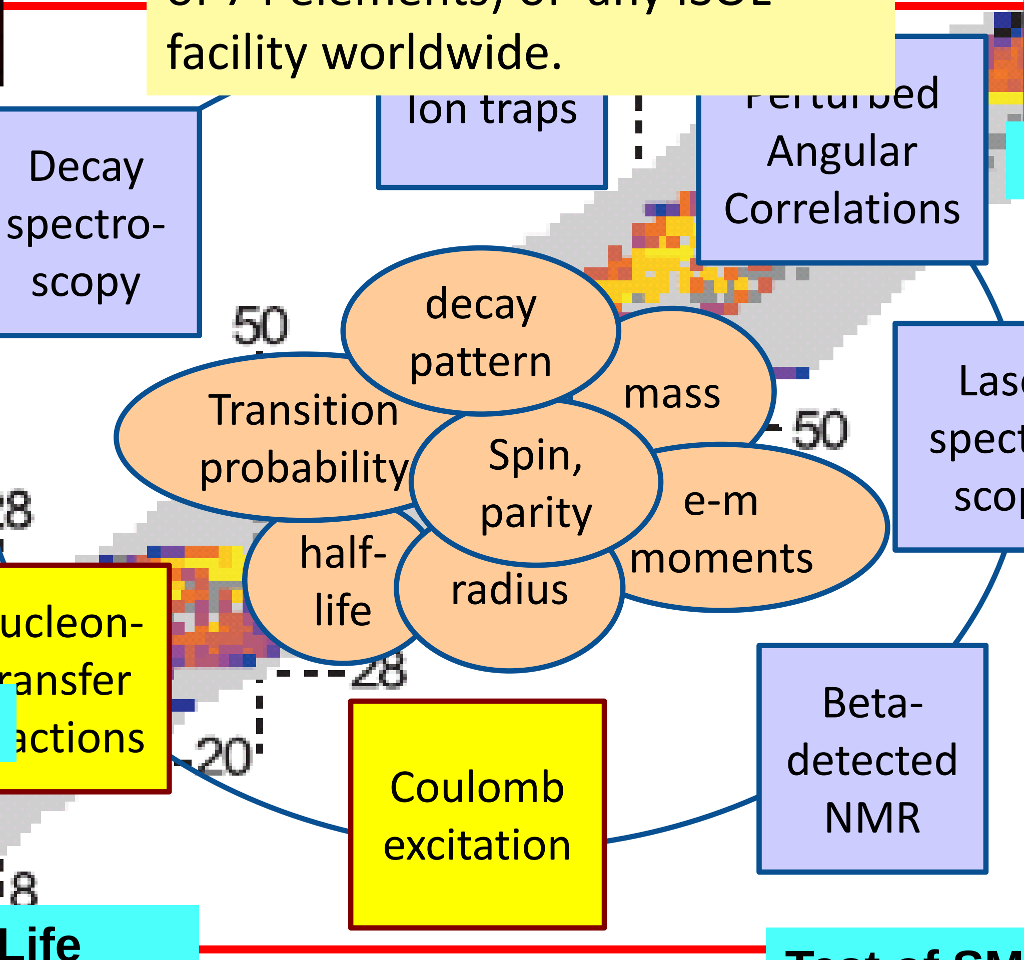
**Nuclear Phys**



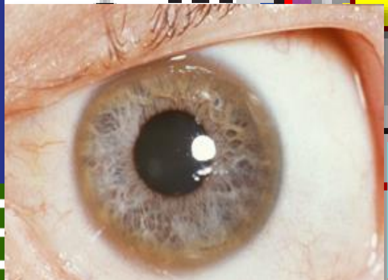
**Atomic Phys**

**Astrophys**

**Nucleo-synthesis**

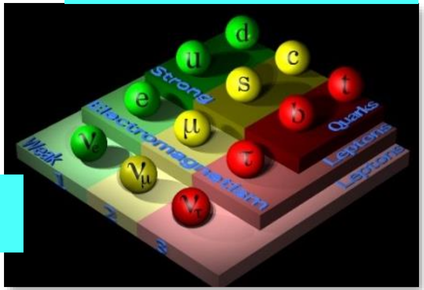


**Material Science**



**Life Science**

**Fundamental Symetries**

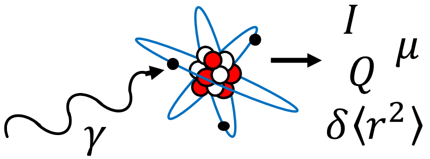


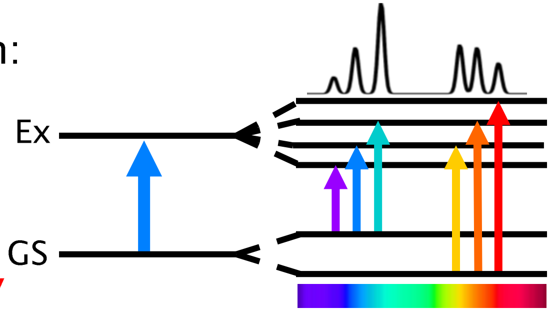
**Test of SM**

Techniques: all available at ISOLDE

# Studying nuclear structure

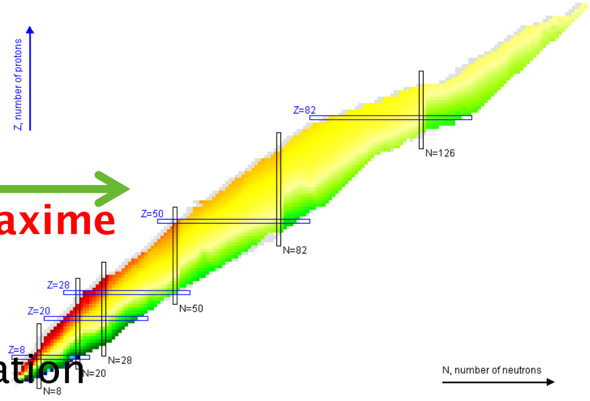
- The atomic hyperfine structure gives you information on:
    - Nuclear spin
    - Magnetic moment
    - Quadrupole moment
    - Relative charge radii



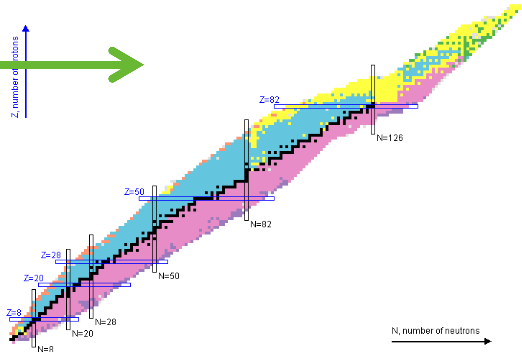


- Method: COLLAPS, CRIS (laser spectroscopy) **See talk by Klaus Wendt**

- The mass of the nucleus gives you information on:
    - Binding energy
    - Proton and neutron separation energy
- Method: ISOLTRAP (mass spectrometry) **See talk by Maxime Brodeur**



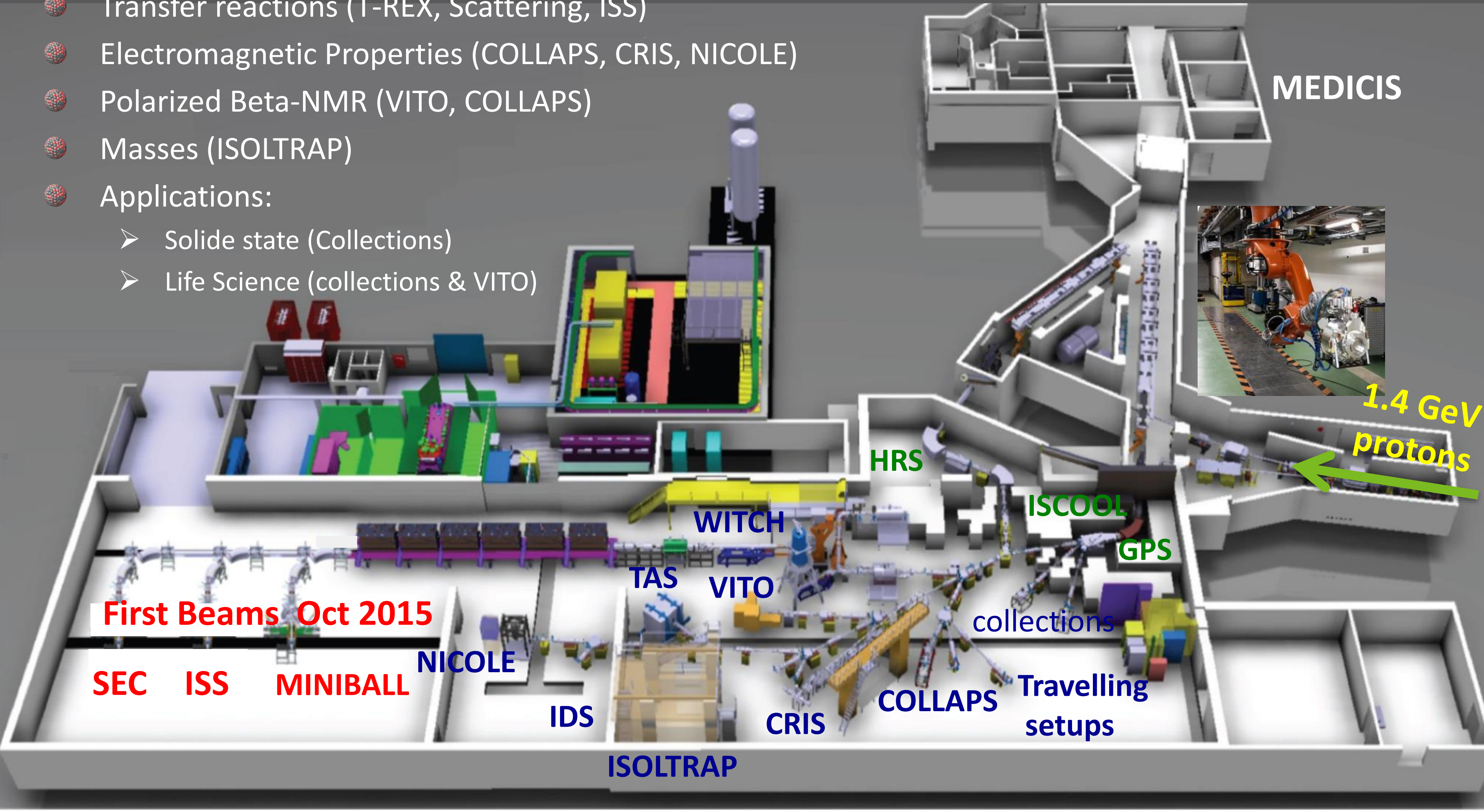
- The radioactive decay of the nucleus gives you information on:
    - Decay mechanism
    - Branching ratio
    - Life time, …
- Method: IDS, MINIBALL, ISS (decay spectroscopy)
- Reaction studies ISS, SEC



**A variety of experimental methods can provide complementary information on the structure of the nucleus!**

# ISOLDE

- Decay spectroscopy (IDS, TAS,..)
- Coulomb excitation (MINIBALL)
- Transfer reactions (T-REX, Scattering, ISS)
- Electromagnetic Properties (COLLAPS, CRIS, NICOLE)
- Polarized Beta-NMR (VITO, COLLAPS)
- Masses (ISOLTRAP)
- Applications:
  - Solide state (Collections)
  - Life Science (collections & VITO)



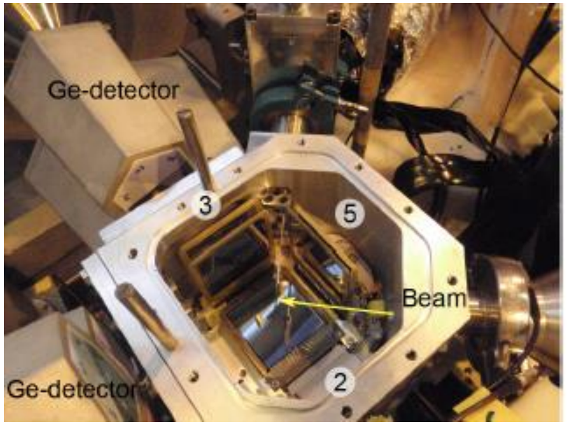
— Post-accelerated Exps (5.5 MeV/u); — Low Energy (30-60kV) Exps, — Machine elements

# Recent Highlights

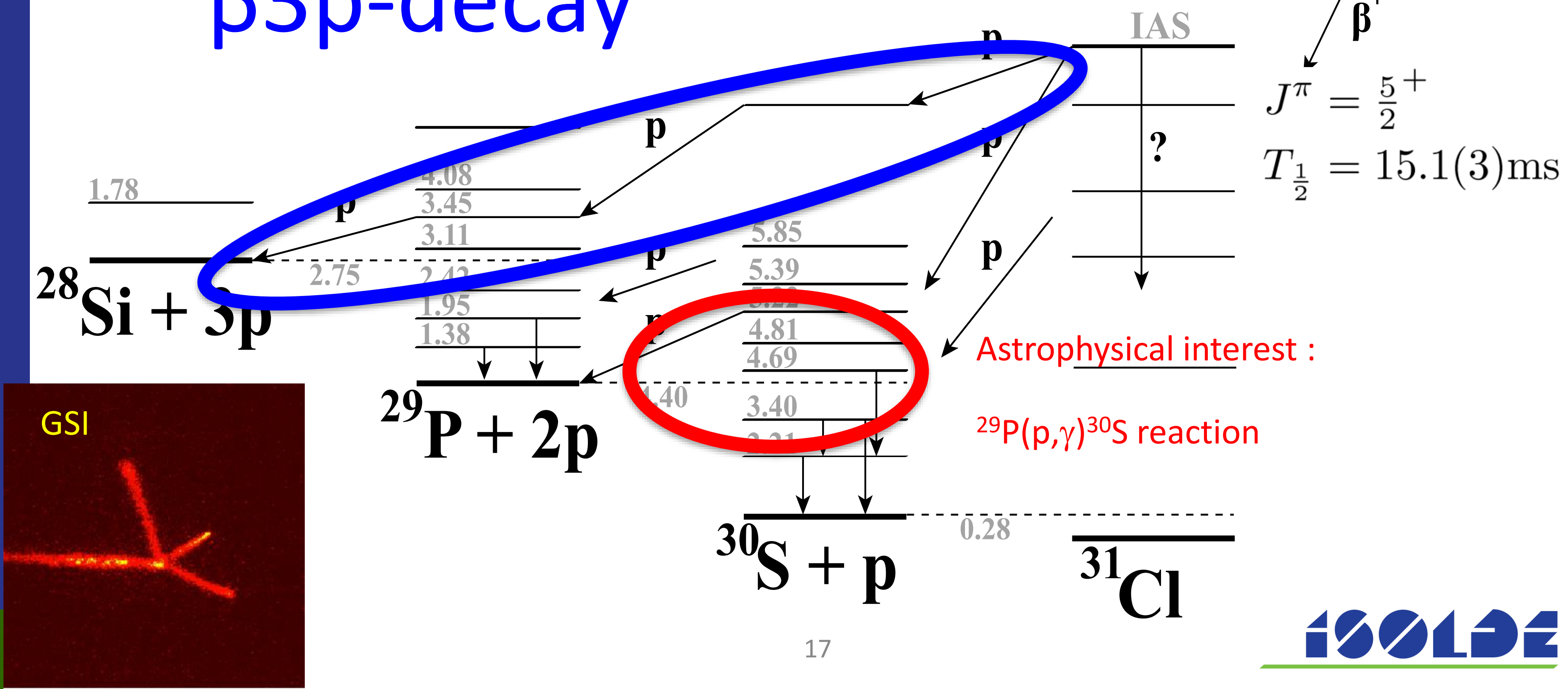
*(Picking flowers in the nuclear landscape)*

# Study of $^{31}$Ar β - Decay

- **Emphasis in levels near the proton threshold of astrophysical interest**
- Interesting due to the mutiple decay modes: **β2p and β3p**



## β3p-decay

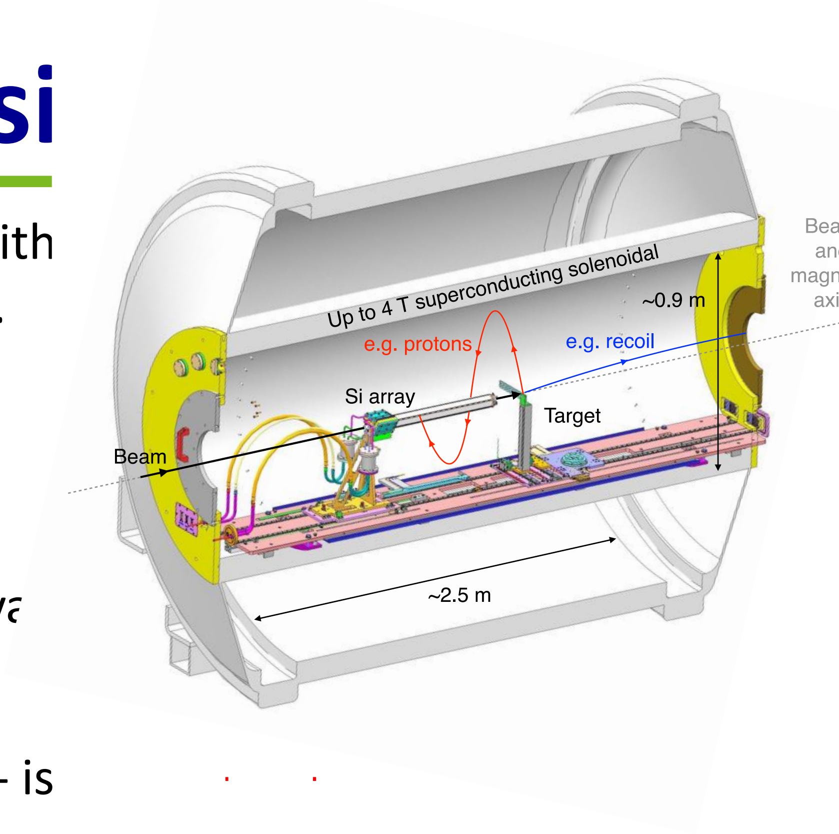


Astrophysical interest :

$^{29}$P(p,γ)$^{30}$S reaction

# Island of Inversi

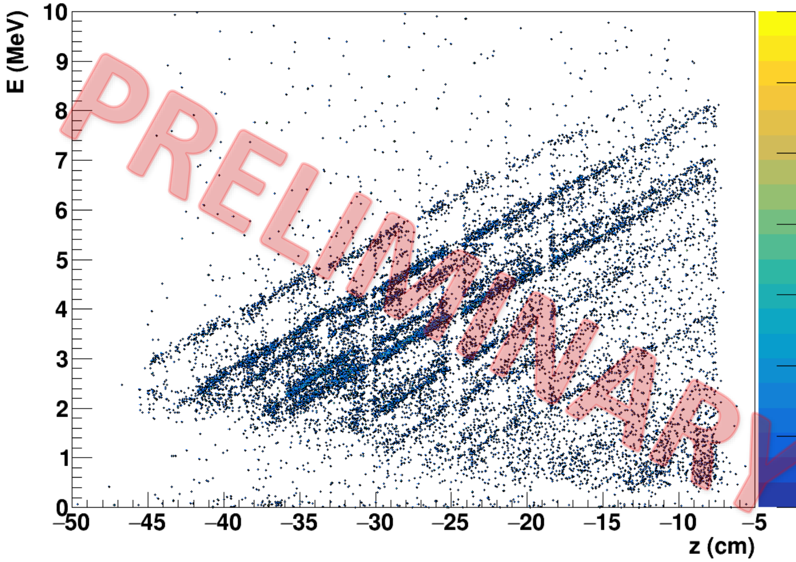
- In Mg isotopes **the transition is sharp** with $^{31}$Mg inside the island and $^{30}$Mg outside.
- Measurements of the **single-particle properties** moving in to the island of inversion provide important systematic information on the behavior of the releva orbitals and shell gaps.



- Single-nucleon transfer reaction - (*d,p*) - is ideal probe of these properties

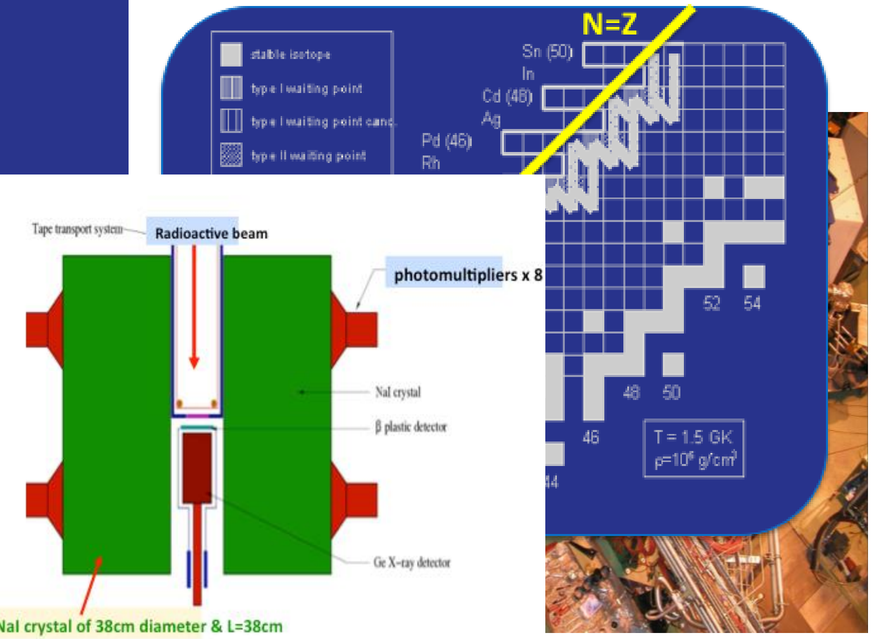
- Proton energy vs position from target for **$^{28}$Mg(d,*p*)$^{29}$Mg** reaction

- **9.473 MeV/u** beam – **highest HIE-ISOLDE beam energy**.

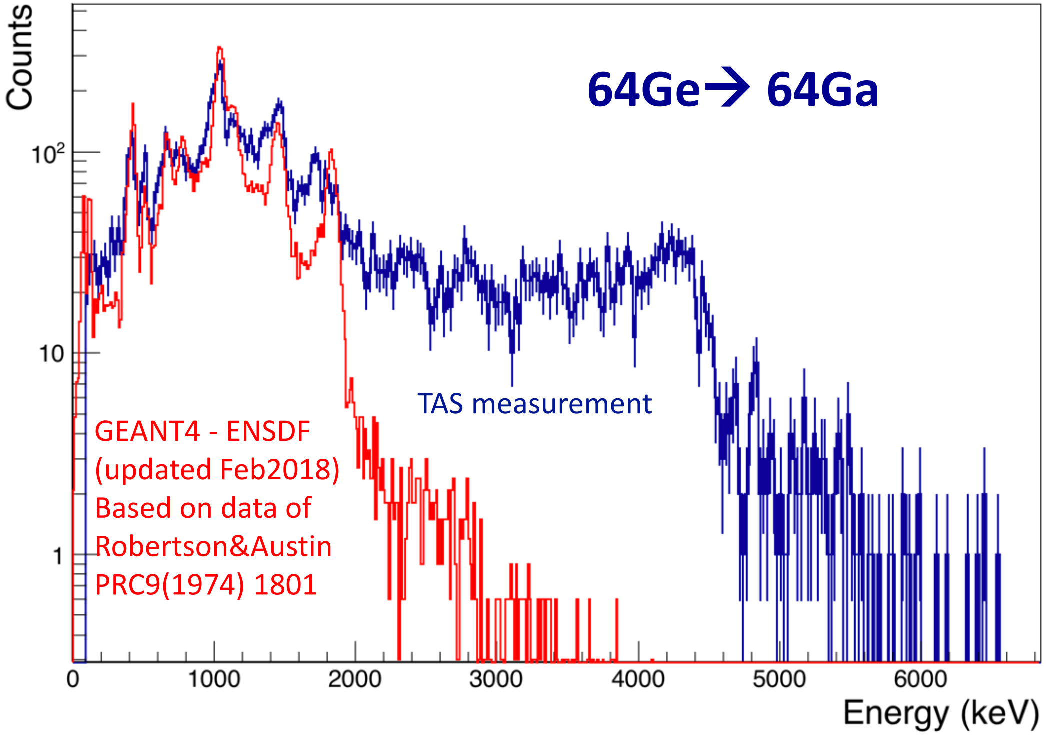


# Studies of astrophysical interest with TAS

- rp-process :a neutron star can get power up by acreting materia from its binary partner.
- rp-process: along the p drip-line => X-ray burst type I ➔Main observable luminosity curves➔
- Observables: mass, $Q_\beta$, EC/$\beta^+$ strength
- Recent RPA calculation show the importante in the decay rate of the continous Electron Capture
- The ration β+/EC should be determine experimen



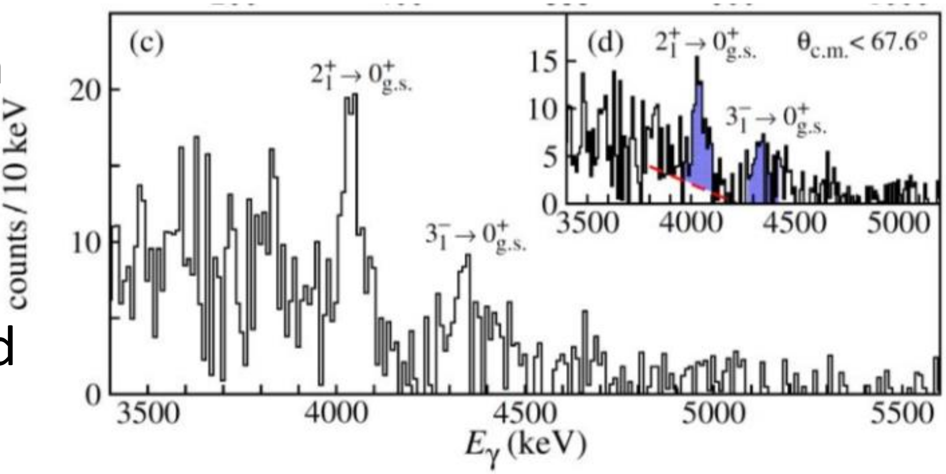
IEM-CSIC, Strasbourg, Surrey, Valencia



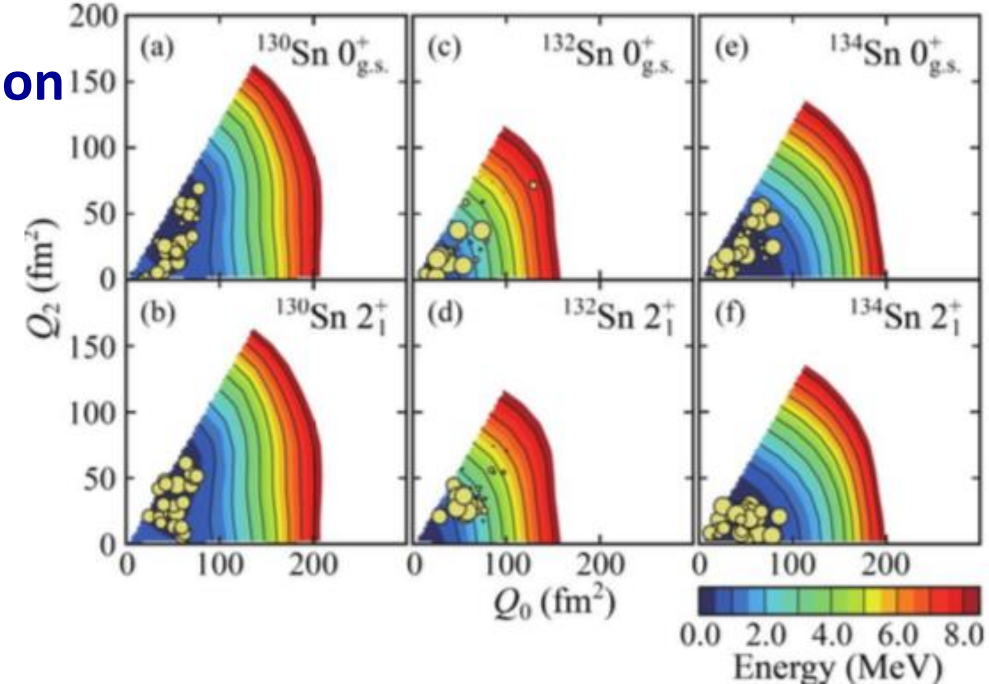
# Study of the Magicity of $^{132}$Sn

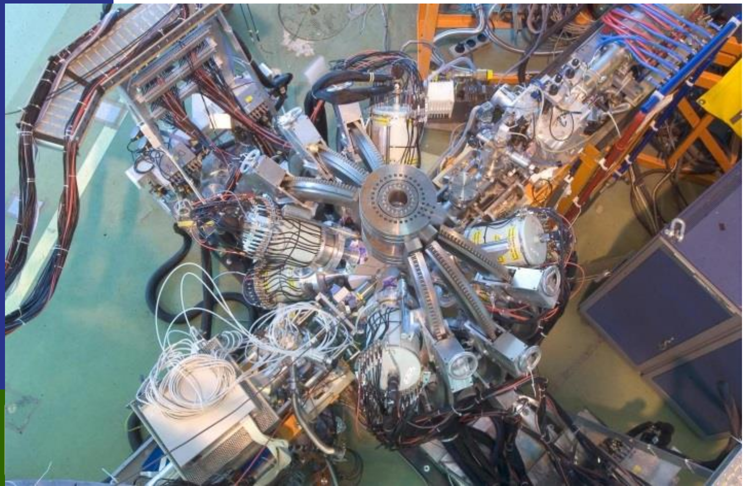
- Study of excited states of $^{132}$Sn @5.39 MeV/u
- Identification of transition to the 2$^+$ and 3$^-$
- Excitation energies of 2$^+$,4$^+$ and B(E2) well reproduced.

The T-plot of Togashi exhibit strong confinement towards spherical limit.➔ **First verification of magicity of $^{132}$Sn**

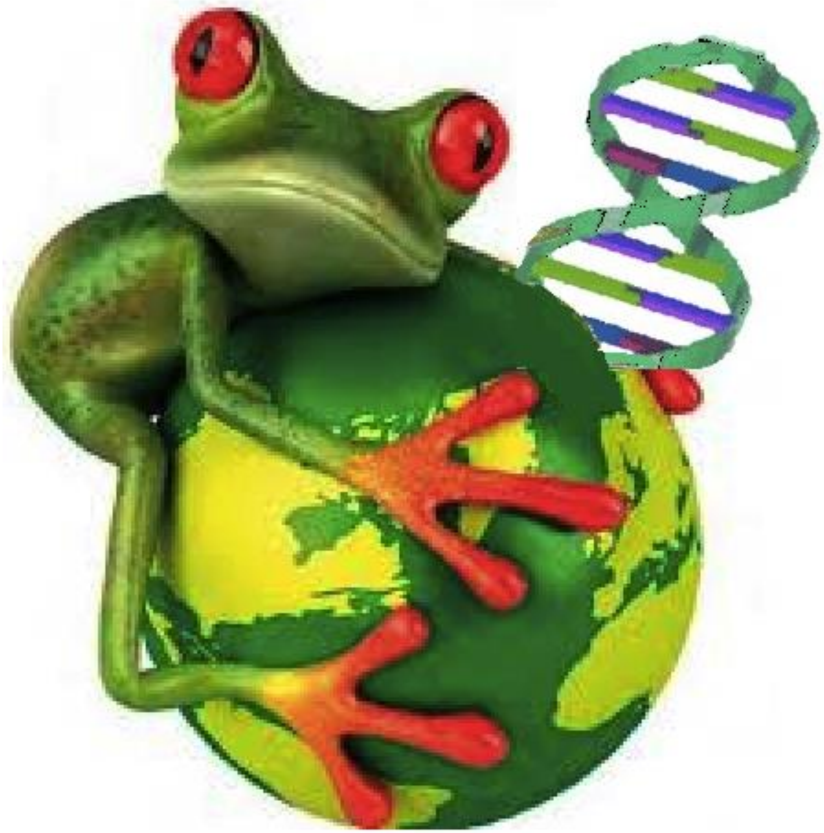


Rosiak et al., PRL121 (2018) 252501



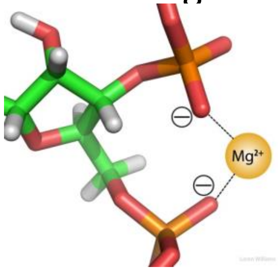


# Application
# To Life Sciences



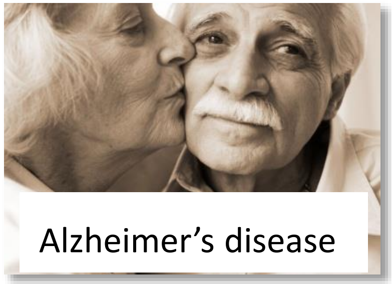
# Biology: metals and biomolecules

- Role of metal ions in human body depends on adopted coordination environment
- Right concentration crucial for correct functioning of cellular processes
- Nuclear Magnetic Resonance is a powerful tool but challenging for metal ions, e.g. Na, K, Mg, Cu, Zn:
  - Closed electron shells
  - Weak and/or broad signals

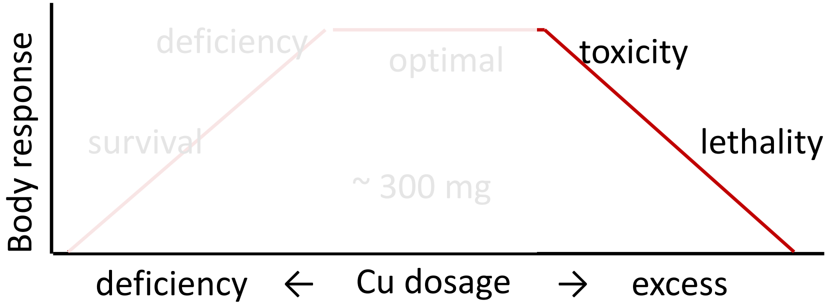


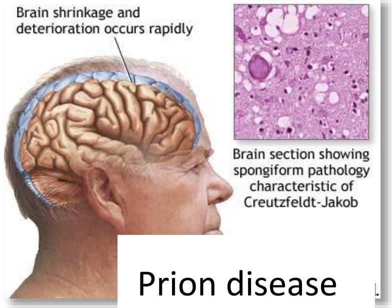
- **Ultrasensitive approach needed: beta-detected NMR**

➢ Copper


Alzheimer's disease


Wilson's disease





Prion disease

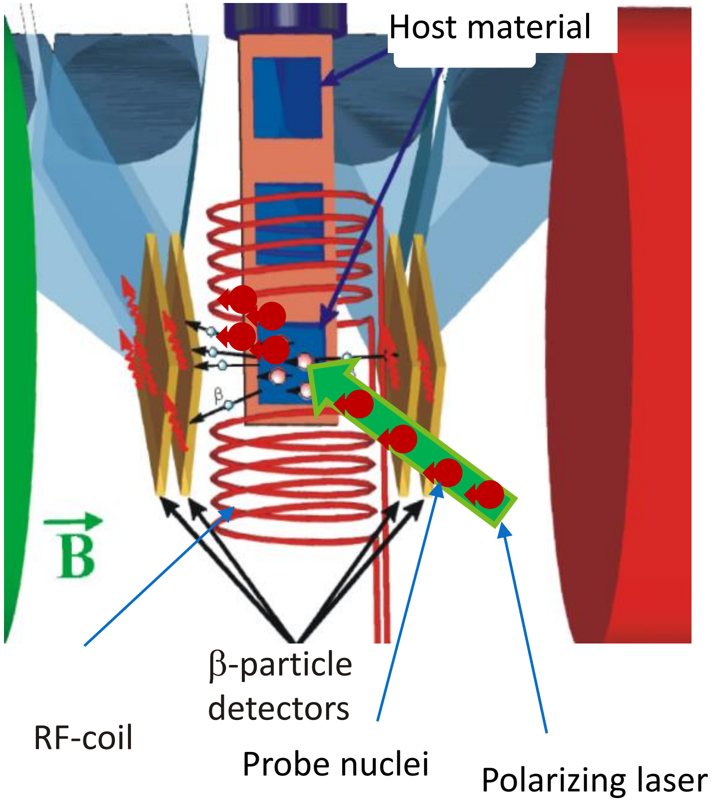

Parkinson's disease

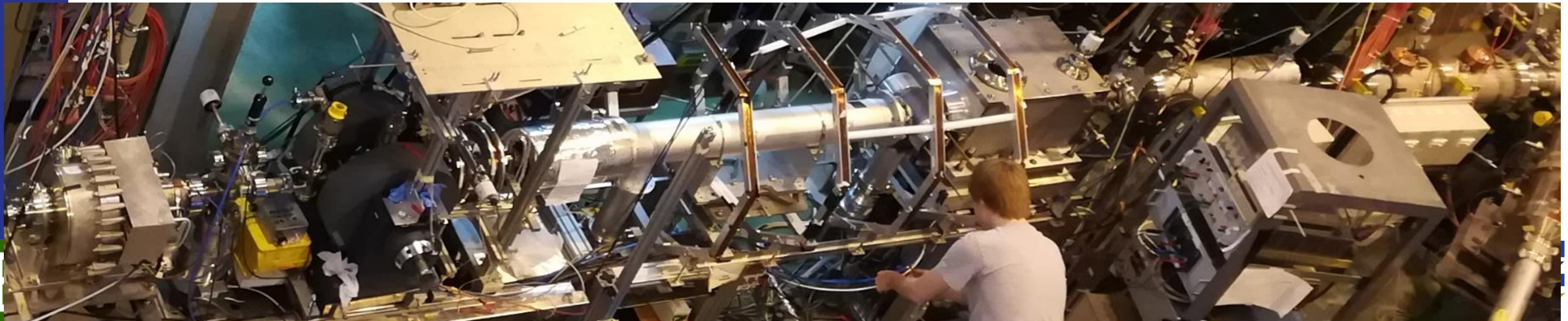
Courtesy of M. Kowalska

# Beta(-detected) NMR

- Same principles as conventional NMR
- Ingredients:
  - Radioactive NMR-active beta-decaying nuclei
  - Beta particles emitted in spin direction
- Detection of NMR resonances:
  - **Asymmetry in beta decay in space**
  - **At resonance: decrease in asymmetry**
- When combined with spin polarization

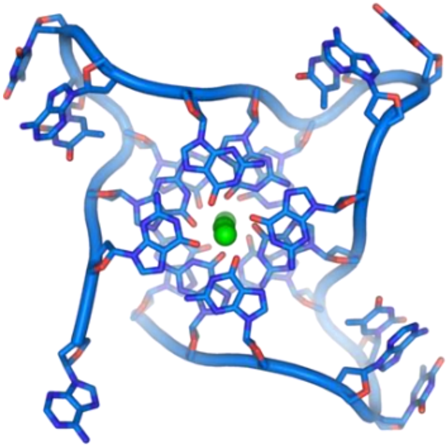
**=> Beta-NMR can be up to $10^{10}$ more sensitive than conventional NMR**

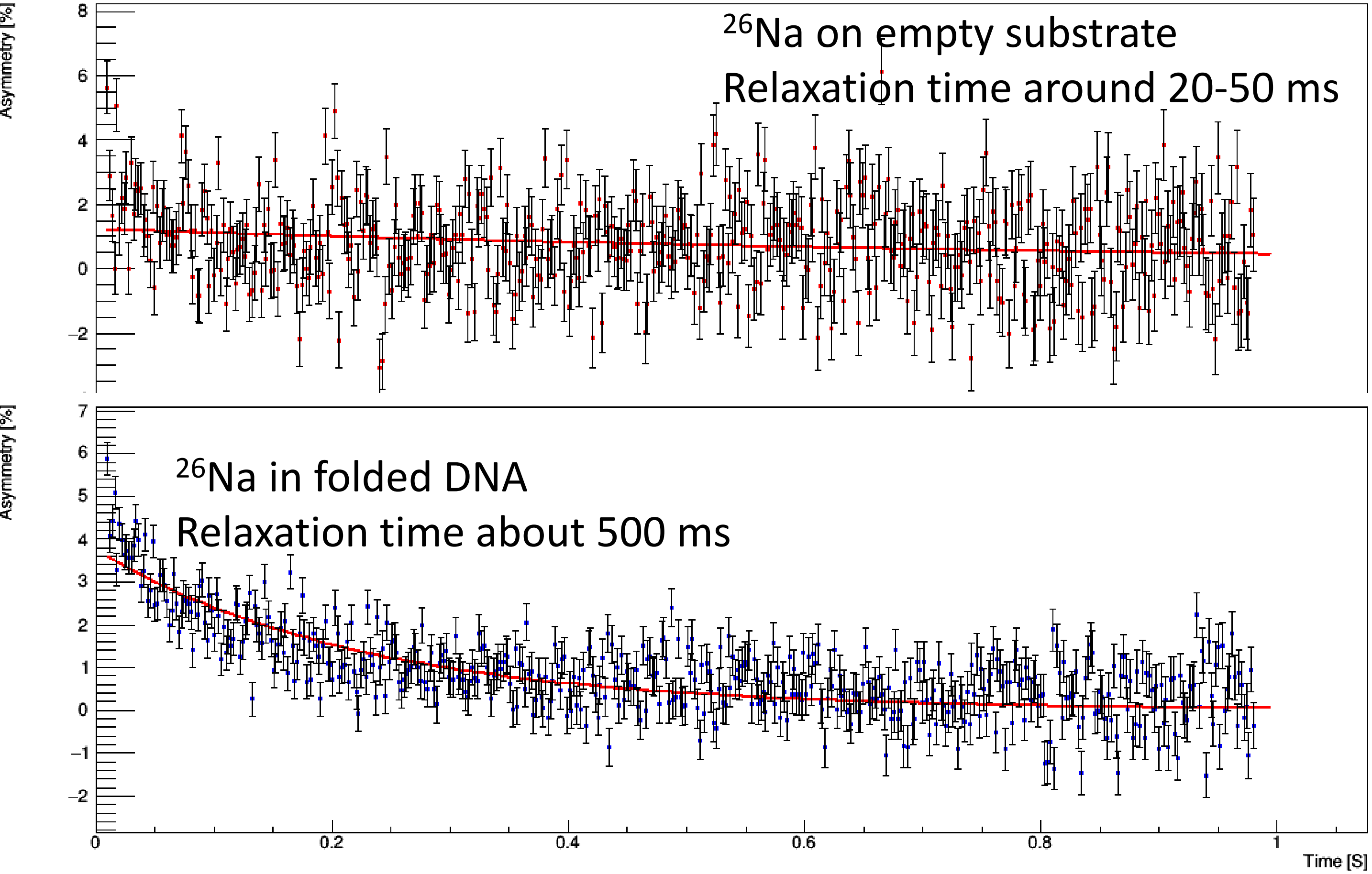




# First bio-study: sodium and DNA

- 2018: Interaction of Na+ with guanine-rich DNA fragments:
  - Formation of so-called G-quadruplex structures





$^{26}$Na on empty substrate

Relaxation time around 20-50 ms

$^{26}$Na in folded DNA

Relaxation time about 500 ms

In presence of DNA: Na environment becomes more homogenous

Courtesy of M. Kowalska

NMR resonances from October 2018: under analysis

M. Kowalska et al, Proposal to the ISOLDE Scientific Committee, June 2017, addendum: January 2018

M. Trajkovski et al, J. Am. Chem. Soc. 134, 4132 (2012)

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# Nuclear Physics & Medicine

The fastest technology transfer

of the history

Diagnosis:

Tracing

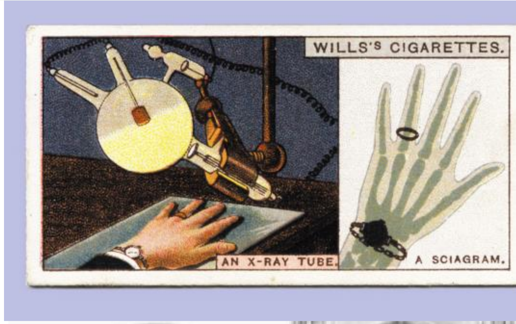
Dynamic of the metabolic system

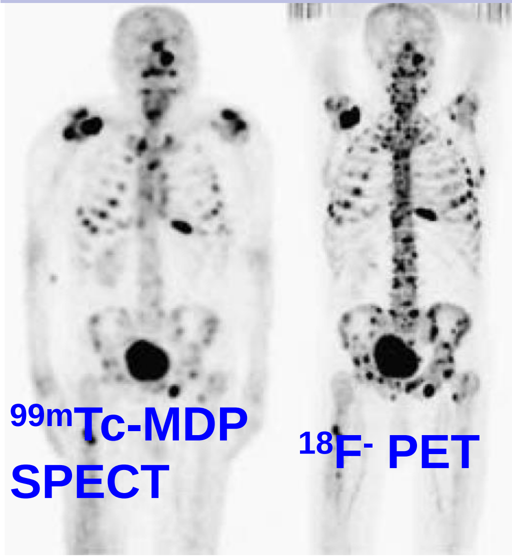
Medical Imaging

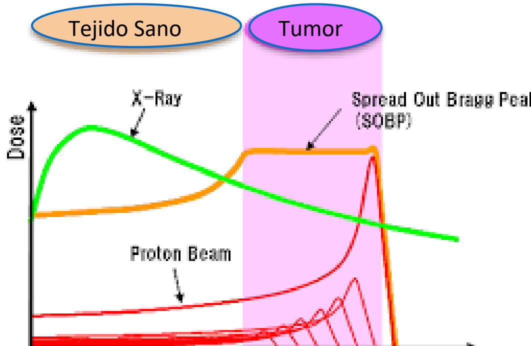
Computatised tomography of 1 photon

Tomography of emission of positron

- Treatment /therapy:
  - Use of radio-isotopes
  - Proton or heavy ion accelerator





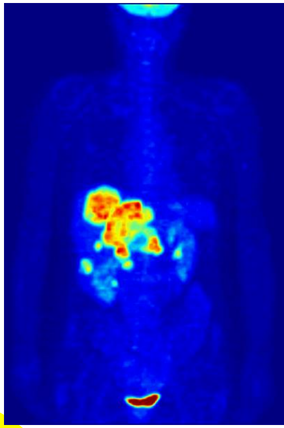


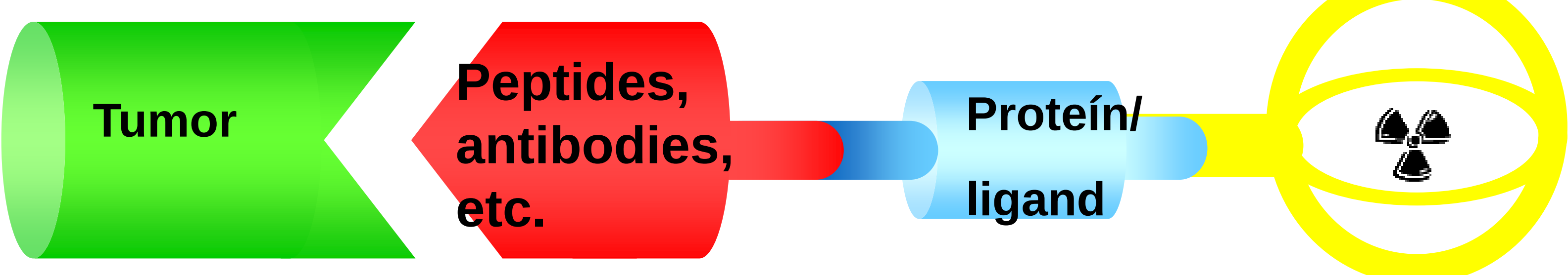
# Multidisciplinary Efforts to fight the cancer

Personalised Treatment ↔ Different responses to the same drug

Same Chemical elements of Diagnosis and Treatment :

Theranostics Pairs





**Tumor**

**Peptides, antibodies, etc.**

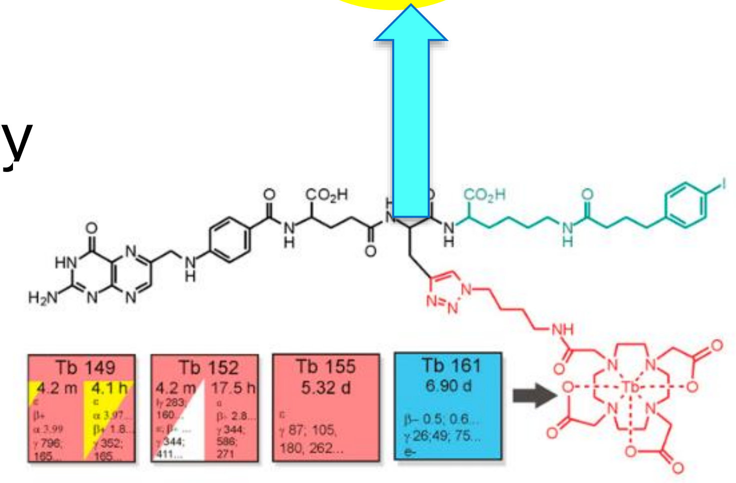
**Proteín/ ligand**

Receptor

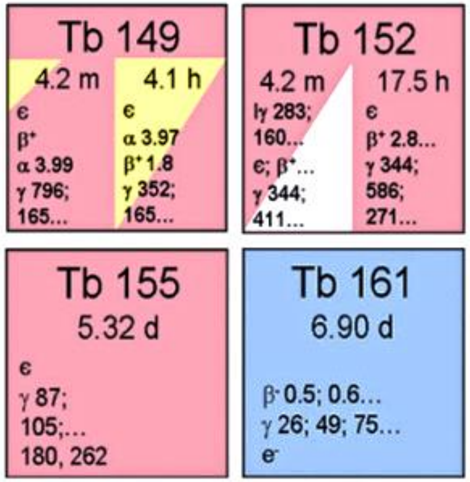
Immunology

Biochemistry

Bombesin is a ligand successfully used with $^{155}$Tb (5 d) and $^{125}$I (59 d) for prostate, mama and stomach cancers



# Terbium:
# a unique element for nuclear medicine



Tb 149
4.2 m
ε
$\beta^+$
α 3.99
γ 796;
165...
4.1 h
ε
α 3.97
$\beta^+$ 1.8
γ 352;
165...

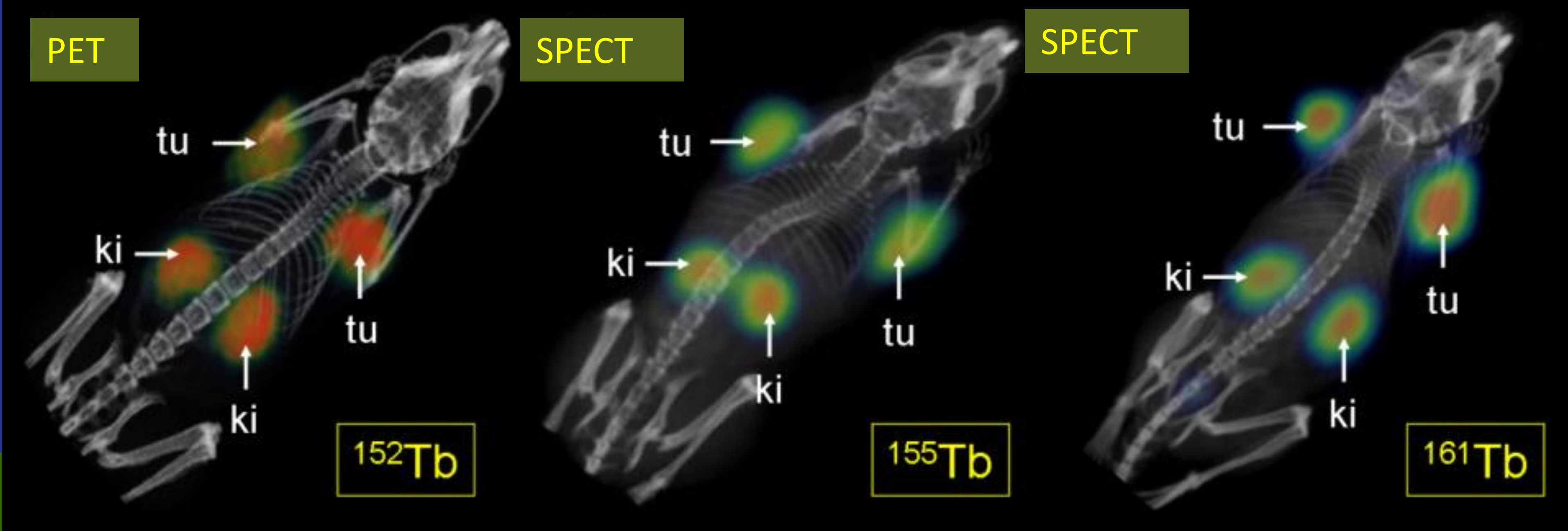
Tb 152
4.2 m
Iγ 283;
160...
ε; $\beta^+$...
γ 344;
411...
17.5 h
ε
$\beta^+$ 2.8...
γ 344;
586;
271...

Tb 155
5.32 d
ε
γ 87;
105;...
180, 262

Tb 161
6.90 d
$\beta^-$ 0.5; 0.6...
γ 26; 49; 75...
$e^-$

14 years ago – now :
Innovative radioisotopes
Tb: 4 isotopes for
Medicine:
Diagnosis & **Therapy**

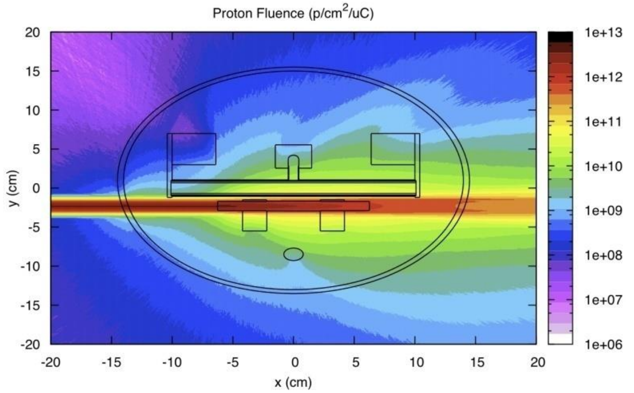
**α ($^{149}$Tb),**
**β+ ($^{152}$Tb)**
**β+ ($^{155}$Tb)**
**β- ($^{161}$Tb)**



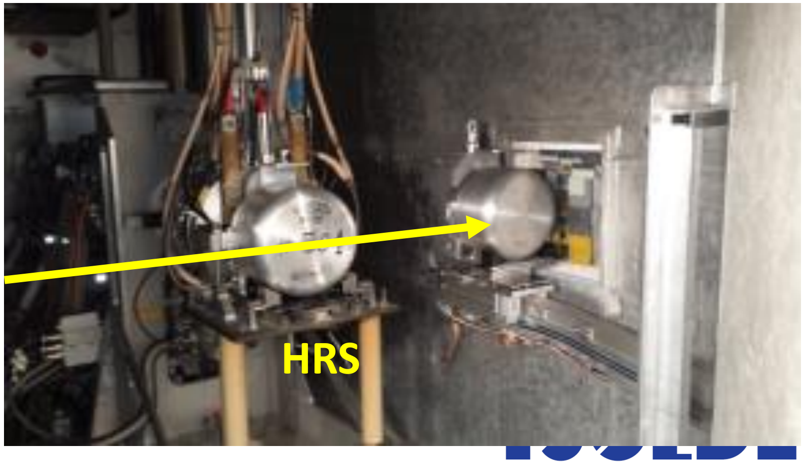
# The CERN proton beam can be recycled

**MEDICIS:** a spin-off dedicated to R&D in life sciences and medical applications. For fundamental studies in cancer research, for new imaging and therapy protocols in cell and animal models and for pre-clinical trials.

- When a CERN proton beam intercepts a target → large part of the proton beam passes through

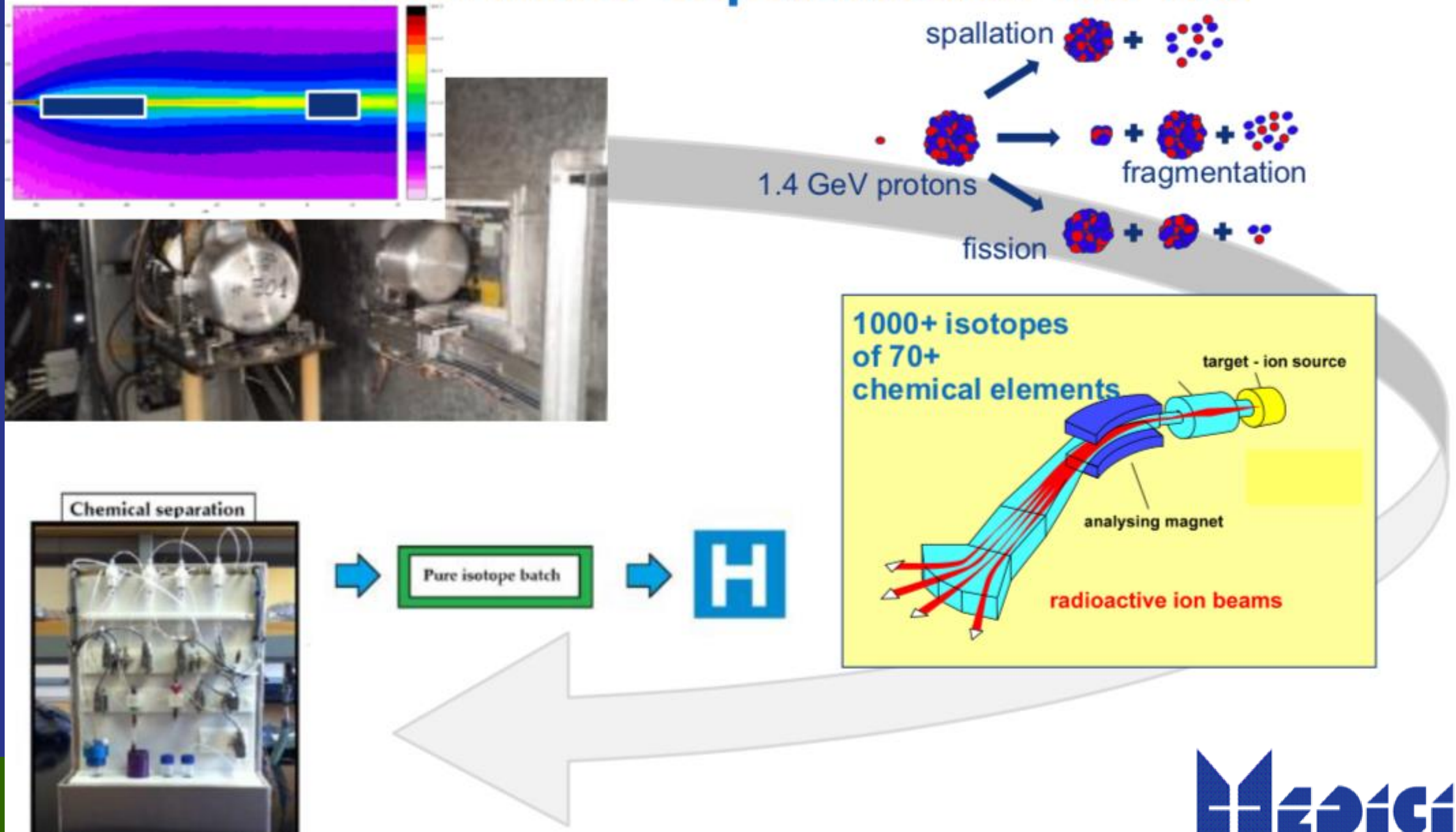


- 30-50% of 1.4 GeV CERN protons reaching the dump and can be use to irradiate another target before being collected in the beam dump



# From CERN- MEDICIS to the lab/Hospital

## Isotope production in the HRS beam dump and mass separation in the lab


1.4 GeV protons

spallation

fragmentation

fission

1000+ isotopes
of 70+
chemical elements

Chemical separation

Pure isotope batch

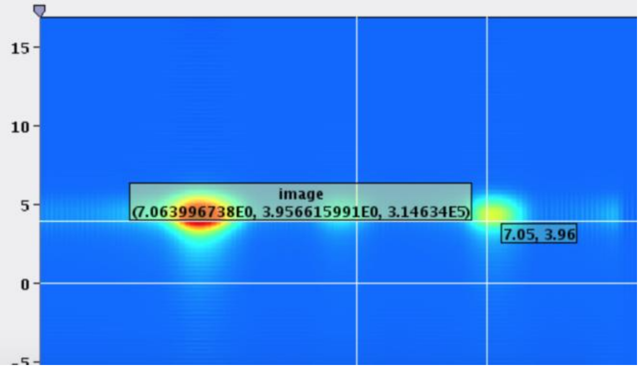
# 1st results from MEDICIS operation

- Irradiation on Ta target started 18th – 22nd May

  $2.7x10^{18}$proton on Target (No Radio-protection issues)

4 Batches produced for UK ($^{155}$Tb) and CHUV ($^{149}$Tb, $^{165}$Tm)

- 1 experiment dedicated to $^{11}$C from BN target



- **2nd used neutron activated targets @ILL (Grenoble)**

  -Isotope separation from external $^{168/169}Er_2O_3$

**-1st Production of 20MBq of non carrier added $^{169}$Er (pure $\beta^-$ emitter);**

Milestones: **1 GBq collected, 10% $^{149}$Tb separation** yields, Uranium target irradiated

**Prospects for increase in yields using laser ion source, simple radiochemistry laboratory**

# MEDICIS-Promed Final Conference, 29 April-4 May 2019 Erice (Sicily), Italy

•*Accelerator techniques for medical isotope production*

•*Devices and engineering for isotopes handling*

•*Methods for production of novel radioisotope in theranostics*

•*Radioisotope beams in hadron therapy*

•*Pre-clinical research and development of new radiopharmaceuticals*

You are very welcome to participate (T Stora)

Preparation of new EU Project INFRA

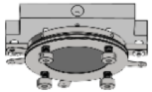
# Summary & Outlook

- ISOLDE offers the **largest variety** of ISOL radioactive and post-accelerated beams in the World.
- ISOLDE is in continuous transformation to stay at the forefront of nuclear physics research.
- The energy upgrade up 10 MeV/u for A/q = 4.5 is operative since 2018.
- The intensity upgrade of the injector operative in 2020.
- MEDICIS started in 2017. Capitalized in the experience gained at ISOLDE.
- Production of radio-isotopes and distribution to different centers of research done in 2018
- Laser Ion Source in 2019 (Melissa), Three collection points,….

Thanks for your attention!!

# Masses & Magic Numbers

MCP

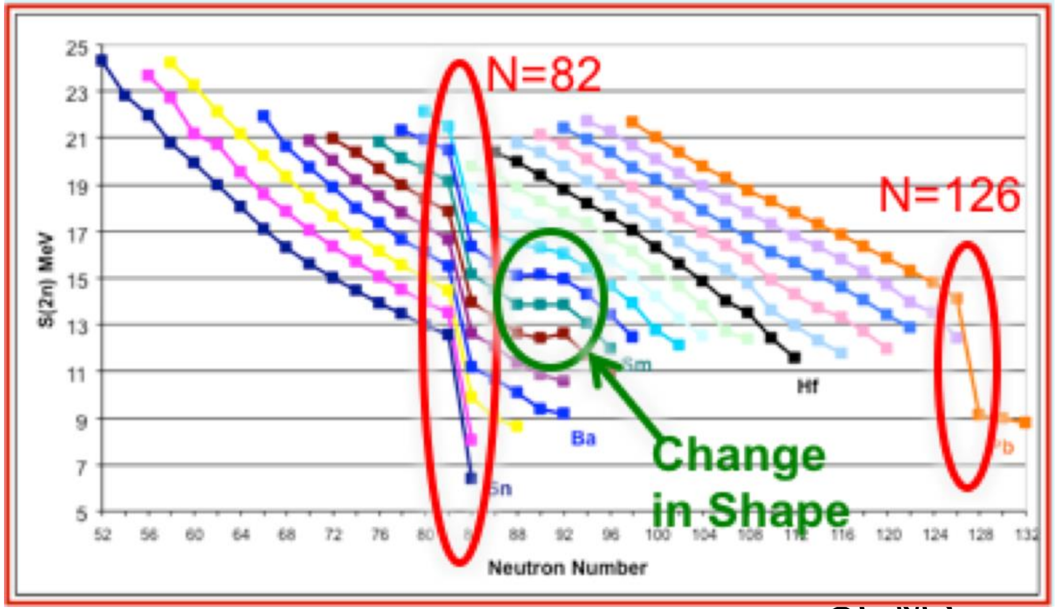


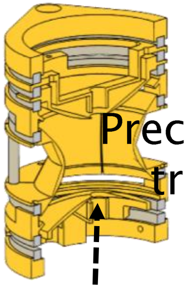
$$M_{Atom} = N \cdot m_{neutron} + Z \cdot m_{proton} + Z \cdot m_{electron} - (B_{atom} + B_{nucleus})/c^2$$

$\delta m/m < 10^{-10}$

$\delta m/m = 10^{-6} - 10^{-8}$

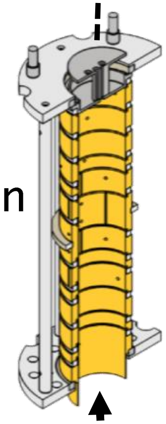
$$S_{2n}(N,Z) = ME(N-2,Z) - ME(N,Z) + 2 \cdot ME(n)$$





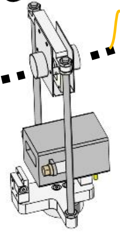
Precision trap

50 – 2000 ms

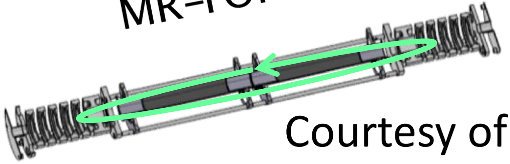


Preparation trap

50 – 200 ms



Bradbury-Nielsen beam gate



MR-TOF MS

Courtesy of V Manea

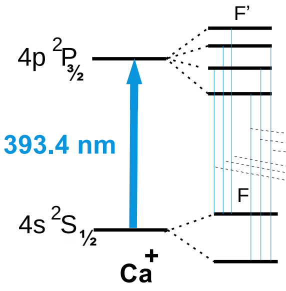
5 – 20 ms

RFQ cooler and buncher

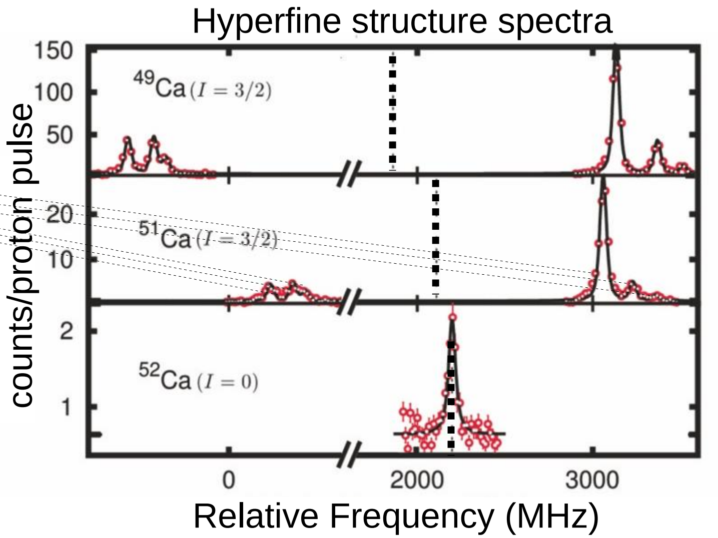
See talk by M. Brodeur!

F. Herfurth *et al.*, NIM A 469, 254 (2001).
R. N. Wolf *et al.*, Int. J. Mass Spectrom 313, 8 (2012).
G. Savard *et al.*, Phys. Lett. A 158, 247 (1991).
M. König *et al.*, Int. J. Mass Spectrom. 142, 95 (1995).

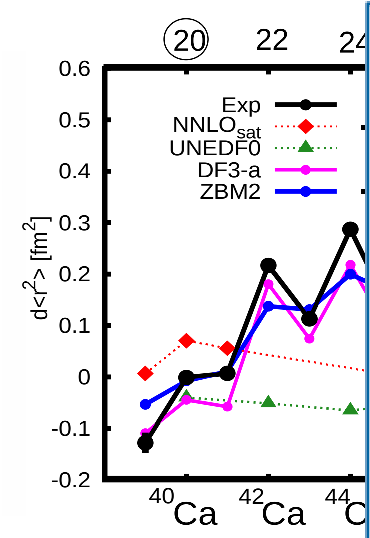
# Exploring the nature of N=32

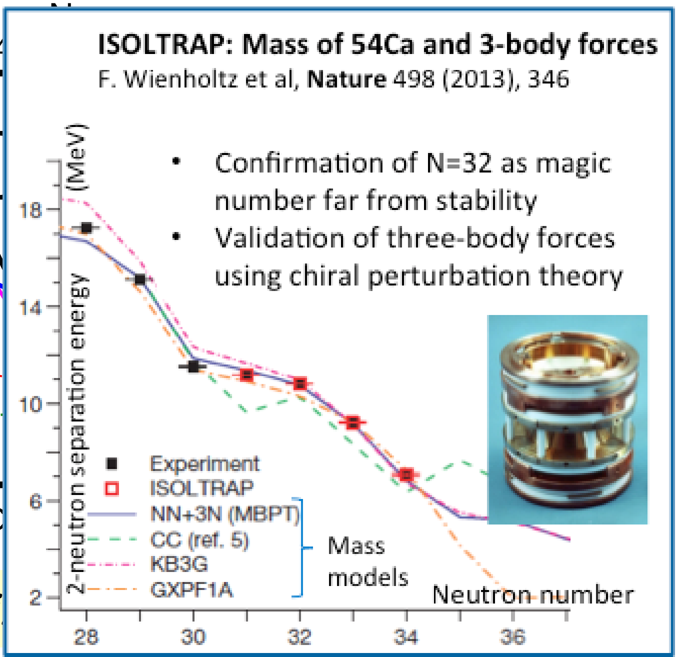


Level scheme for resonance excitation



- Collinear laser Spectroscopy study of Ca-isotopes: $^{40\text{-}52}$Ca
- Change in nuclear size produces a shift in the hfs.

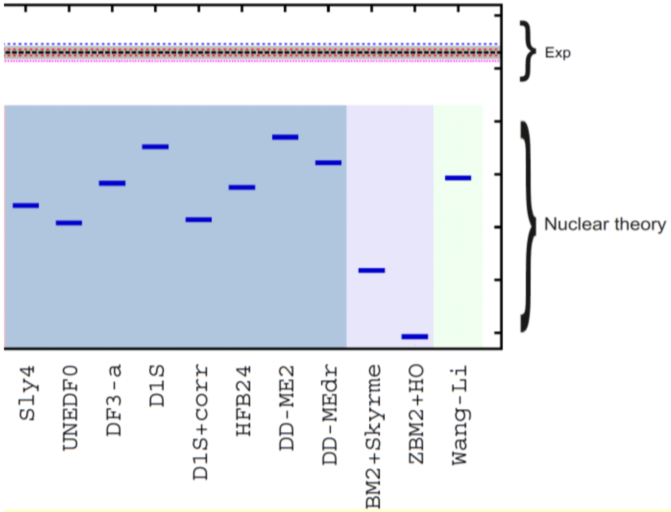




**ISOLTRAP: Mass of 54Ca and 3-body forces**

F. Wienholtz et al, **Nature** 498 (2013), 346

- Confirmation of N=32 as magic number far from stability
- Validation of three-body forces using chiral perturbation theory



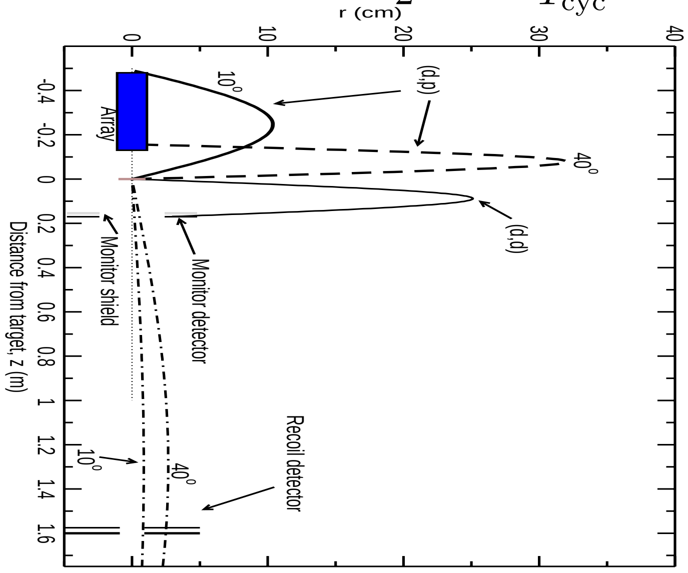
*R. F Garcia Rui* **12 (2016) 594**

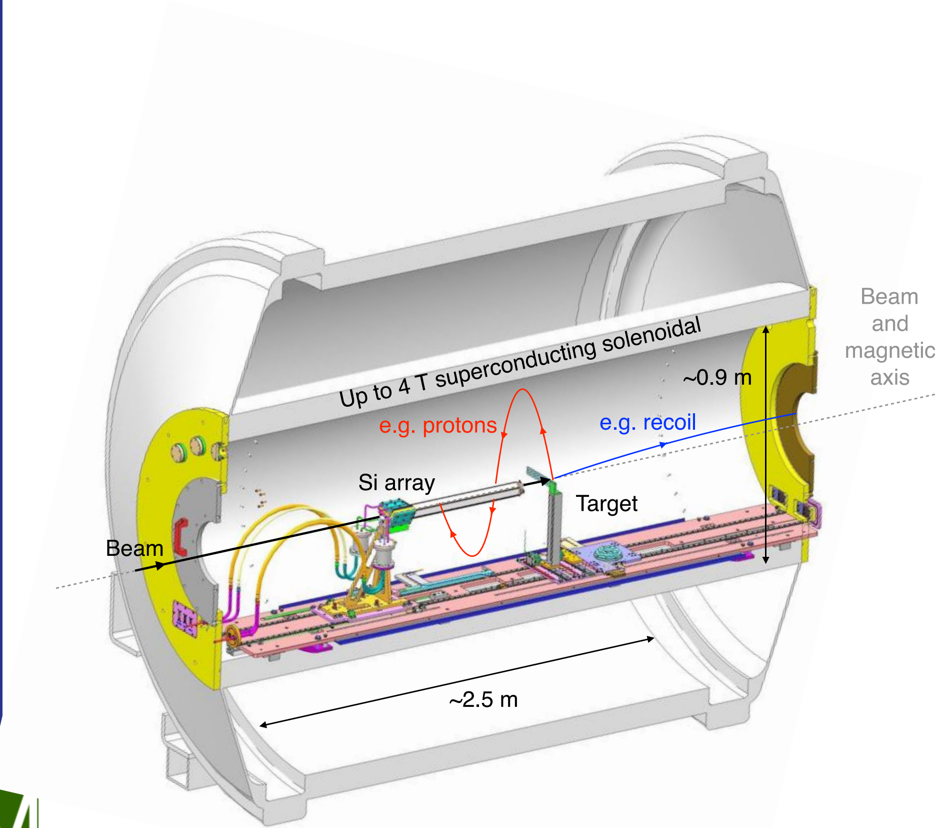
# ISOLDE Solenoidal Spectrometer

Solenoid with target on field axis.

*MEASURED QUANTITIES:* position *z*, cyclotron period $T_{cyc}$ and lab particle energy $E_p$

$$E_{\rm cm} = E_{\rm lab} + \frac{mV_{\rm cm}^2}{2} - \frac{mzV_{\rm cm}}{T_{\rm cyc}}$$

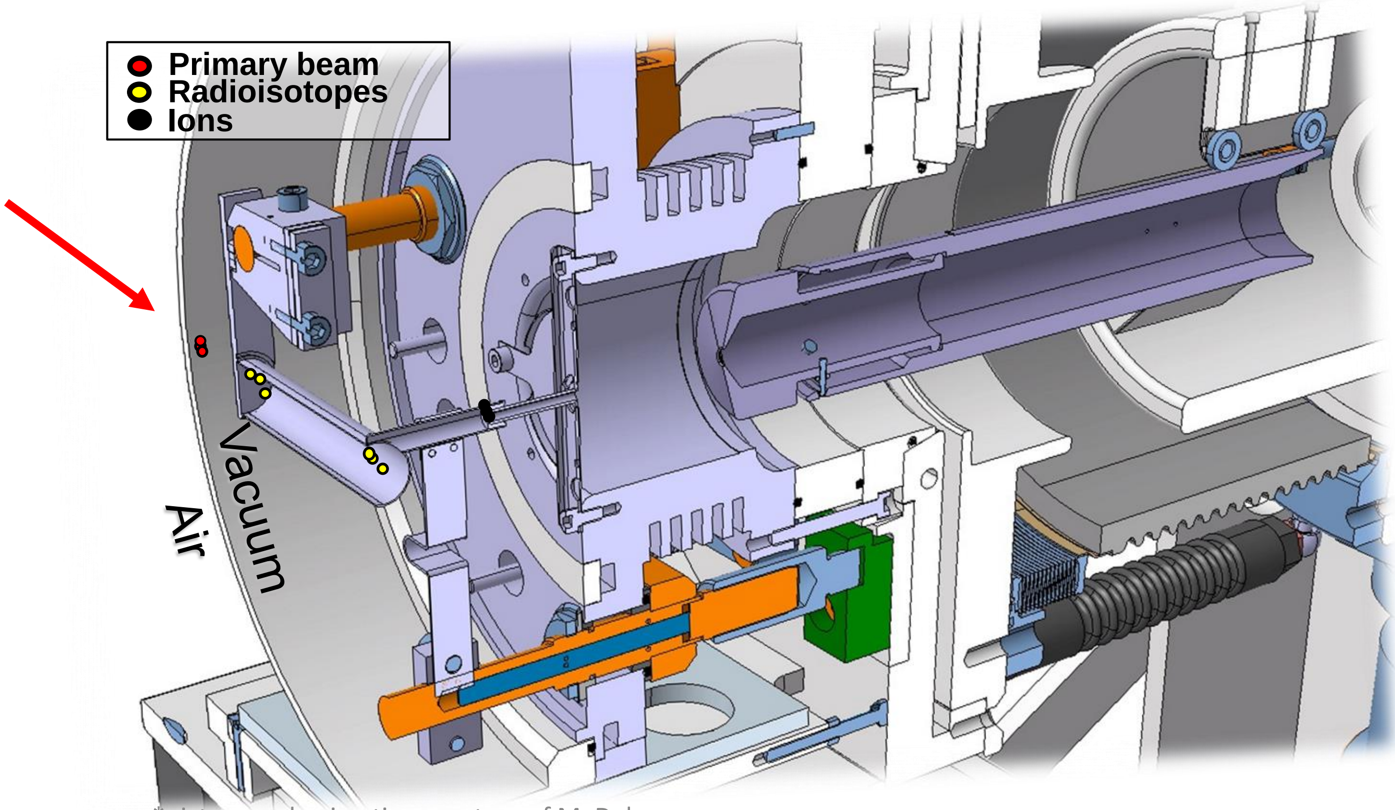




Outgoing protons from (*d,p*) reaction follow helical orbits back to the beam/magnetic axis and are detected by position sensitive silicon array.

Recoils detected downstream in dE-E silicon detector.

# Production Targets

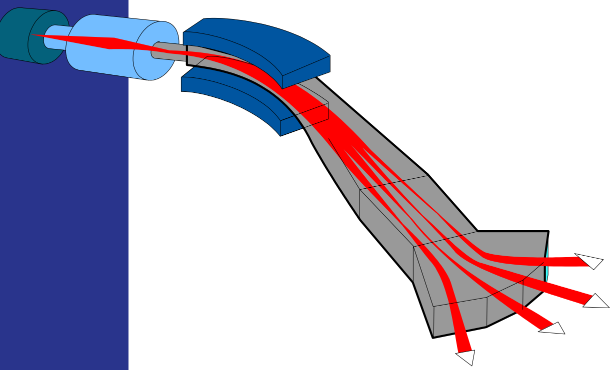


*picture and animation courtesy of M. Delonca

- 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

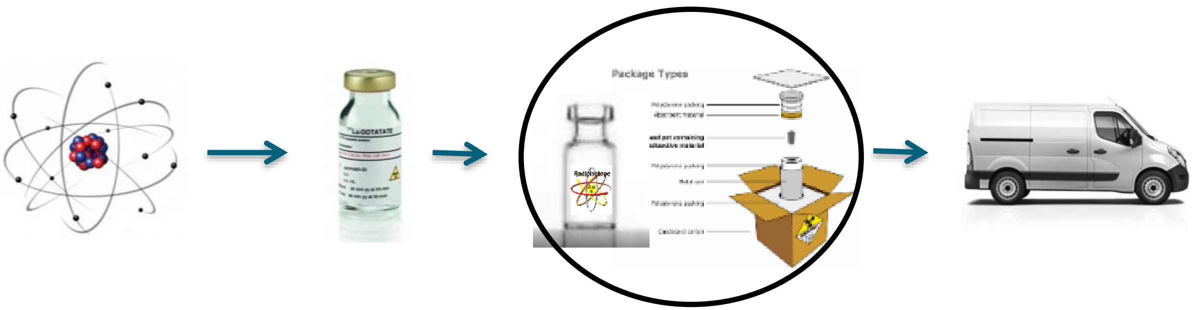
# From CERN- MEDICIS to the lab/Hospital

- The irradiated target-ion source unit in batch mode is taken by a monotrac and plug to the mass separator. Then it is heated to 2000C and the products are mass separated and send for distribution.



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

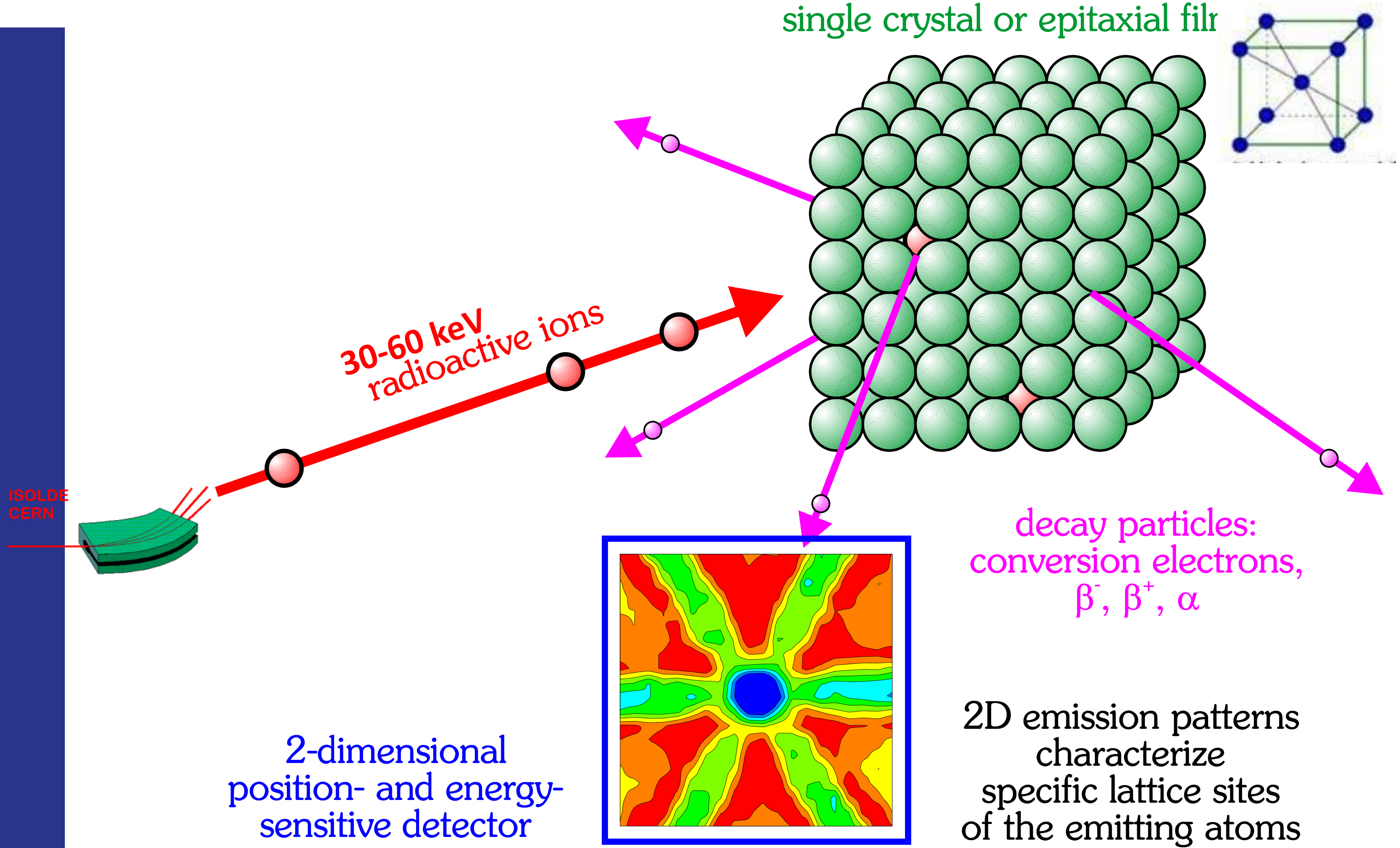
```
Gd-149  @  9.28E+000 D   0.632  8.36E+005 ±  14.9%
Tb-149  @  4.12E+000 H   0.964  1.71E+006 ±   9.4%
Er-165     1.04E+001 H   0.894
Tm-165  @  1.25E+000 D   0.979  1.21E+008 ±   6.3%
```



**1000+ isotopes of 70+ chemical elements**

Simple radiochemistry Lab will be available in 2018

# Emission channeling at ISOLDE



single crystal or epitaxial fil

**30-60 keV** radioactive ions

decay particles: conversion electrons, $\beta^-$, $\beta^+$, $\alpha$

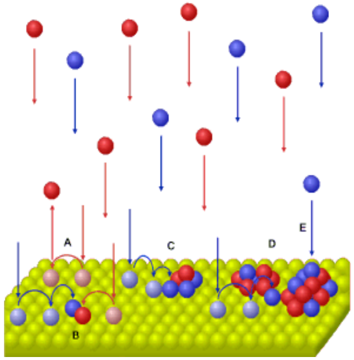
2-dimensional position- and energy-sensitive detector

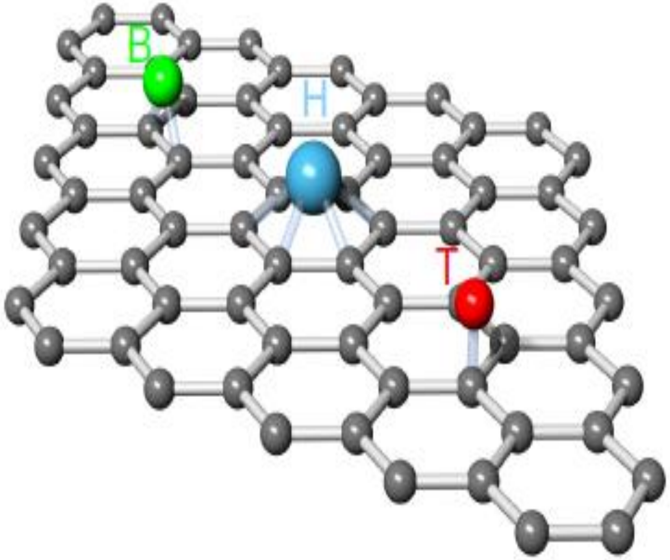
2D emission patterns characterize specific lattice sites of the emitting atoms

# Testing properties of Graphene

"Controlled deposit"

ASPIC Camera for study of surfaces





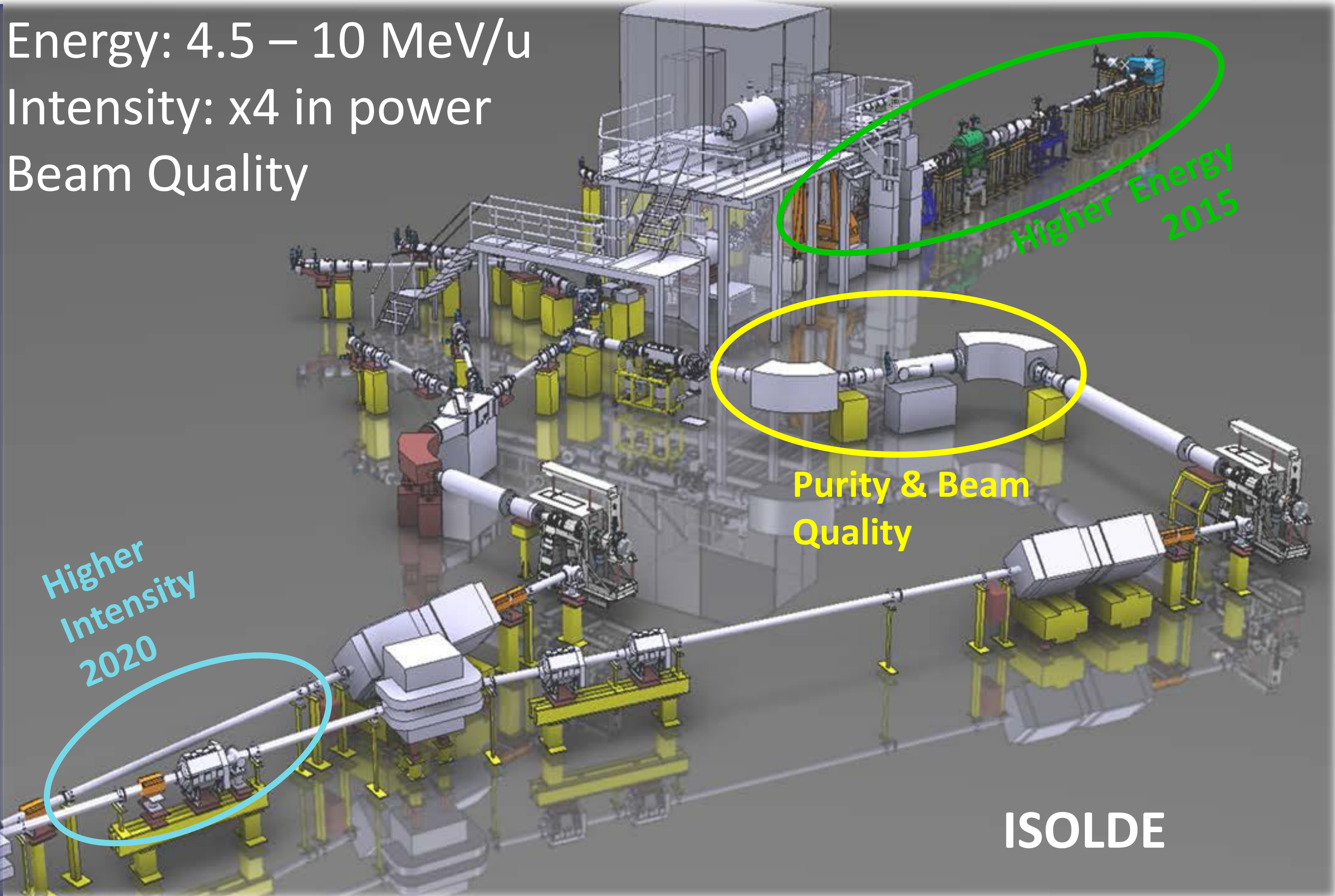
**Objetive: Study of the change of properties of graphene in contact of impurities and dopants**

# The HIE-ISOLDE project (2010 -)

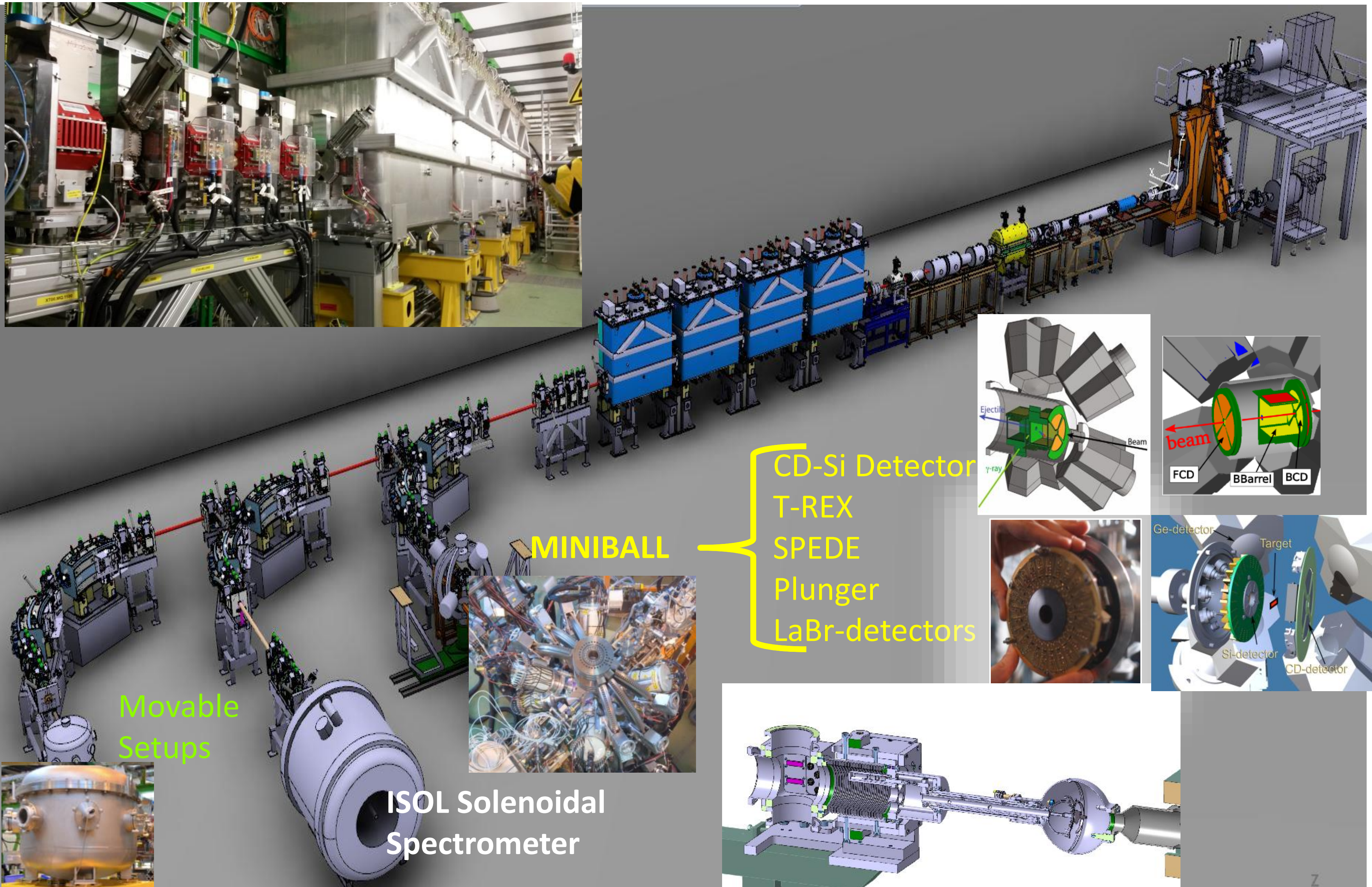
Energy: 4.5 – 10 MeV/u

Intensity: x4 in power

Beam Quality



# HIE-ISOLDE Phase 2 (2017-2018)



**MINIBALL**

- CD-Si Detector
- T-REX
- SPEDE
- Plunger
- LaBr-detectors

Movable Setups

**ISOL Solenoidal Spectrometer**

# Physics at HIE-ISOLDE

The new energy window gives the opportunity to address new physics questions

- Isospin symmetry
- Magic numbers far from stability
- Collectivity versus Single Particle
- Shape Coexistence
- Quadrupole and Octupole degrees of freedom
- Reaction for nucleo-synthesis studies