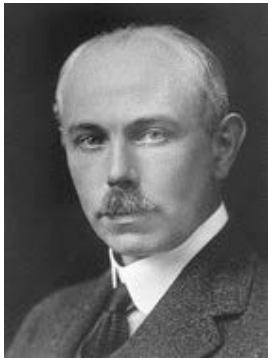

Welcome,
French teachers!

- Notions du “noyau”
- L’installation ISOLDE
- Les manips (résultats)

# Il y a 100 ans… la naissance de la spectrométrie de masse

F.W.Aston (~1920‘s): 212 isotopes discovered
Packing fraction



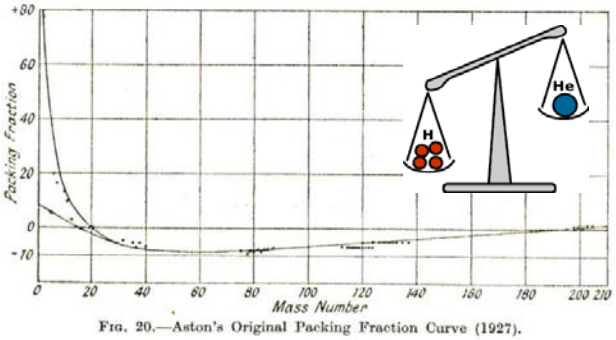
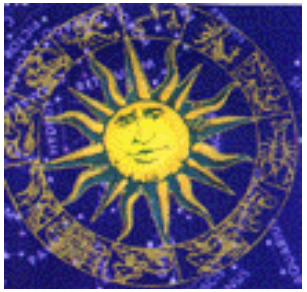
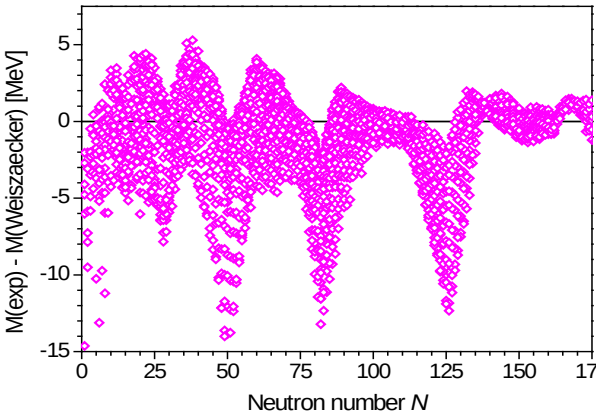


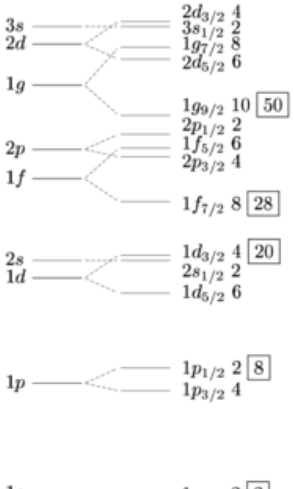
Fig. 20.—Aston's Original Packing Fraction Curve (1927).

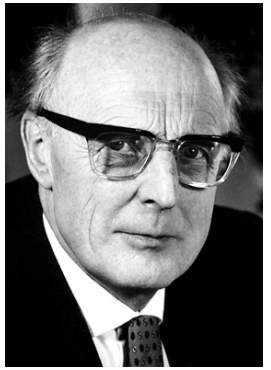
$E = mc^2$



A. Eddington (~1920)
Stellar combustion



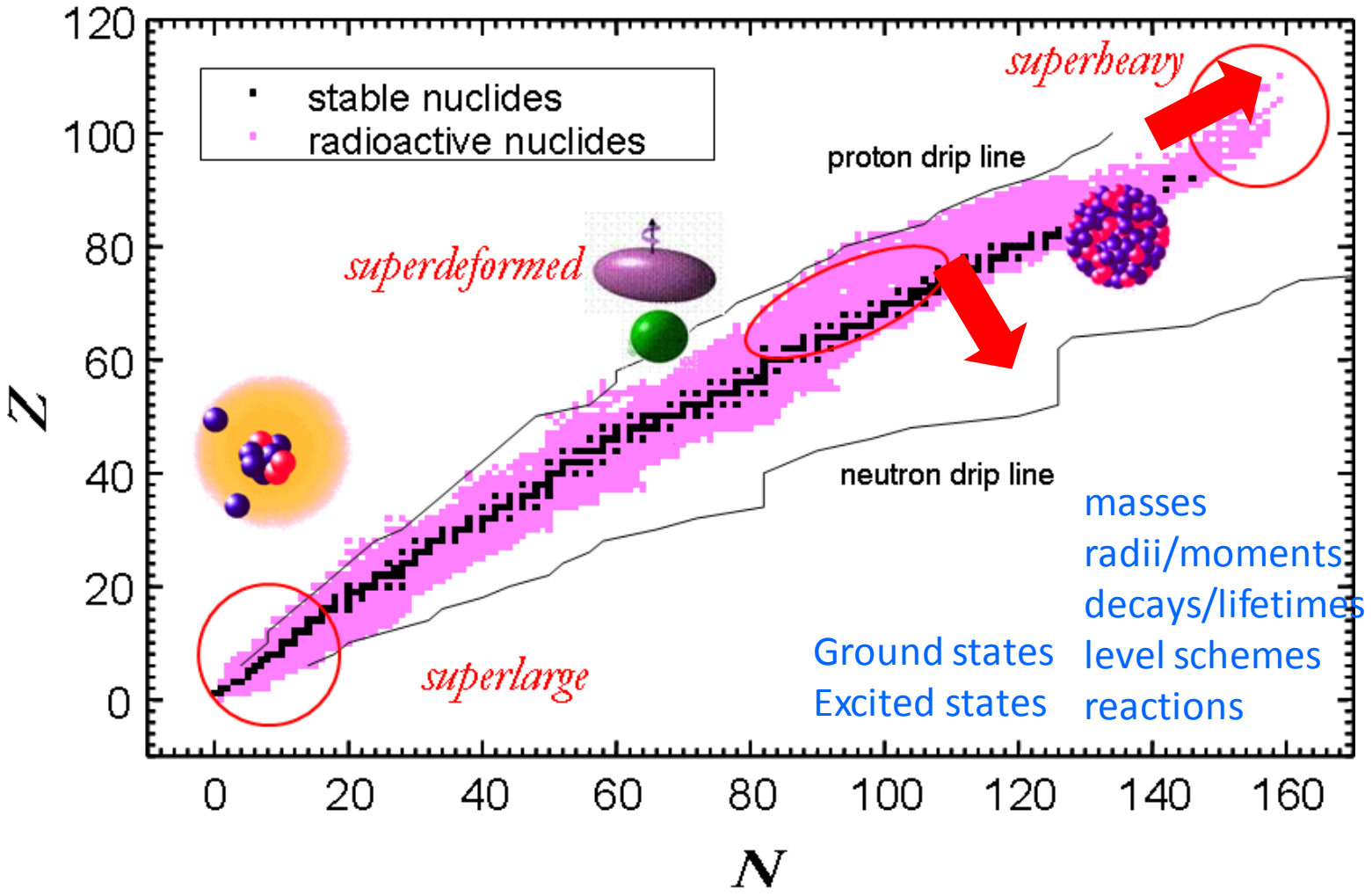



C.F. von Weiszaecker (~1935)
Liquid-drop mass formula

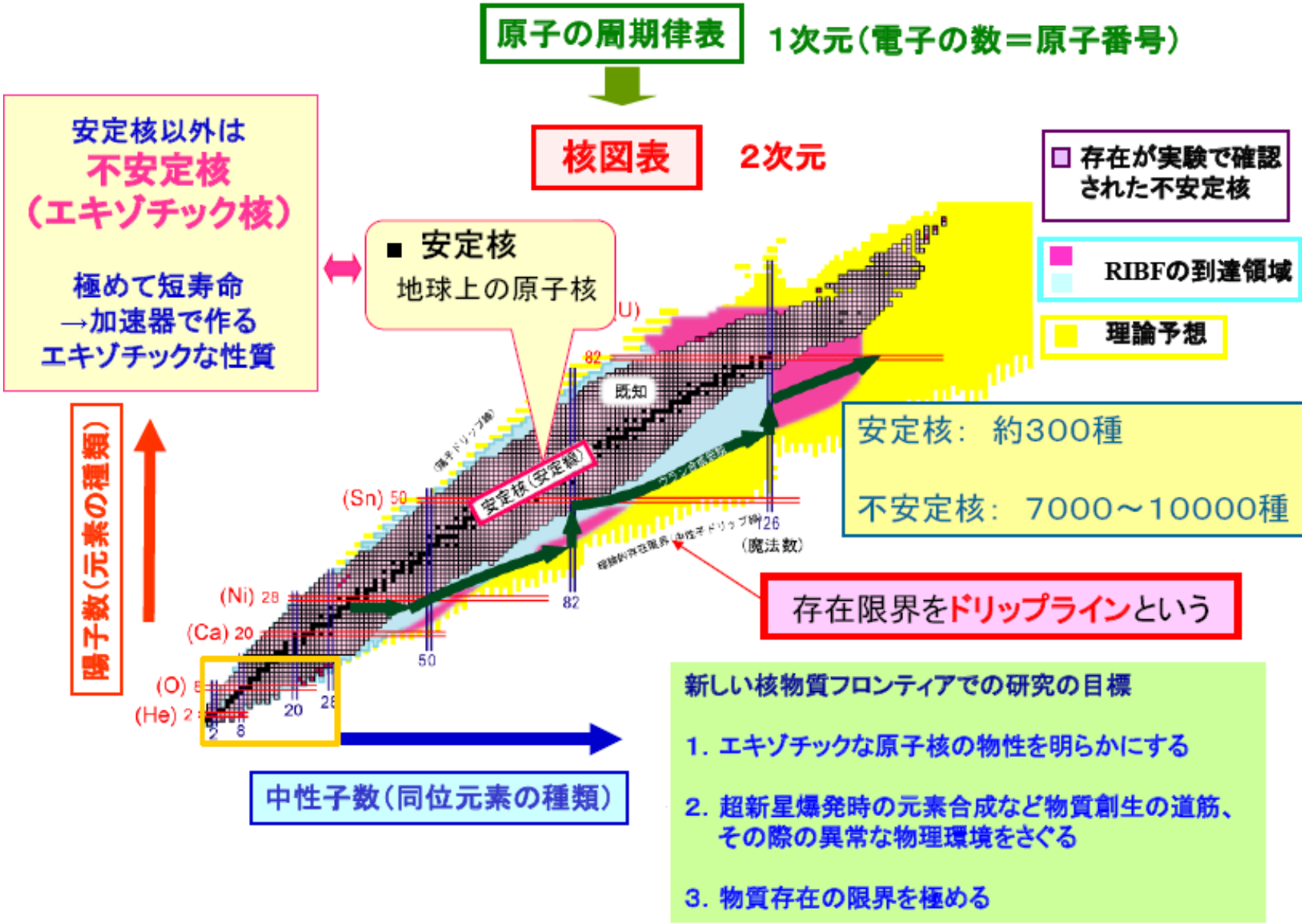
M. Goeppert/H. Jensen (~1963)
Nuclear shell model

# Nuclear chart

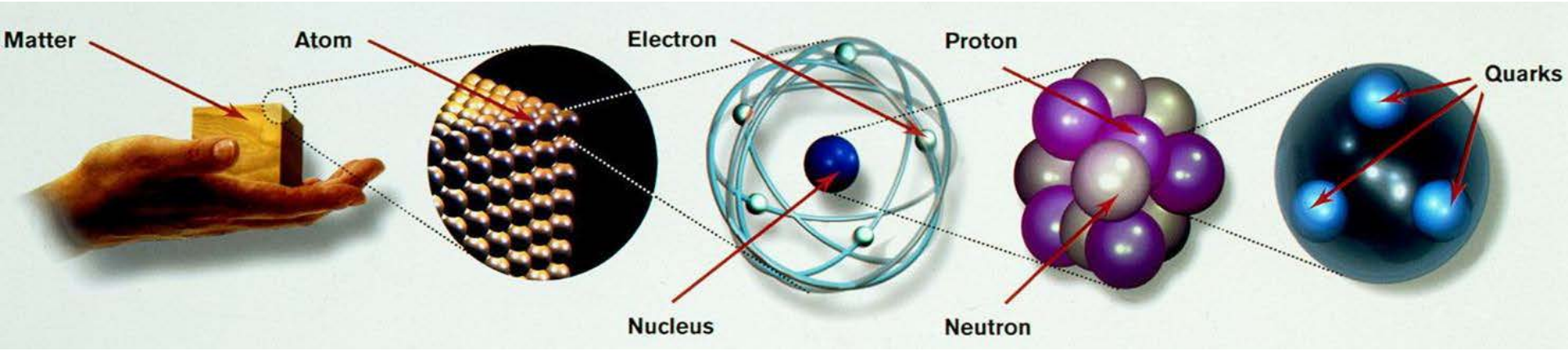


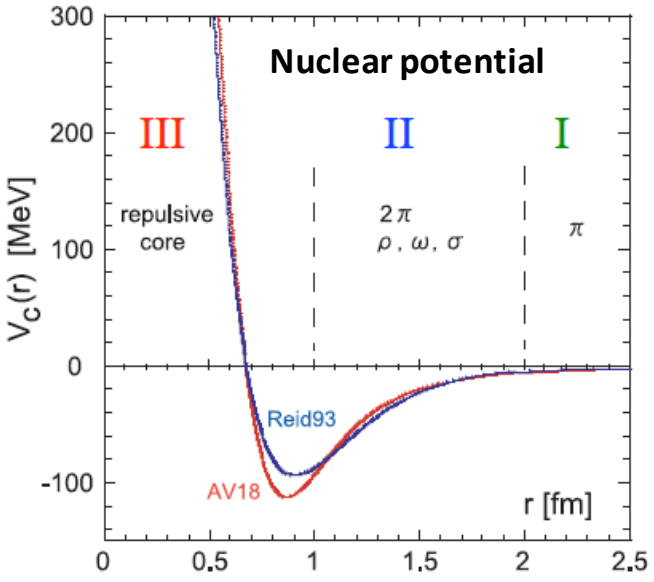
# Nuclear chart

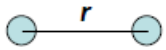
## (as seen by a particle physicist!)



# La matière : l'atome – le noyau – les quarks…




I Long range part

one pion exchange potential

II Medium range part

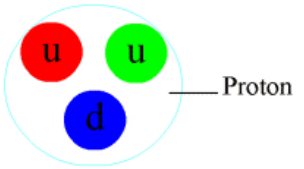
$\sigma$, $\rho$, $\omega$ exchange

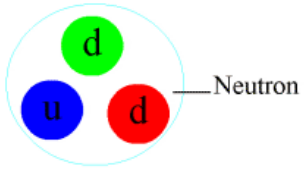
$2\pi$ exchange

III Short range part

repulsive core (RC)

quark ?

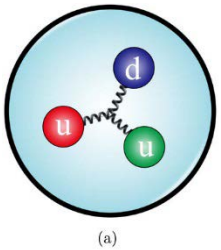


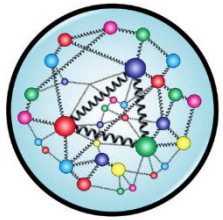

Animation: Wikipedia

**gluons : 99% de la masse du nucléon !**

Internal structure of proton from (a) traditional quark model and (b) quantum chromodynamics.



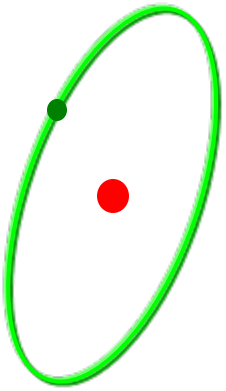

(a)



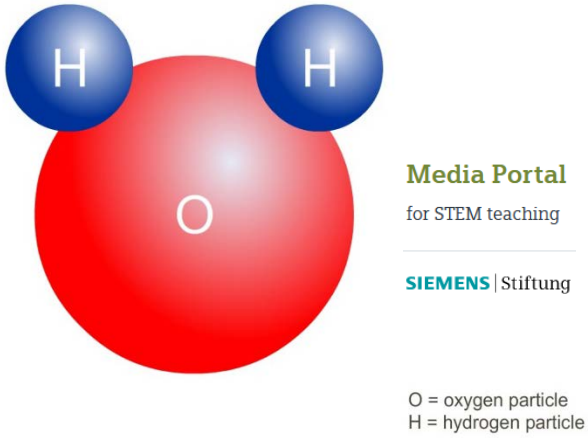
(b)

Rep. Prog. Phys. 86 (2023) 026201

# Emergent (versus resultant) phenomena



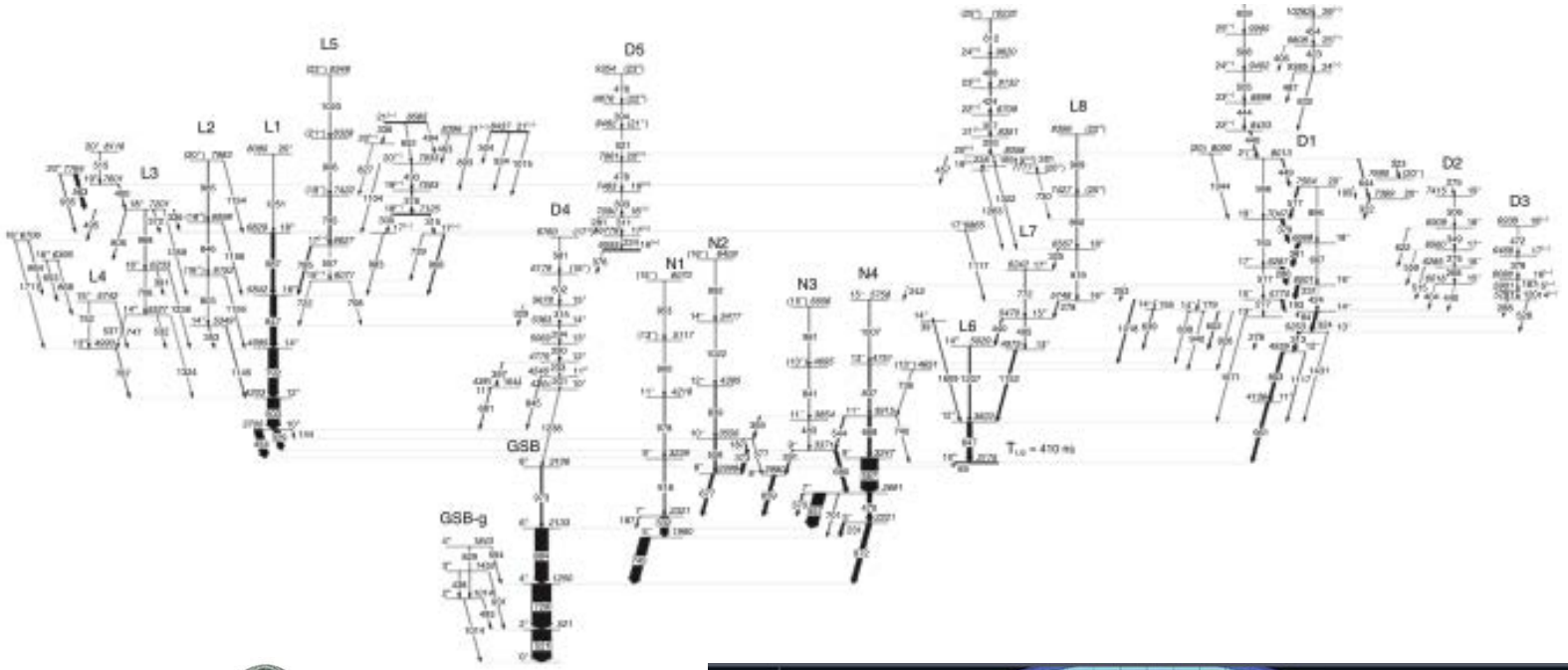
hydrogen atom

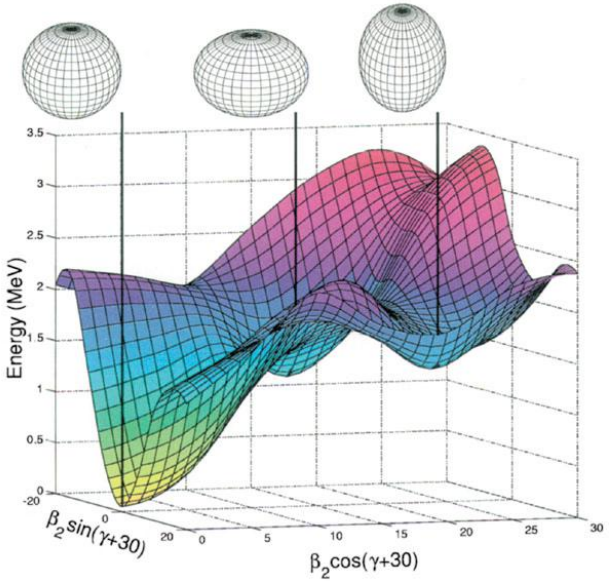


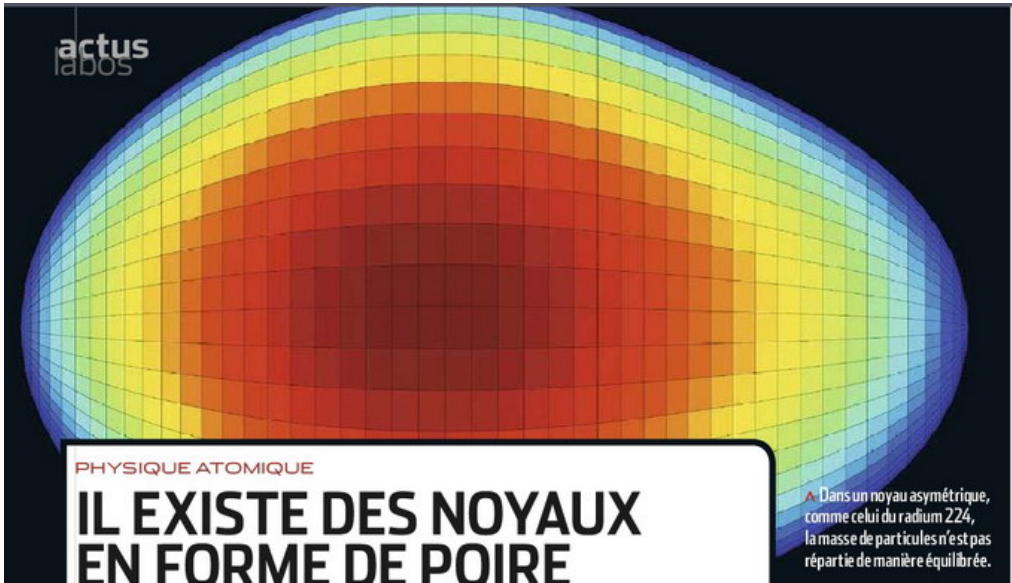

water molecule


snowflake

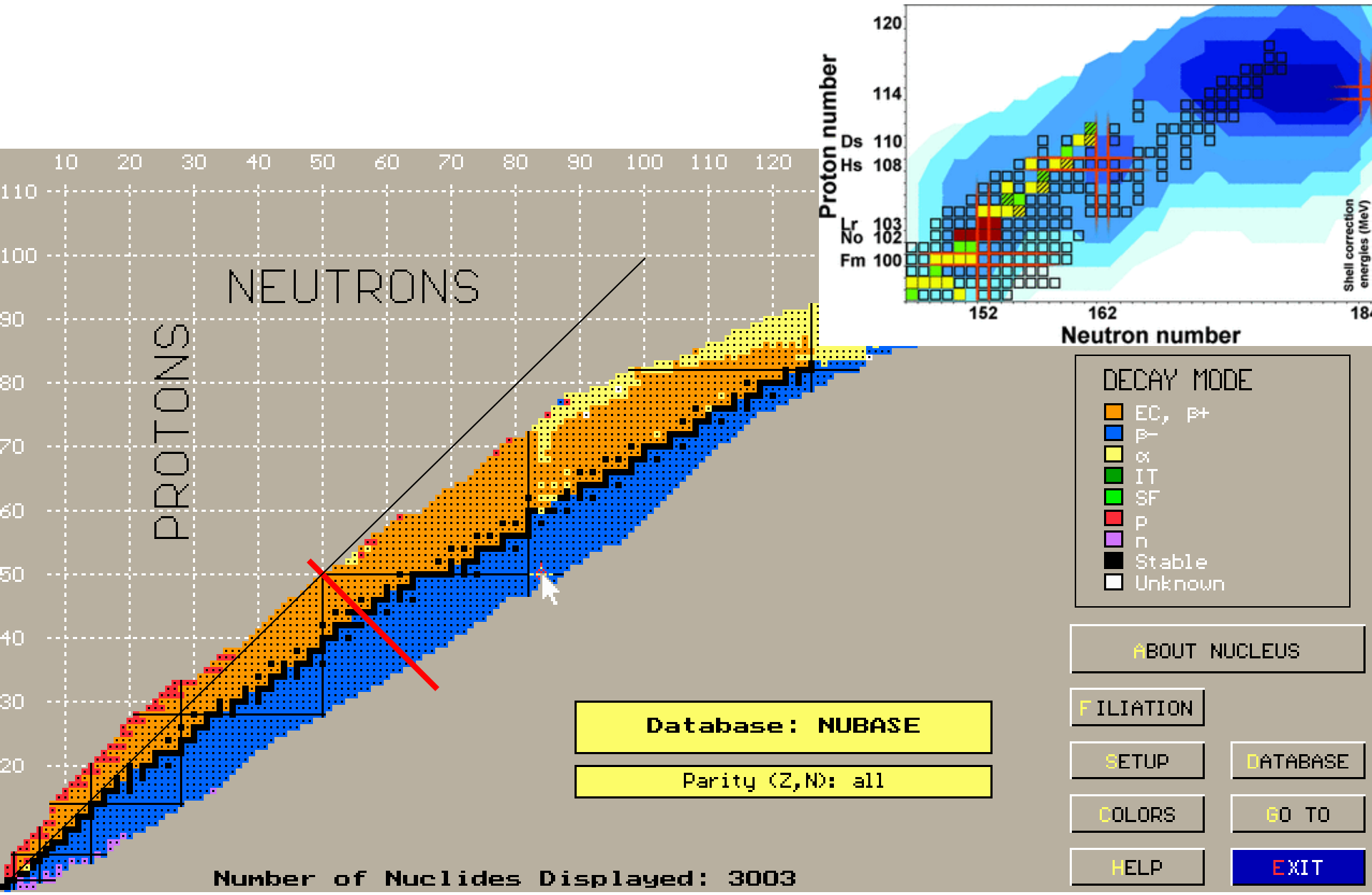
# Que deux ingrédients pour le noyau, mais…



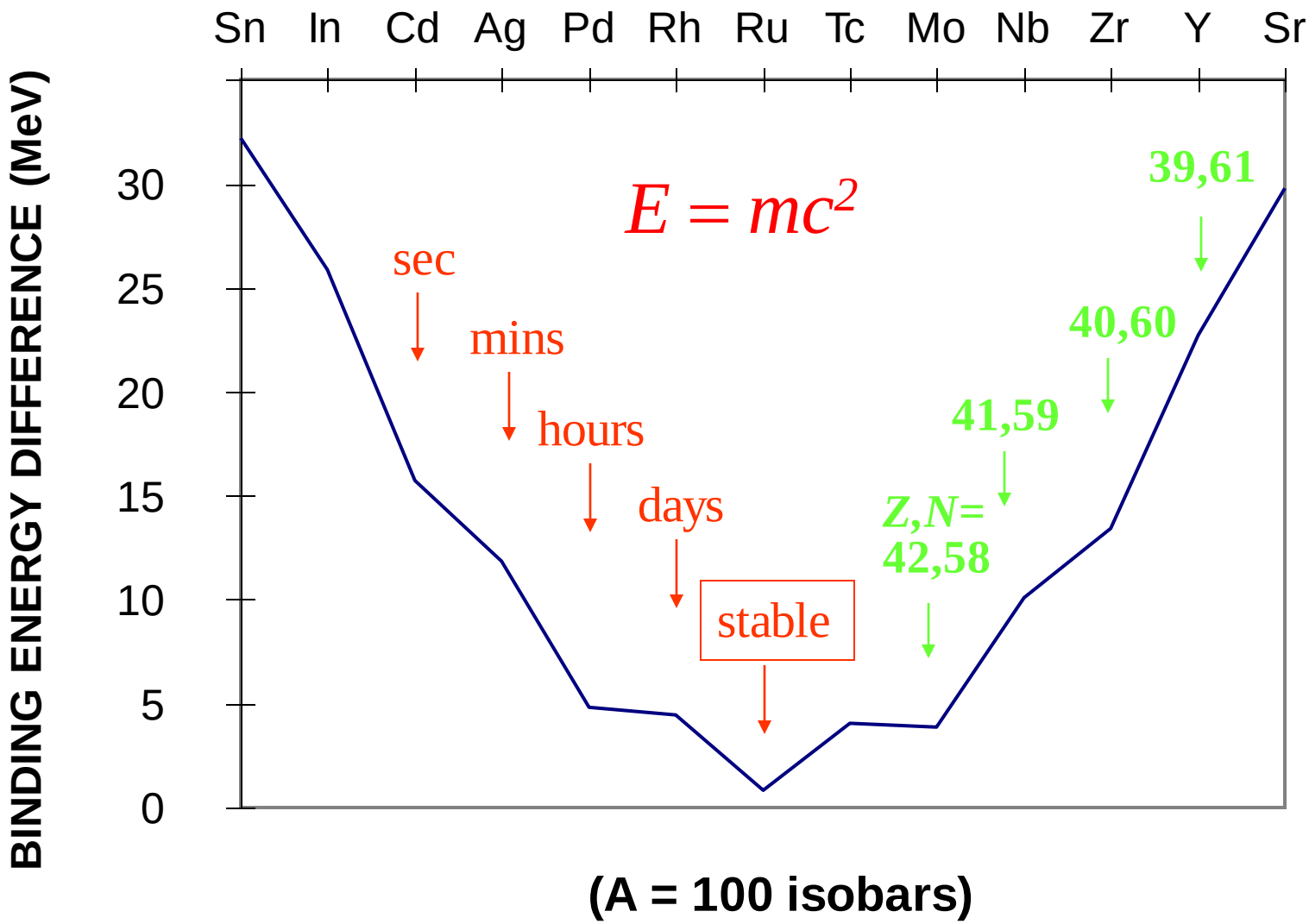



# *La carte nucléaire*



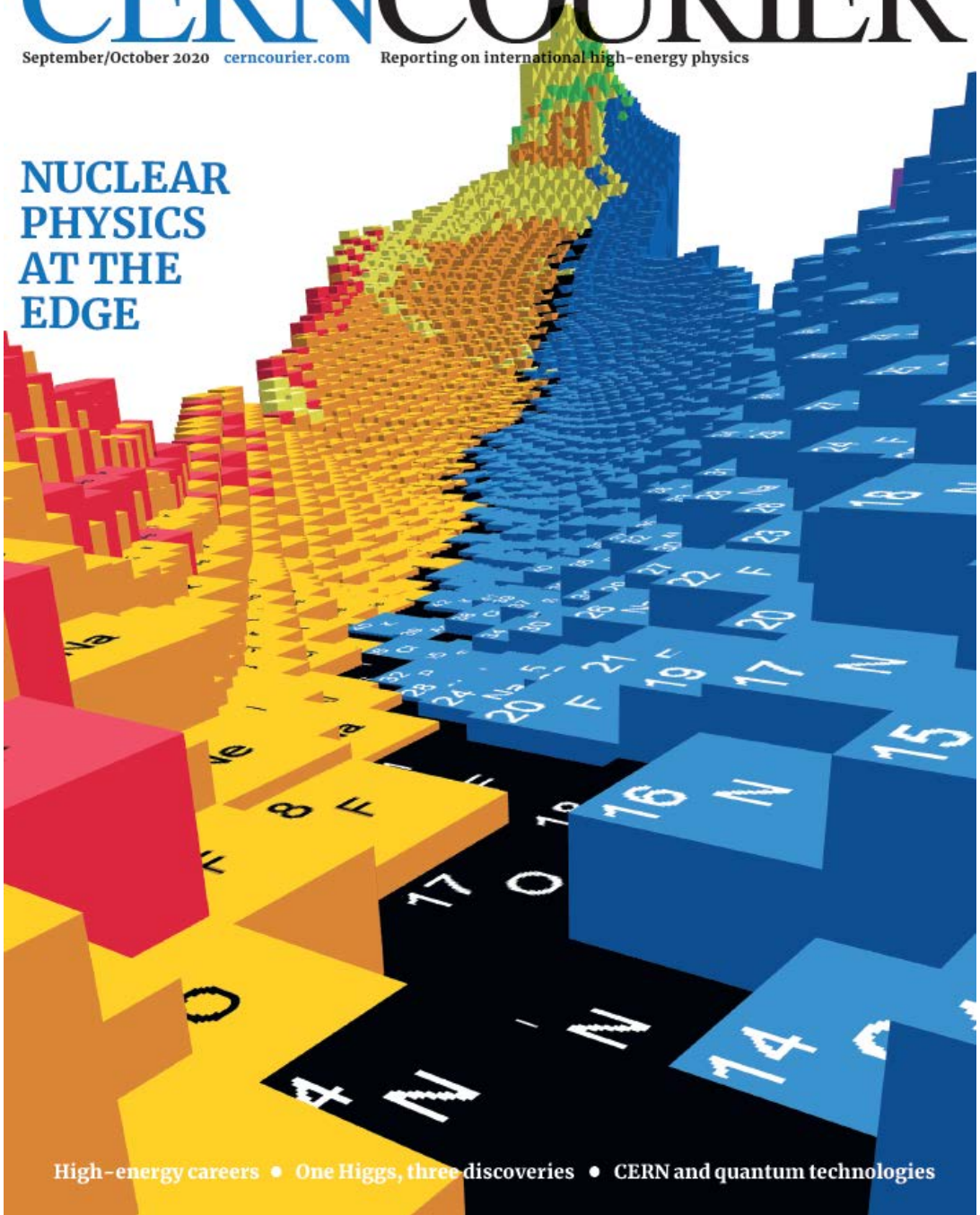

AMDC-Nucleus



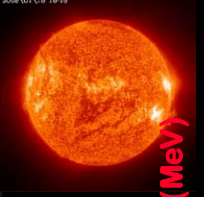

$Z \cdot m_p + N \cdot m_n - BE$ *Binding Energy : (énergie de liaison)*

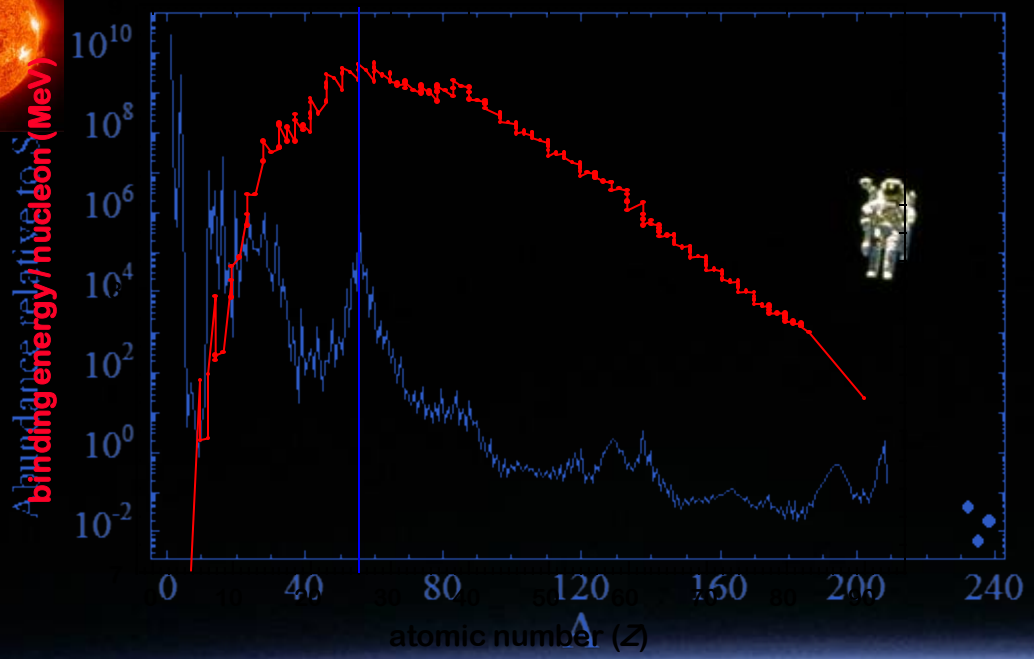
CERN COURIER
September/October 2020 cerncourier.com Reporting on international high-energy physics

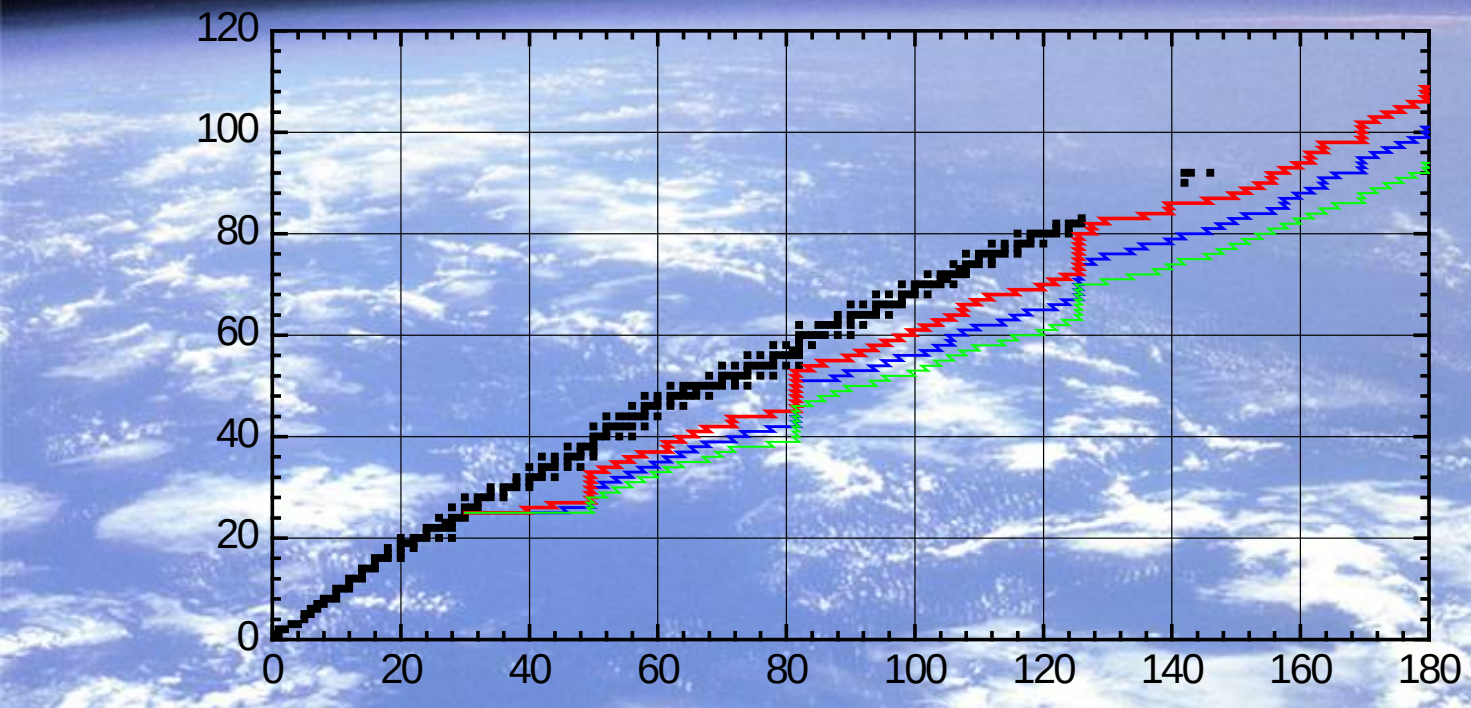
# NUCLEAR PHYSICS AT THE EDGE



High-energy careers • One Higgs, three discoveries • CERN and quantum technologies

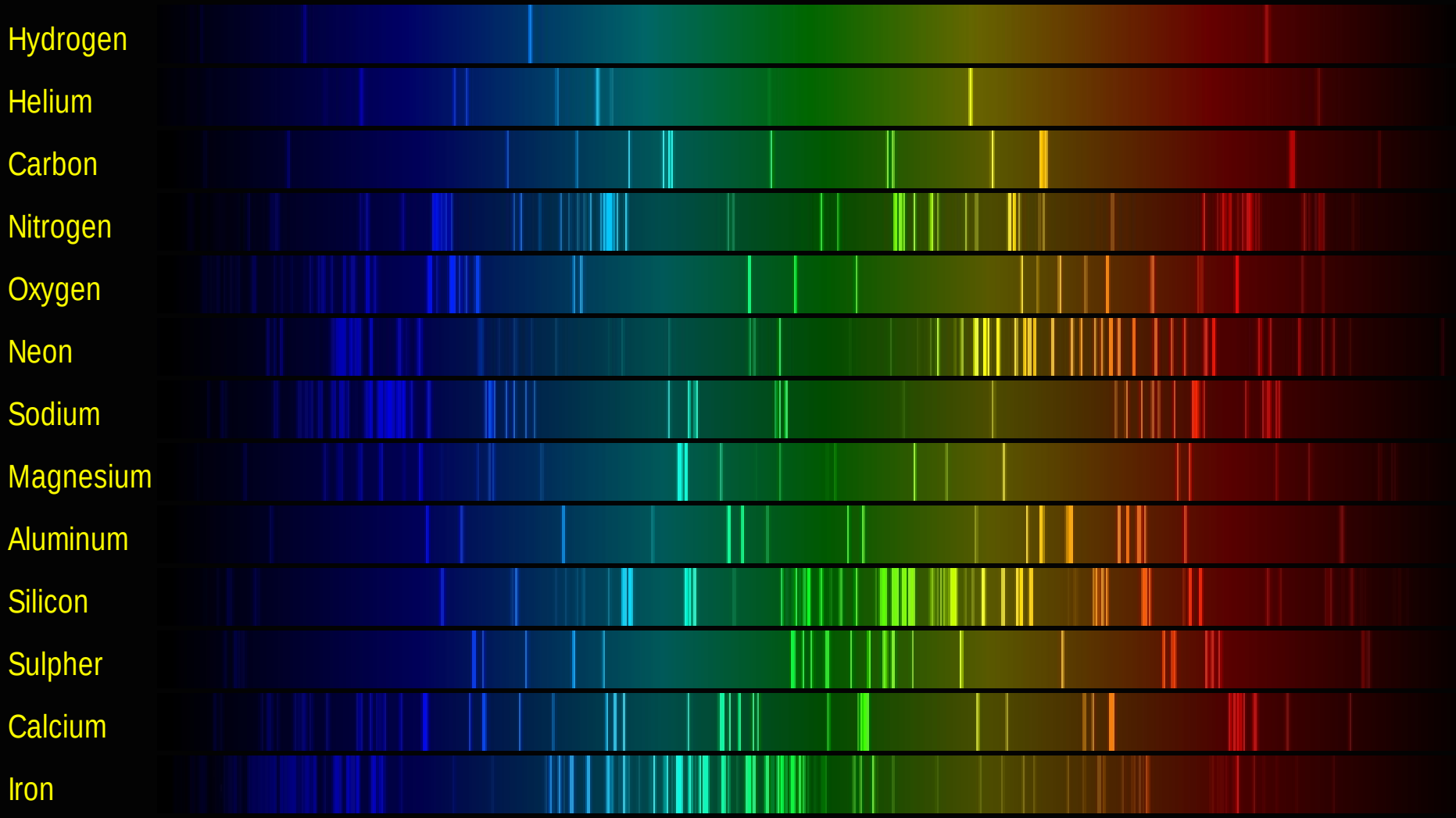



binding energy/nucleon (MeV)
atomic number (Z)

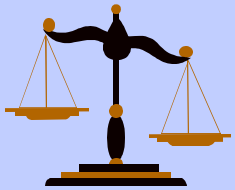

120
100
80
60
40
20
0
0
20
40
60
80
100
120
140
160
180

?

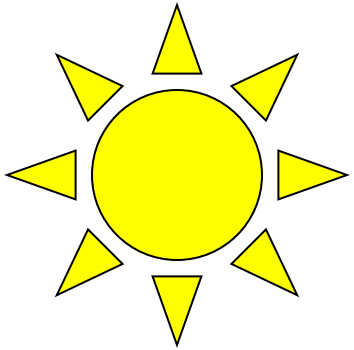
# Spectral pattern of different elements



# *nucléosynthèse stellaire*



## *hydrostatique*



fusion: $p + p \rightarrow He$
(milliards d'années)

:

$^{12}C\ (\alpha,\gamma)\ ^{16}O$

:

$\rightarrow Fe$

capture neutronique processus-*s* (pulsation): 1000 ans

## *explosive*

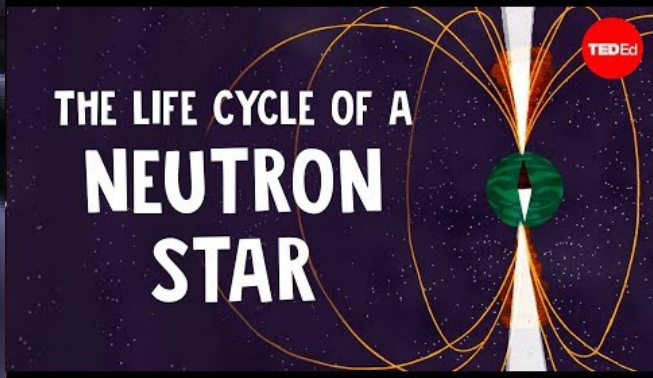


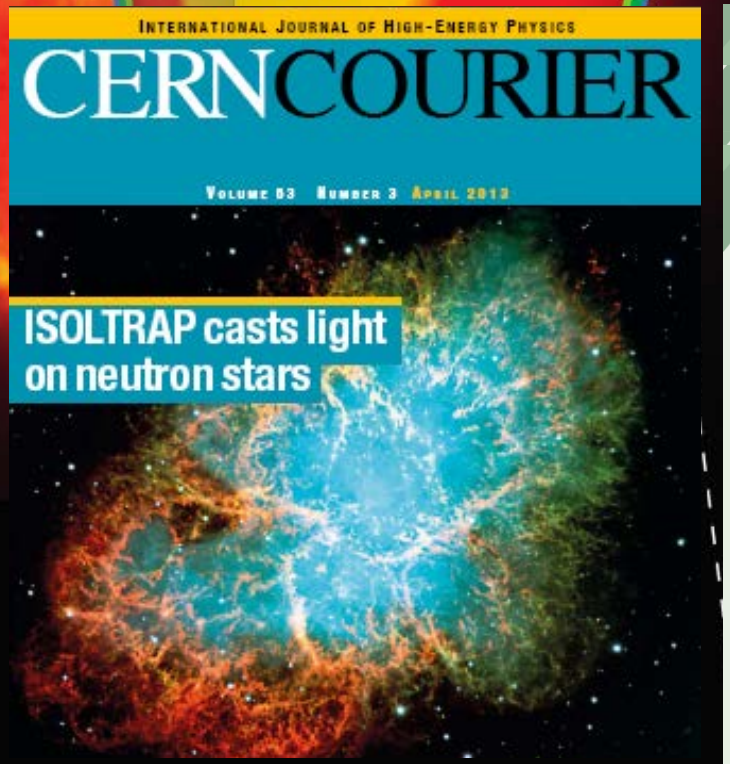
processus-*r*: secondes

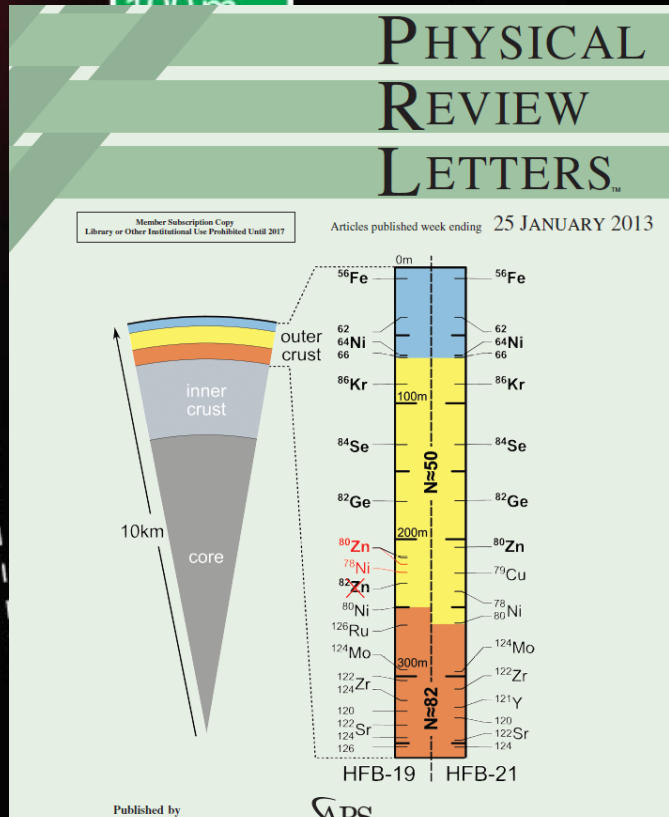
processus-*p*: $(\gamma,p)\ (\gamma,n)$

NASA

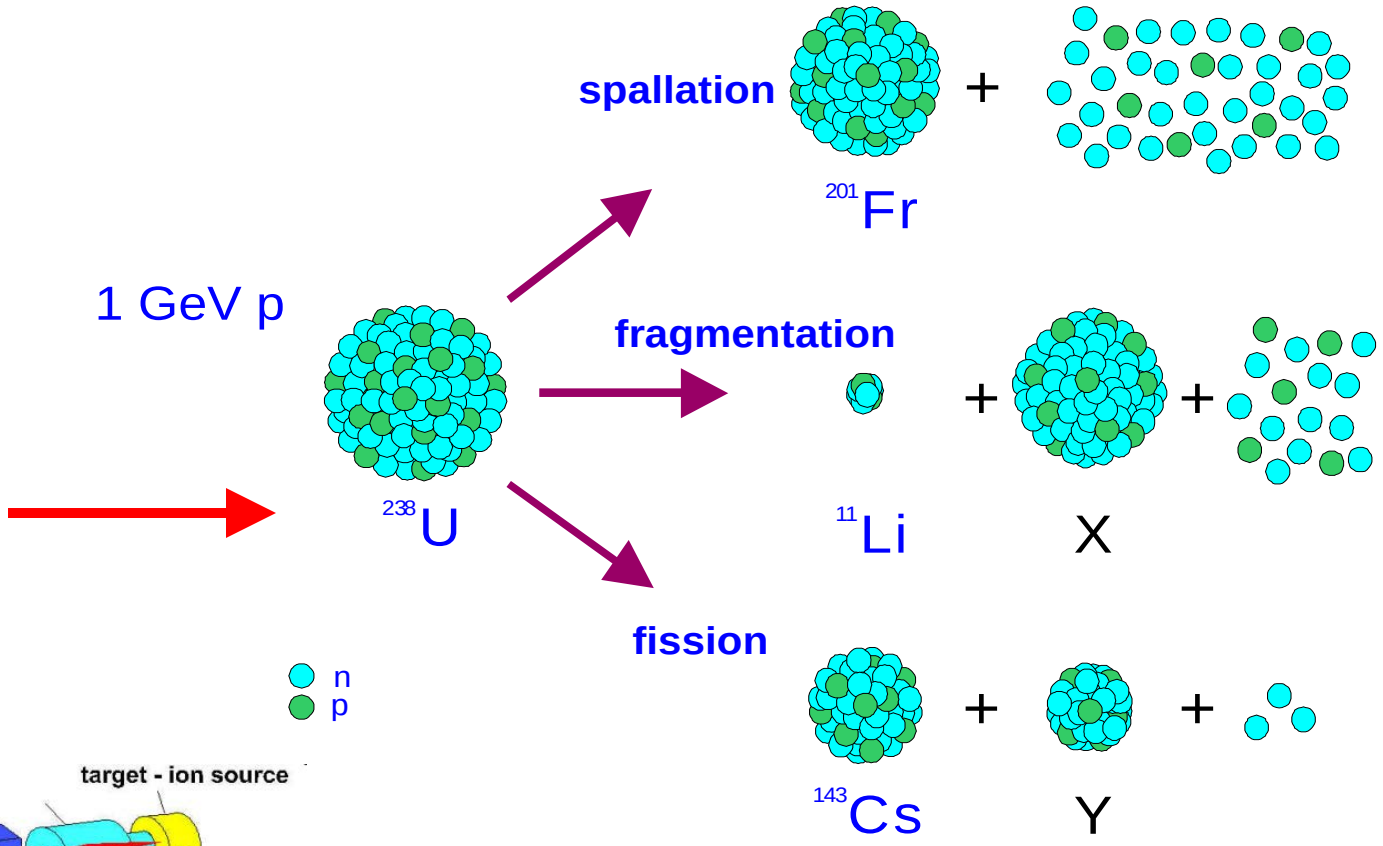
GW170817: dawn of multimessenger astronomy (image: ESA)

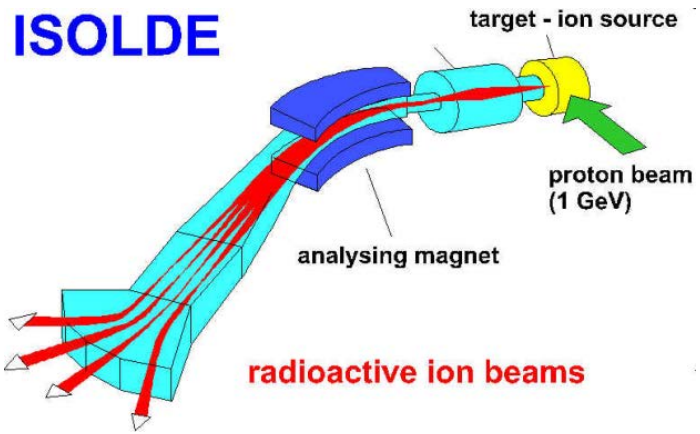


# ISOTOPE production



# *Production (and separation) techniques for exotic nuclides*

## Isotope Separation On-Line (ISOL)

GeVprotons
MeV heavy ions
neutrons / electrons

**ionizer**

g/cm$^2$

Diffusion:
release time
and chemistry

10-100 keV

good beam quality

(charge-breeding)
post-acceleration

## Fragmentation In-Flight Separation (FIFS)

**driver**

0.1 - 1 GeV/u
heavy ions

**target**

mg/cm$^2$

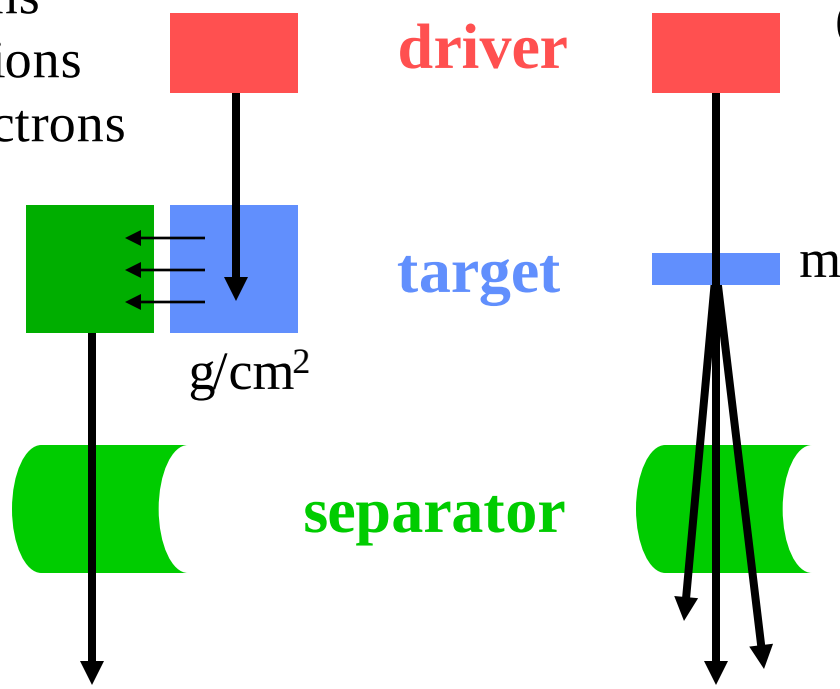
Straggling:
phase space

0.1-1 GeV

short lived / unbound

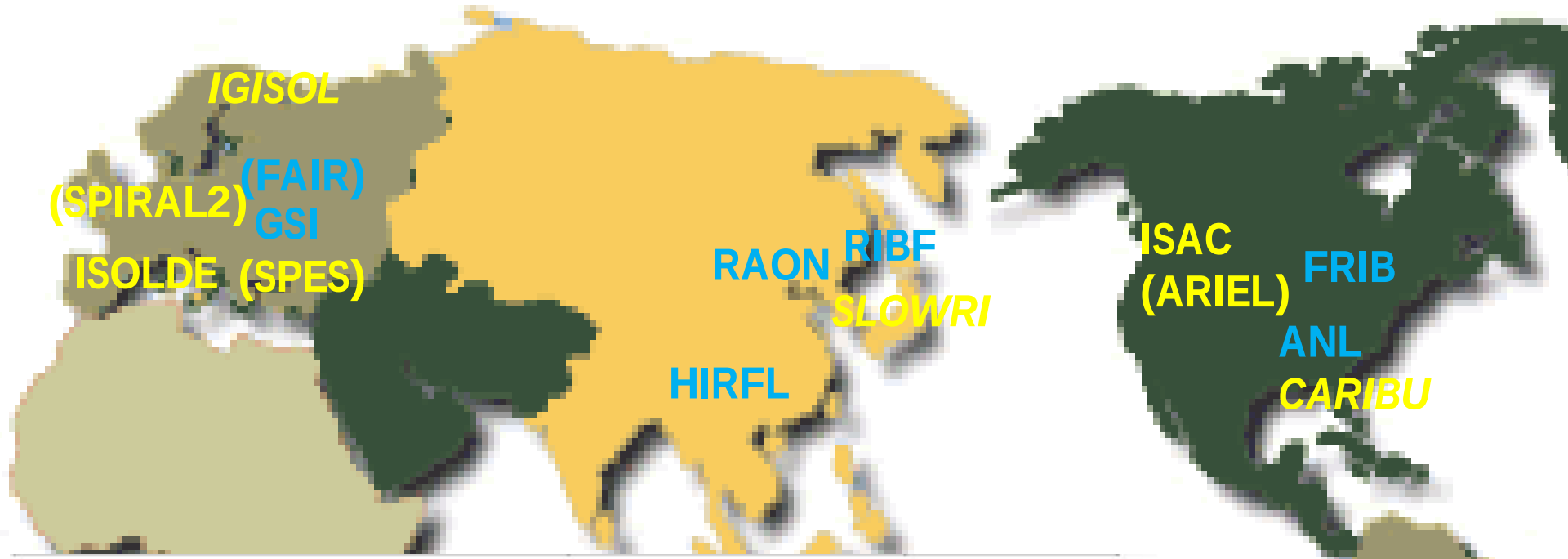
deceleration
or stopping

**separator**

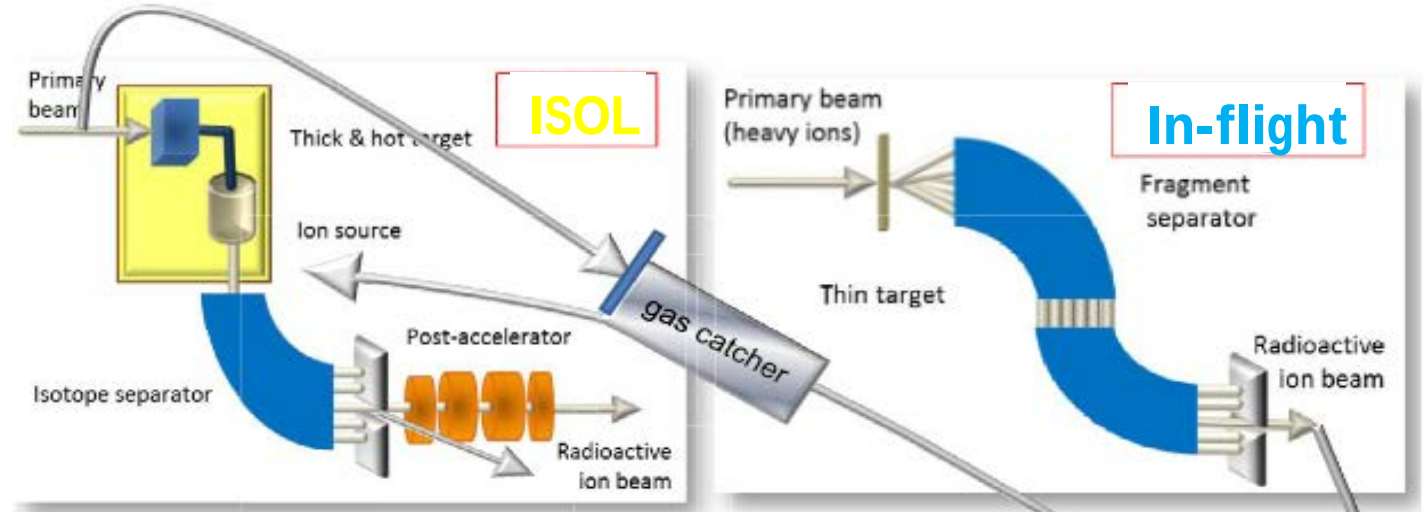


# Major Radioactive Beam Facilities Worldwide

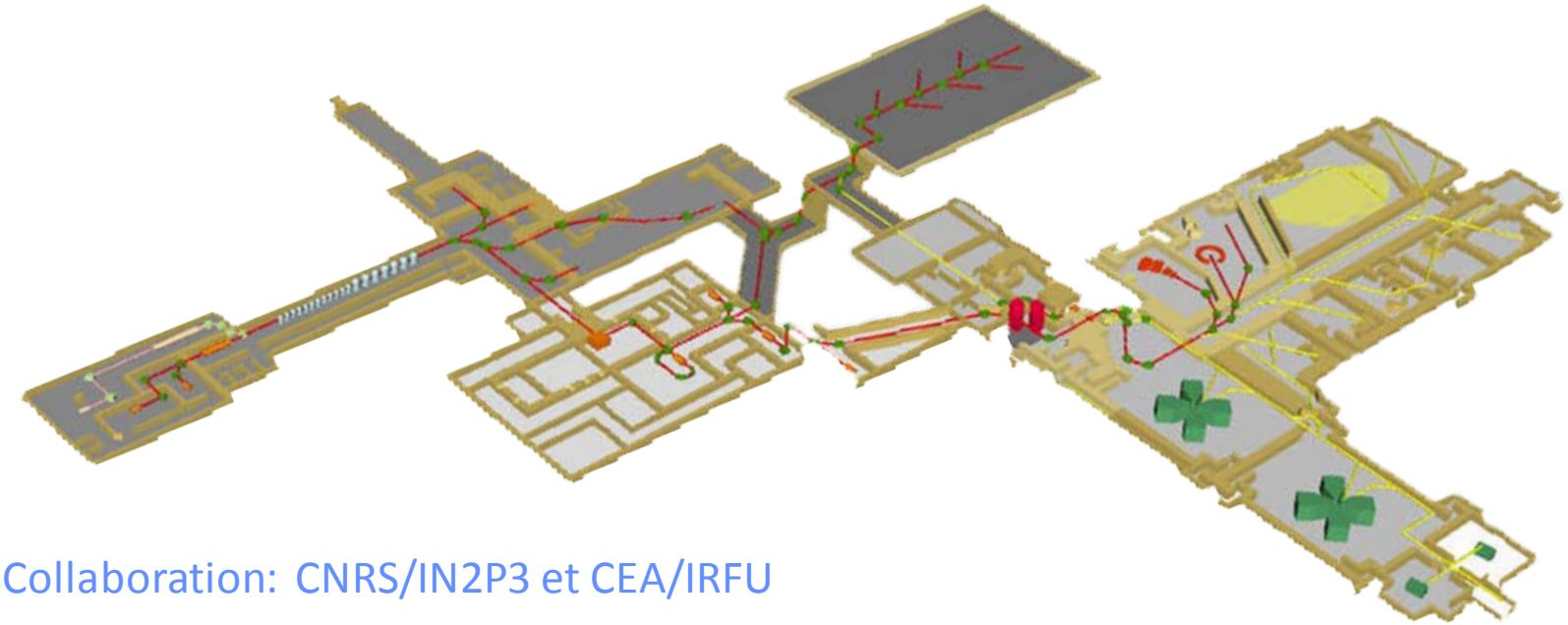
**In-flight** **ISOL***gaswerks* **(future)**



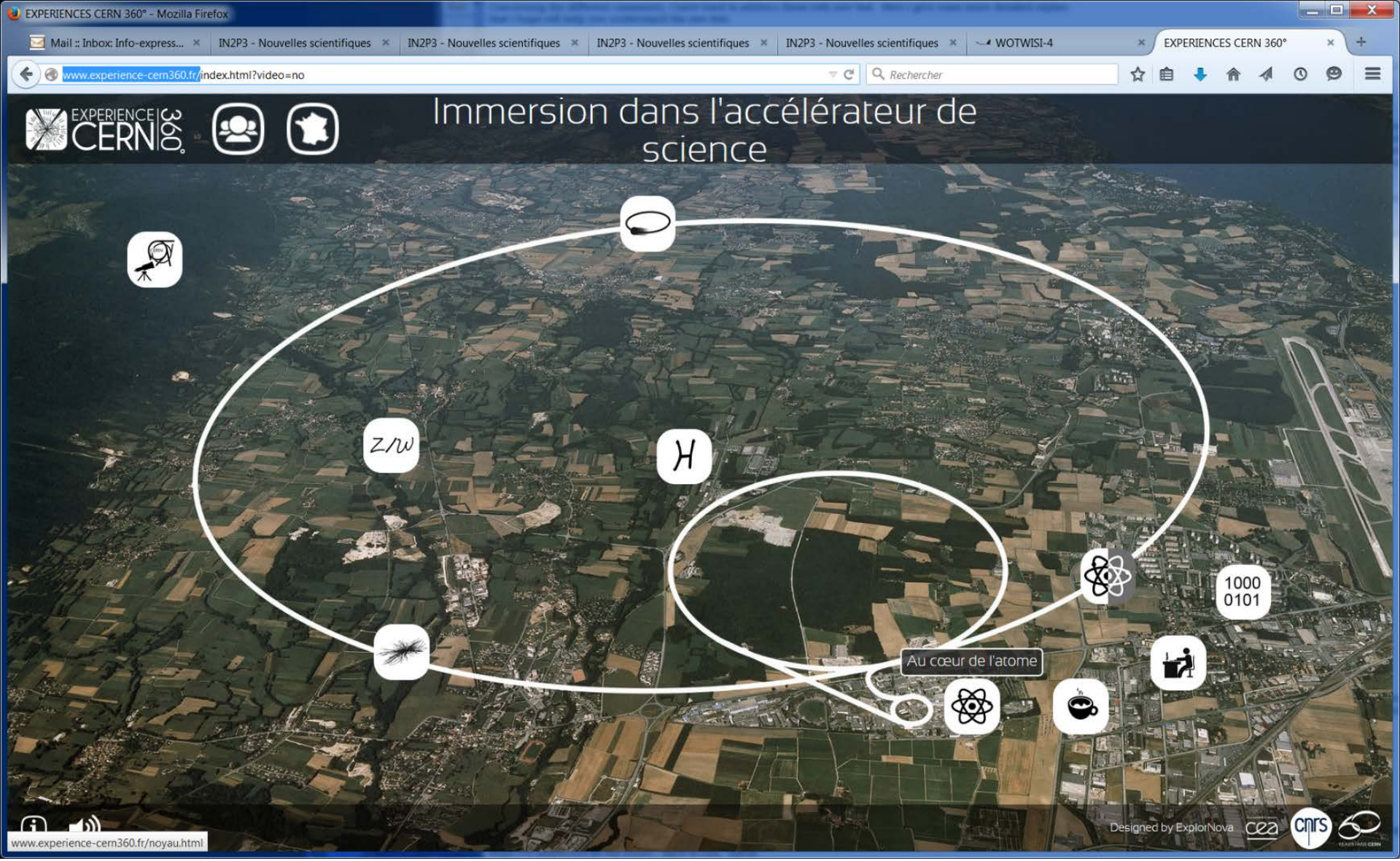

Phys. Scr. T152 (2013) 014023 Y Blumenfeld *et al*



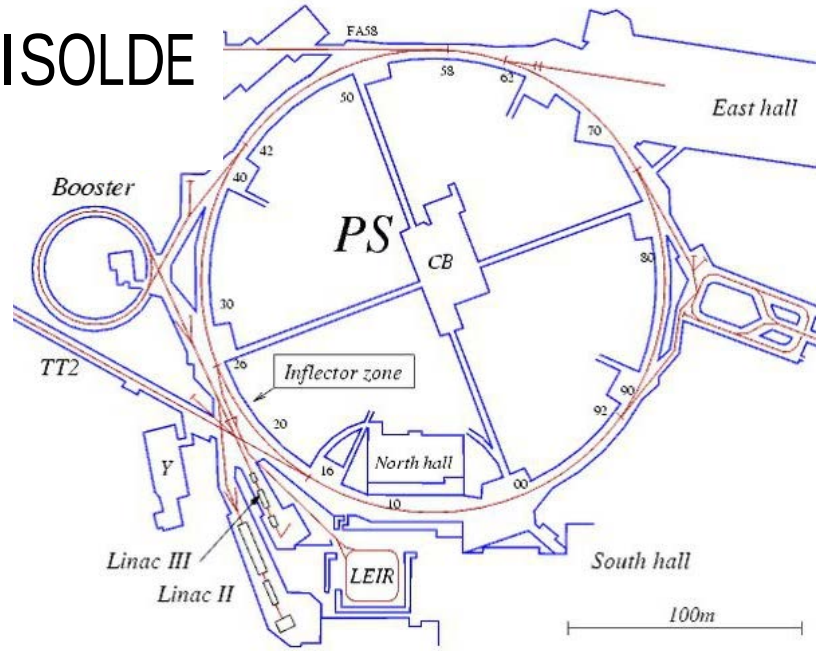
# SPIRAL 2 : nouvelle installation pour les noyaux exotiques actuellement en construction auprès du GANIL à Caen

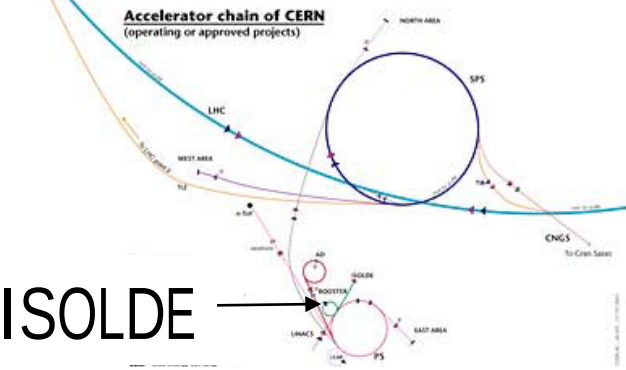


Collaboration: CNRS/IN2P3 et CEA/IRFU


EXPERIENCES CERN 360° - Mozilla Firefox
Mail :: Inbox: Info-express...
IN2P3 - Nouvelles scientifiques
IN2P3 - Nouvelles scientifiques
IN2P3 - Nouvelles scientifiques
IN2P3 - Nouvelles scientifiques
WOTWISI-4
EXPERIENCES CERN 360°
www.experience-cern360.fr/index.html?video=no
Rechercher
EXPERIENCE CERN 360°
Immersion dans l'accélérateur de science
Z/W
H
1000
0101
Au cœur de l'atome
Designed by ExplorNova
cea
cnrs
www.experience-cern360.fr/noyau.html

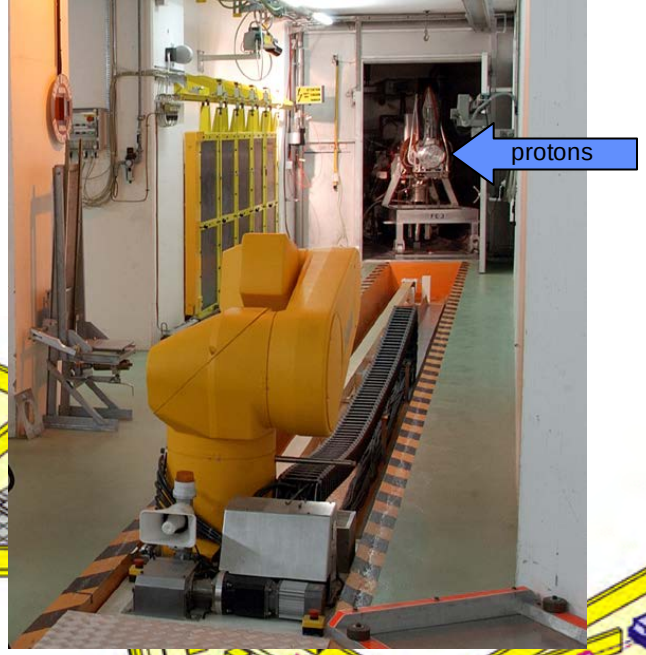
ISOLDE

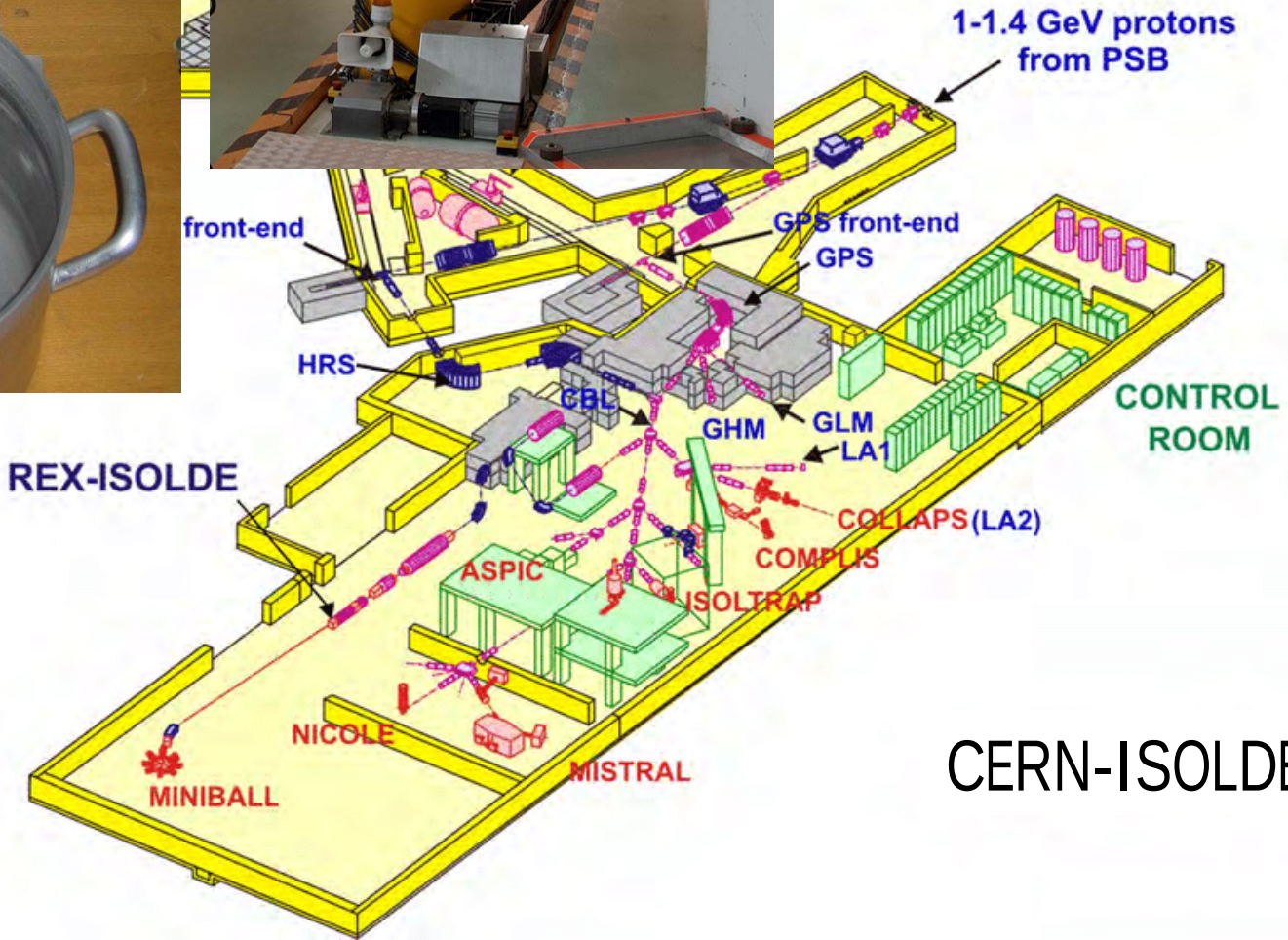



ISOLDE


protons

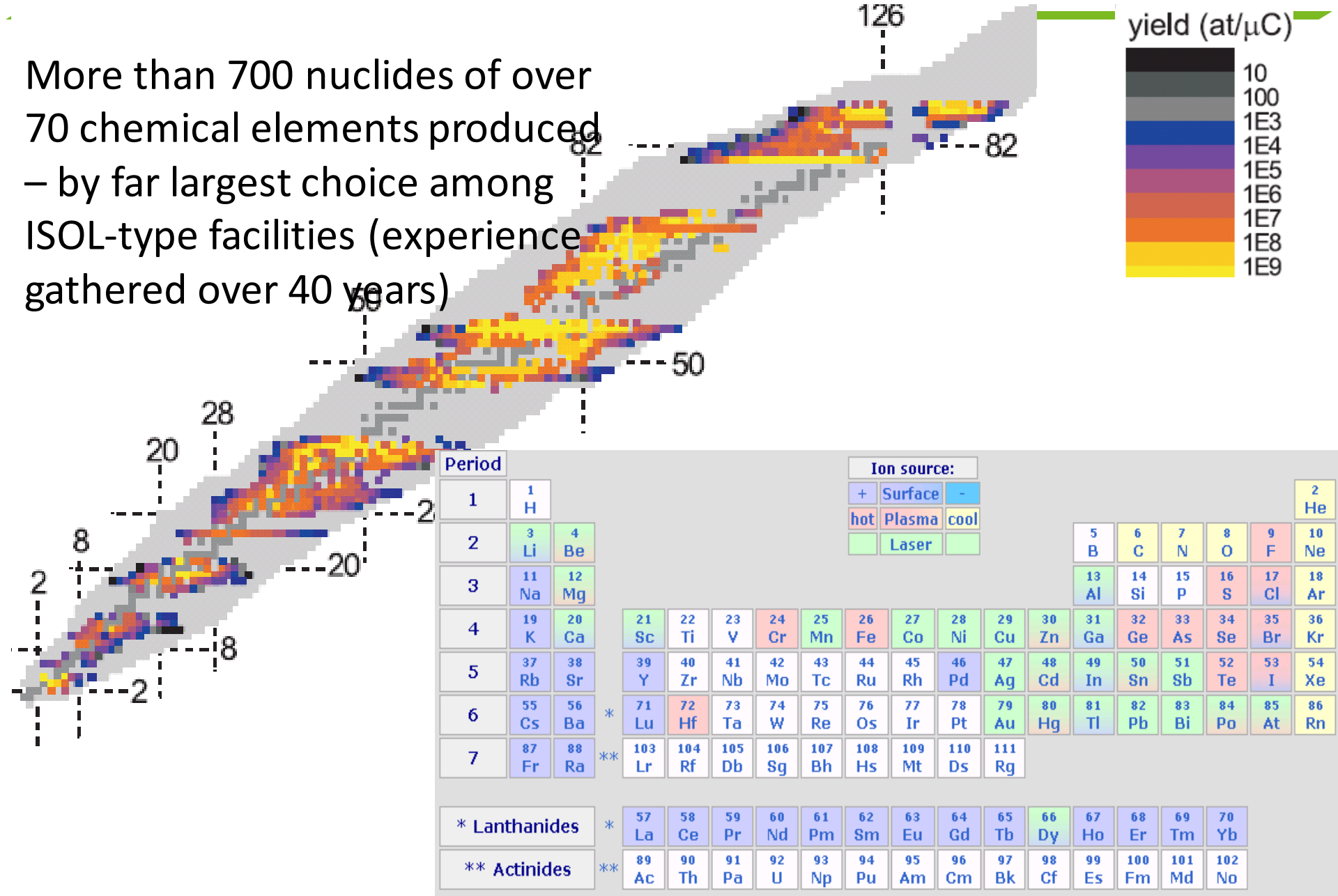

protons

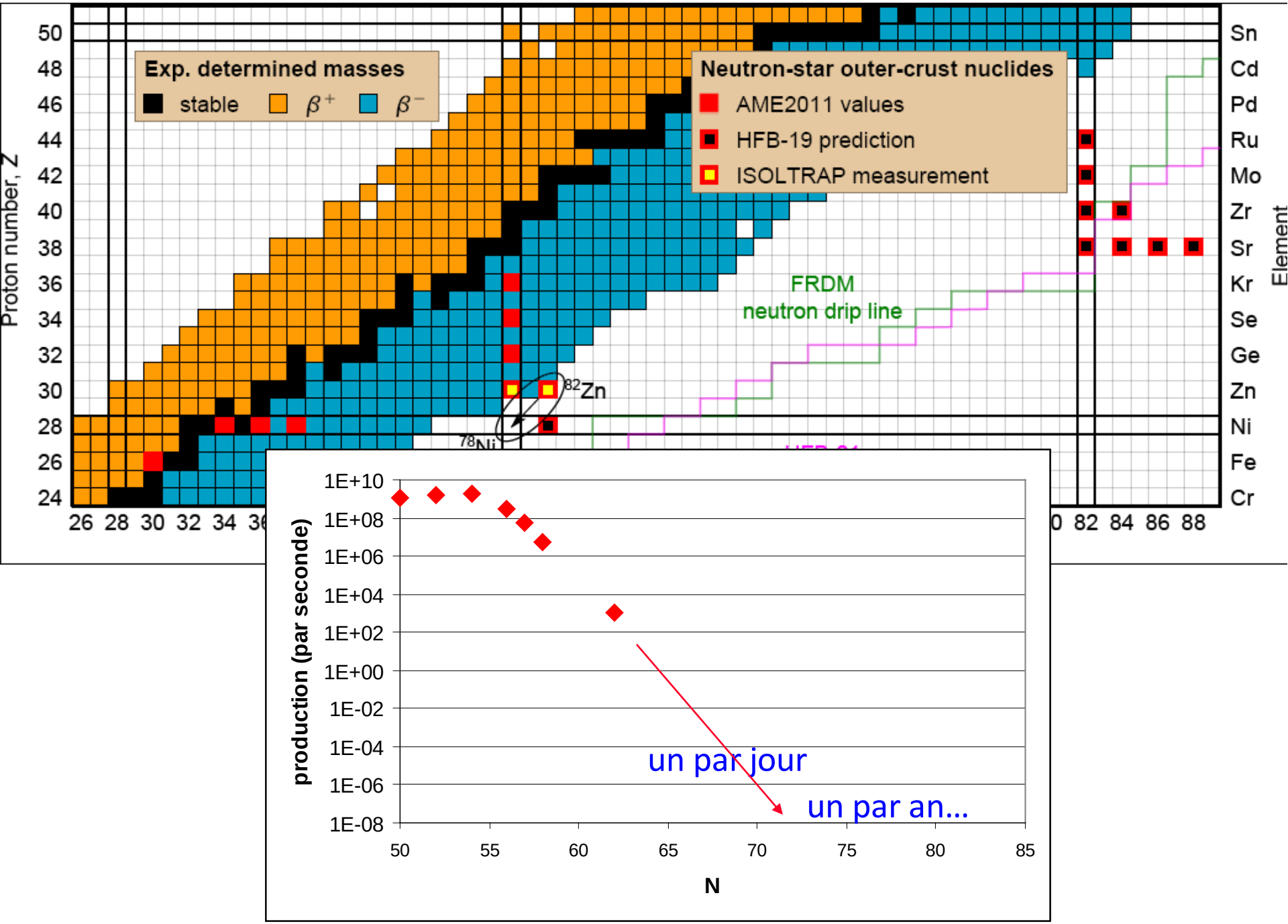

1-1.4 GeV protons
from PSB
front-end
GPS front-end
GPS
HRS
CBL
GHM
GLM
LA1
CONTROL
ROOM
REX-ISOLDE
COLLAPS (LA2)
COMPLIS
ASPIC
ISOLTRAP
NICOLE
MISTRAL
MINIBALL

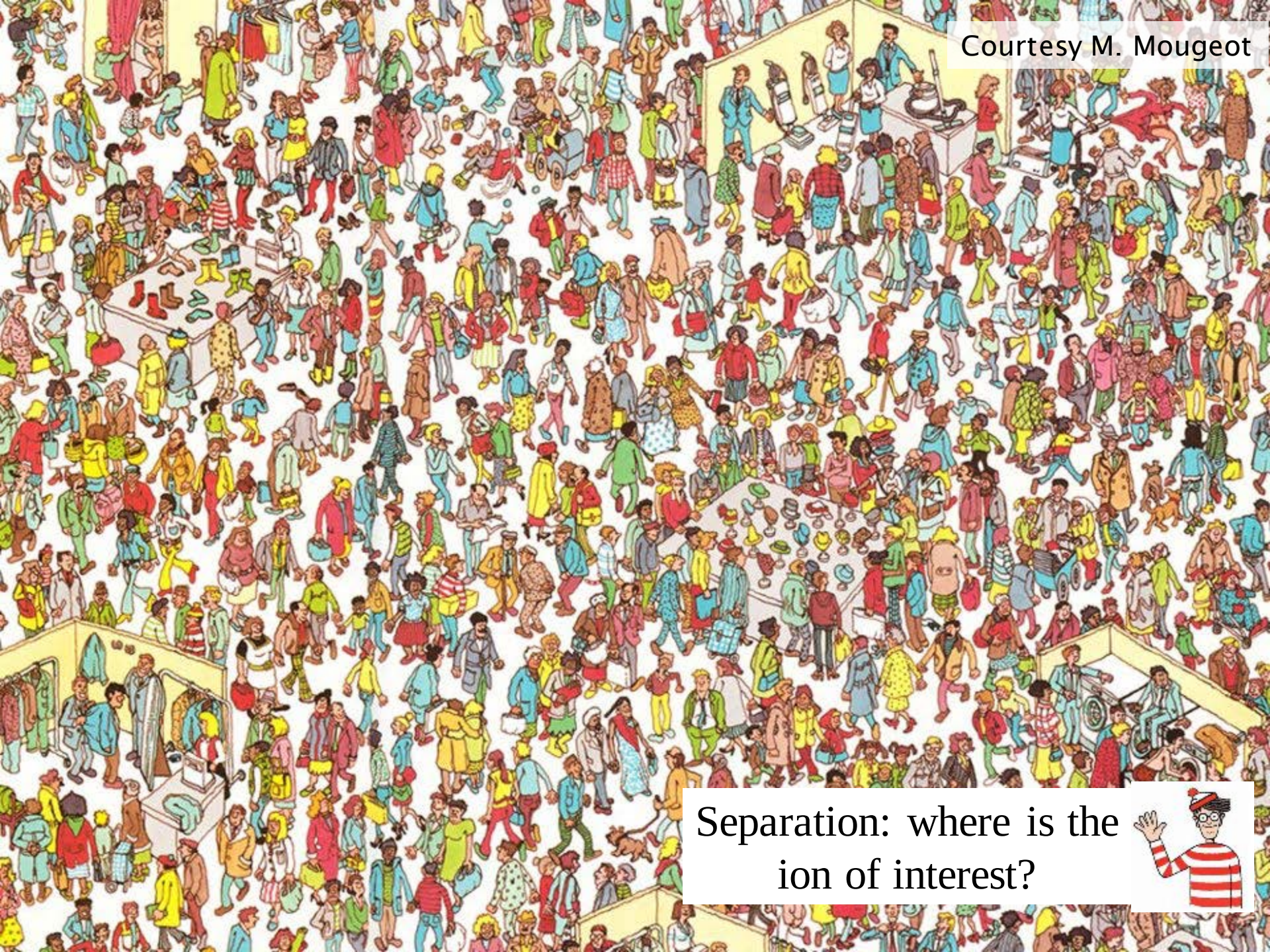
CERN-ISOLDE

# Produced nuclides

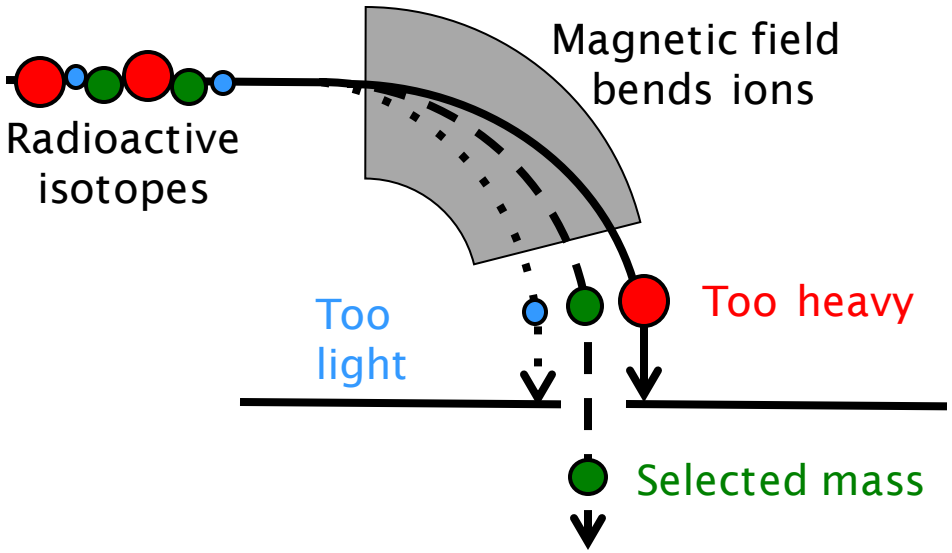
More than 700 nuclides of over 70 chemical elements produced – by far largest choice among ISOL-type facilities (experience gathered over 40 years)



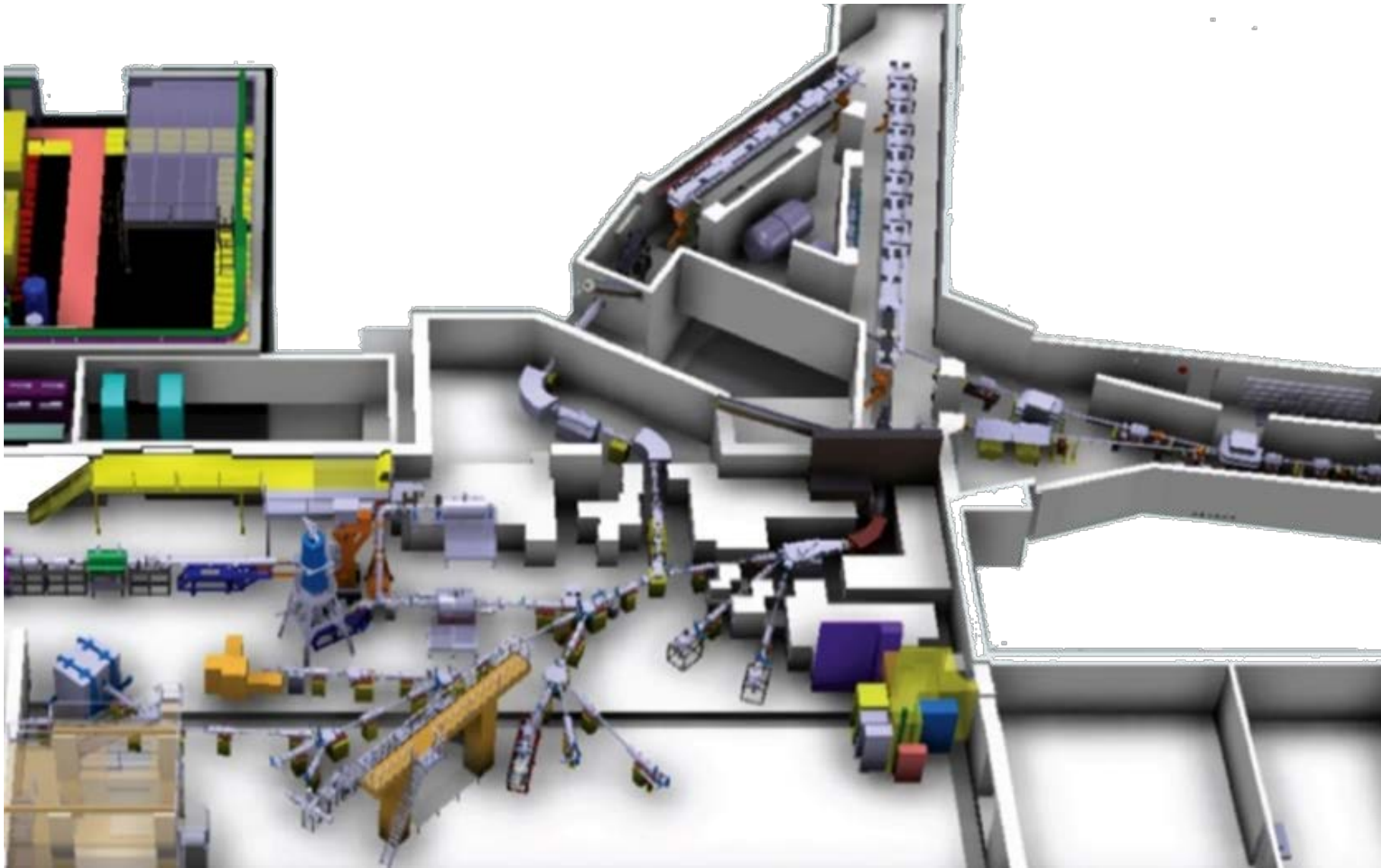

Exp. determined masses
stable
$\beta^+$
$\beta^-$
Neutron-star outer-crust nuclides
AME2011 values
HFB-19 prediction
ISOLTRAP measurement
FRDM
neutron drip line
$^{82}$Zn
$^{78}$Ni
Proton number, Z
Element
Sn
Cd
Pd
Ru
Mo
Zr
Sr
Kr
Se
Ge
Zn
Ni
Fe
Cr
50
48
46
44
42
40
38
36
34
32
30
28
26
24
26 28 30 32 34
82 84 86 88
production (par seconde)
1E+10
1E+08
1E+06
1E+04
1E+02
1E+00
1E-02
1E-04
1E-06
1E-08
50 55 60 65 70 75 80 85
N
un par jour
un par an...


Courtesy M. Mougeot
Separation: where is the
ion of interest?

Thanks to M. Mougeot for the idea

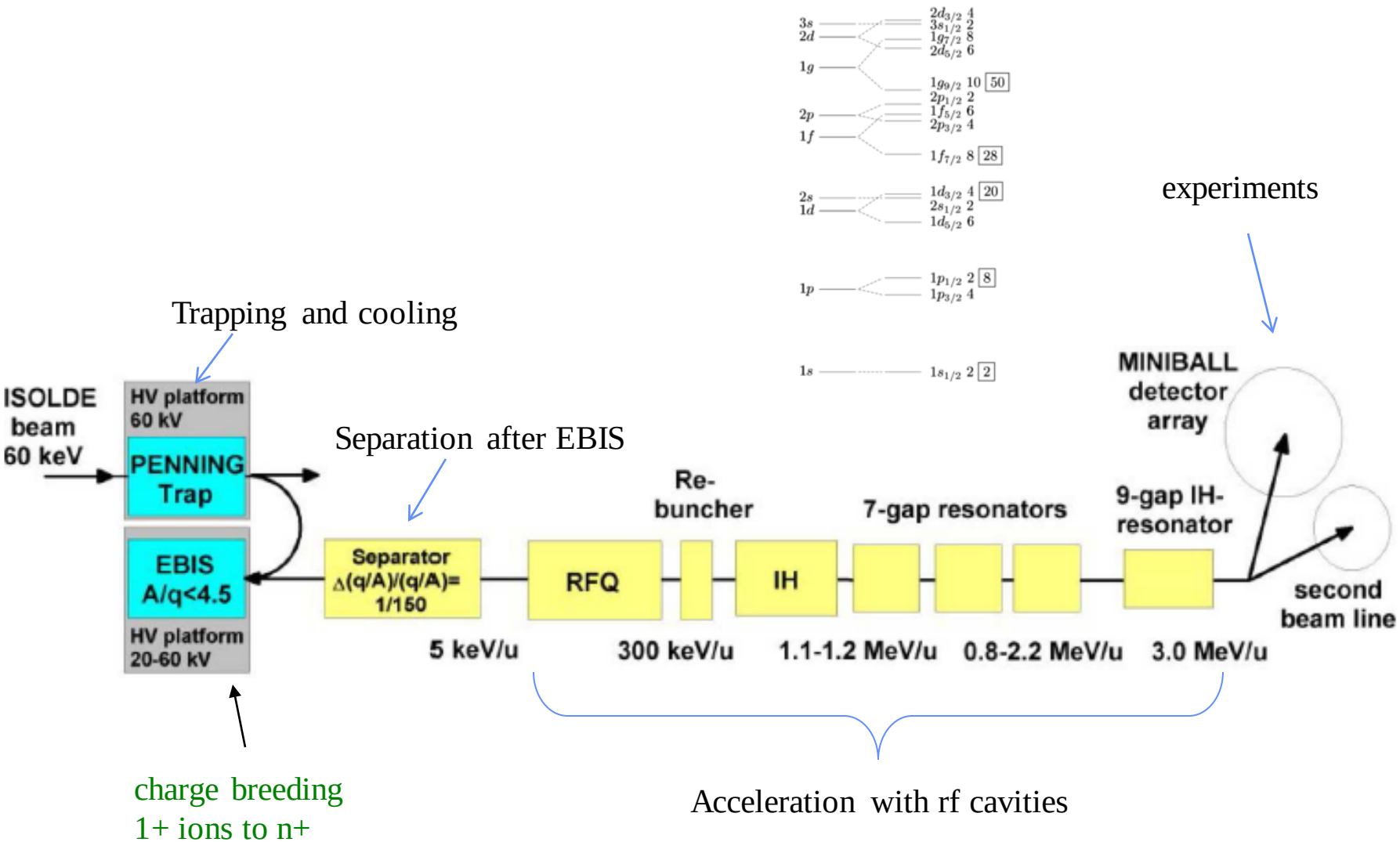


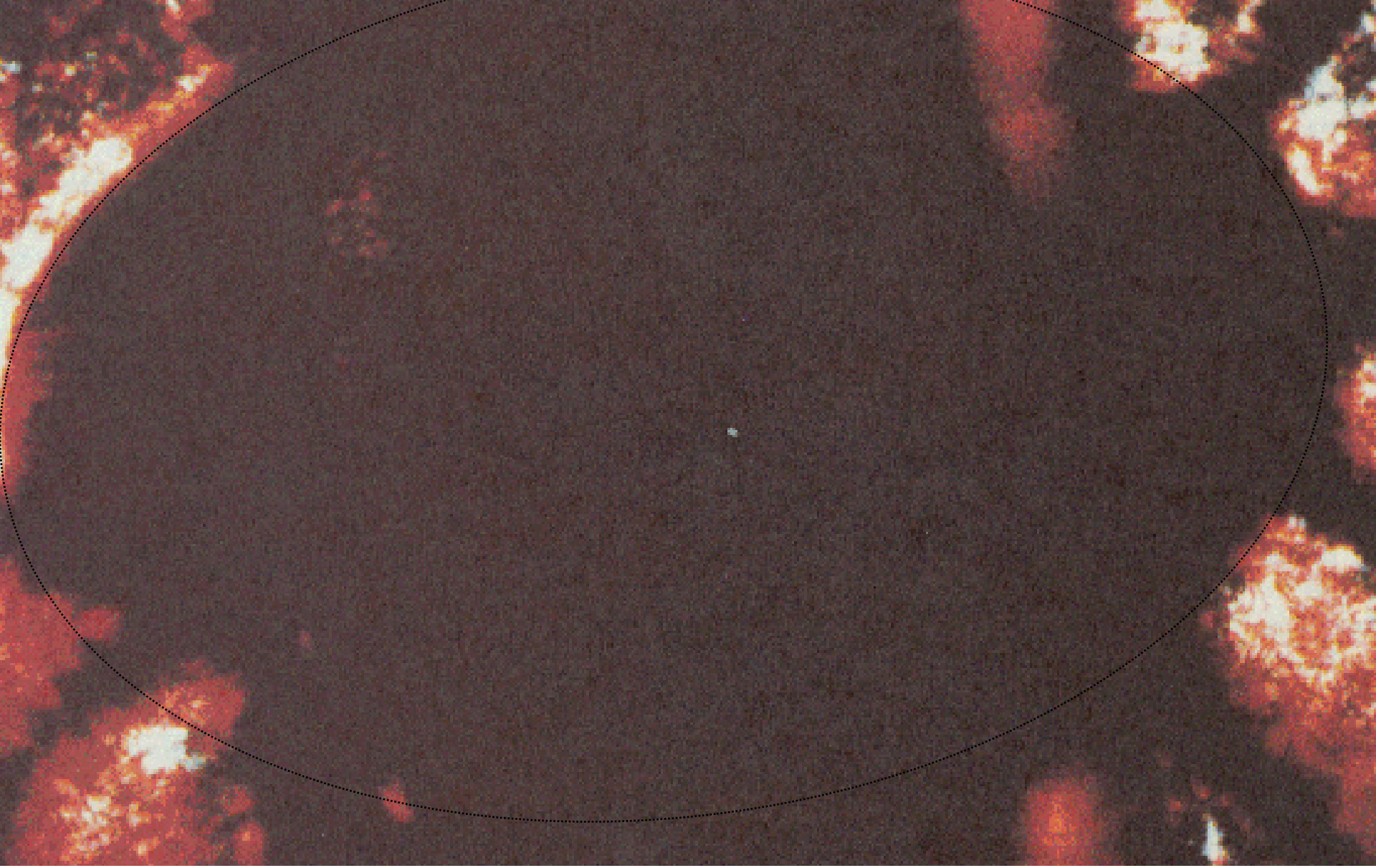
# ISOLDE layout




EXPERIENCES CERN 360° - Mozilla Firefox
Mail :: Inbox: Info-express...
IN2P3 - Nouvelles scientifiques
IN2P3 - Nouvelles scientifiques
IN2P3 - Nouvelles scientifiques
IN2P3 - Nouvelles scientifiques
WOTWISI-4
EXPERIENCES CERN 360°
www.experience-cern360.fr/noyau.html
Rechercher
EXPERIENCE CERN 360°
Au cœur de l'atome
David Lunney
www.experience-cern360.fr/res/portraits/base.html?name=davidlunney

# Beam post-acceleration: REX-ISOLDE

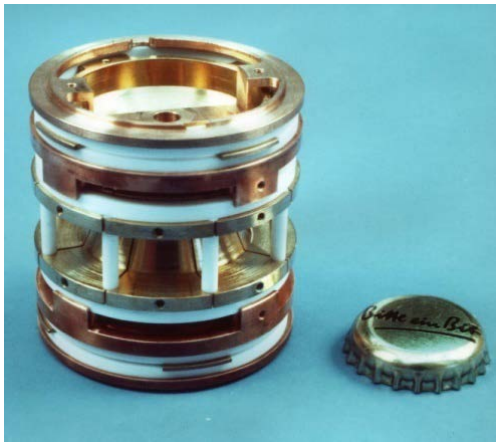


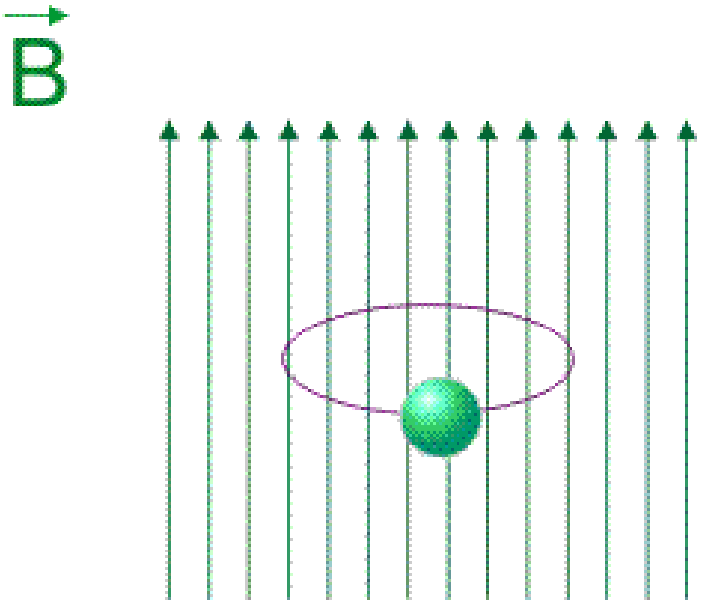


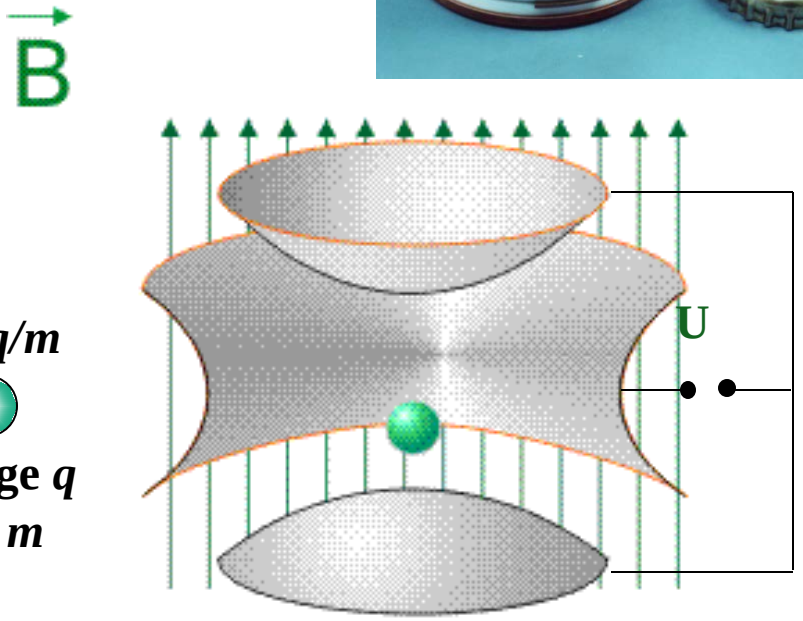
*Astrid* - H. Dehmelt (prix Nobel, 1989)

# Penning trap mass spectrometry

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






**Ion *q/m***

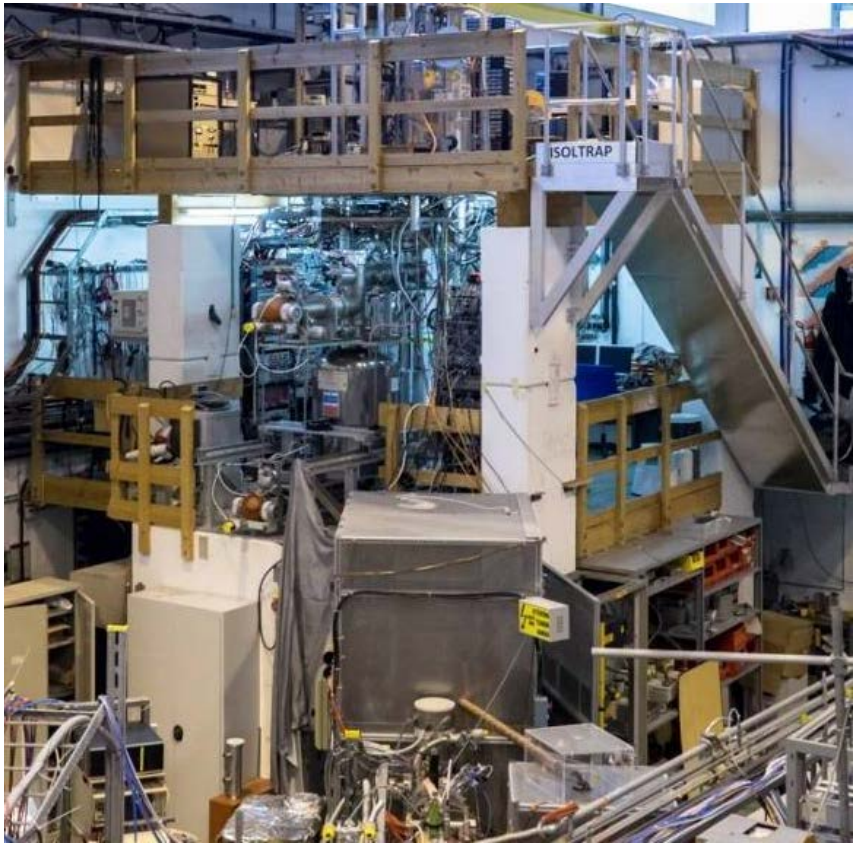
**Charge *q***
**Mass *m***

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

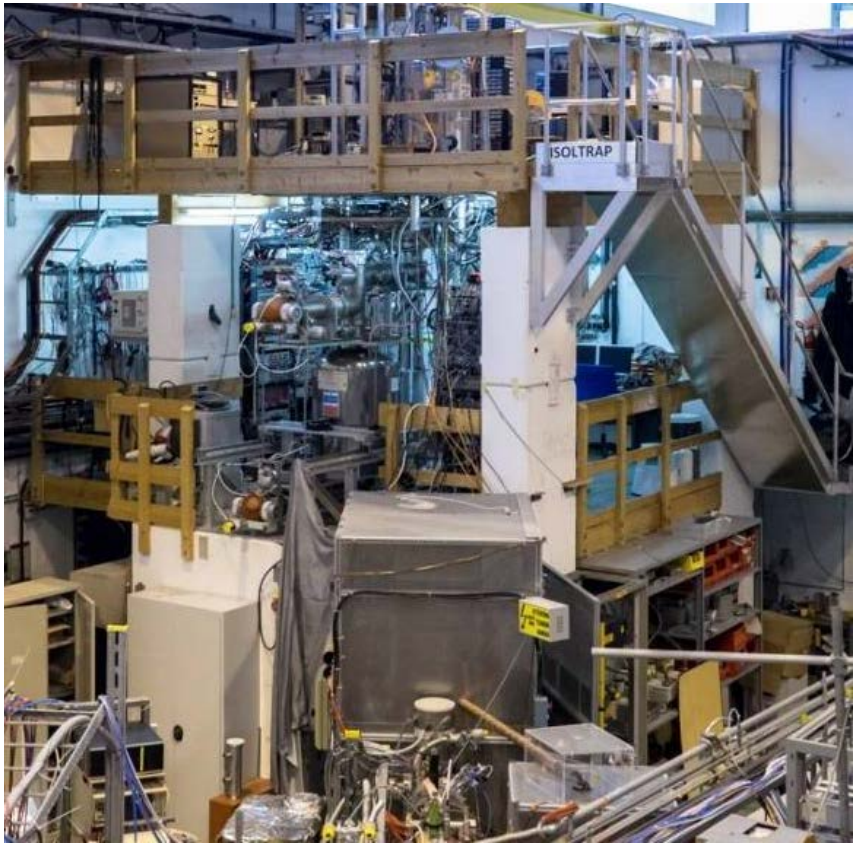
$$\omega_c = qB/m$$

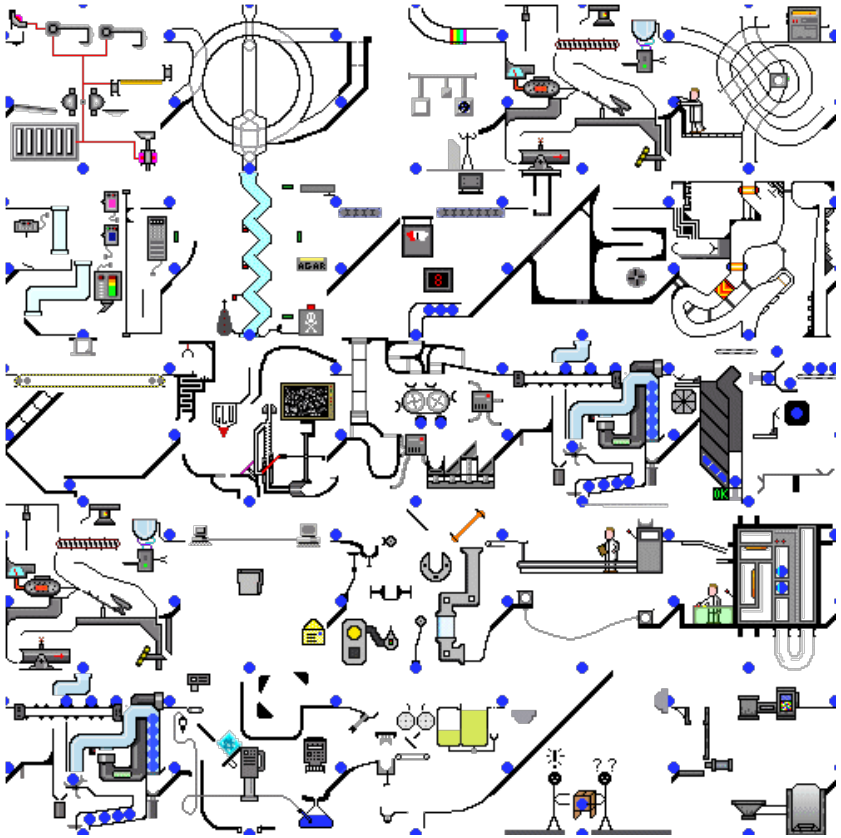
ISOLTRAP setup

# The ISOLTRAP spectrometer @ ISOLDE

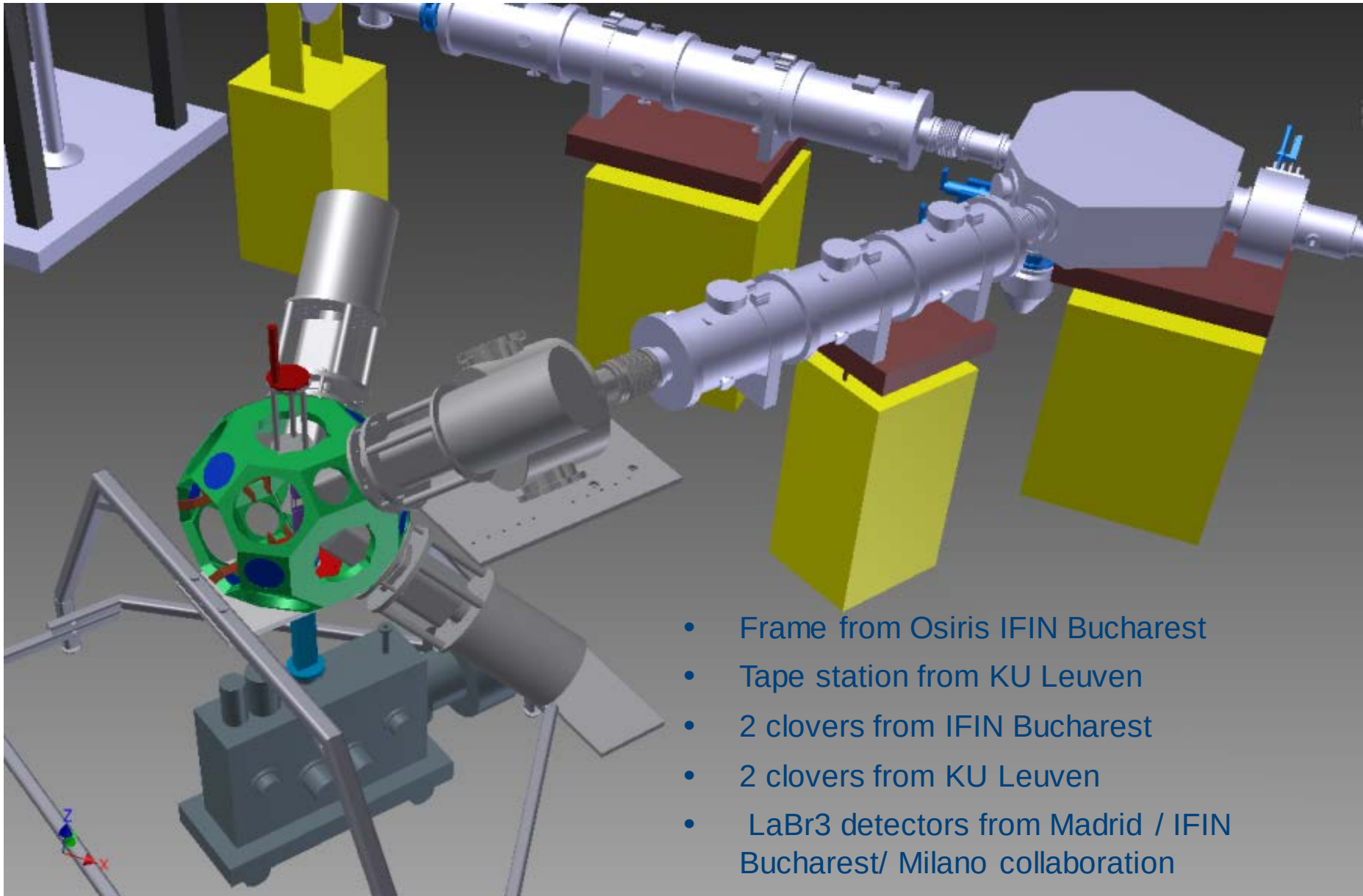


# The ISOLTRAP spectrometer @ ISOLDE



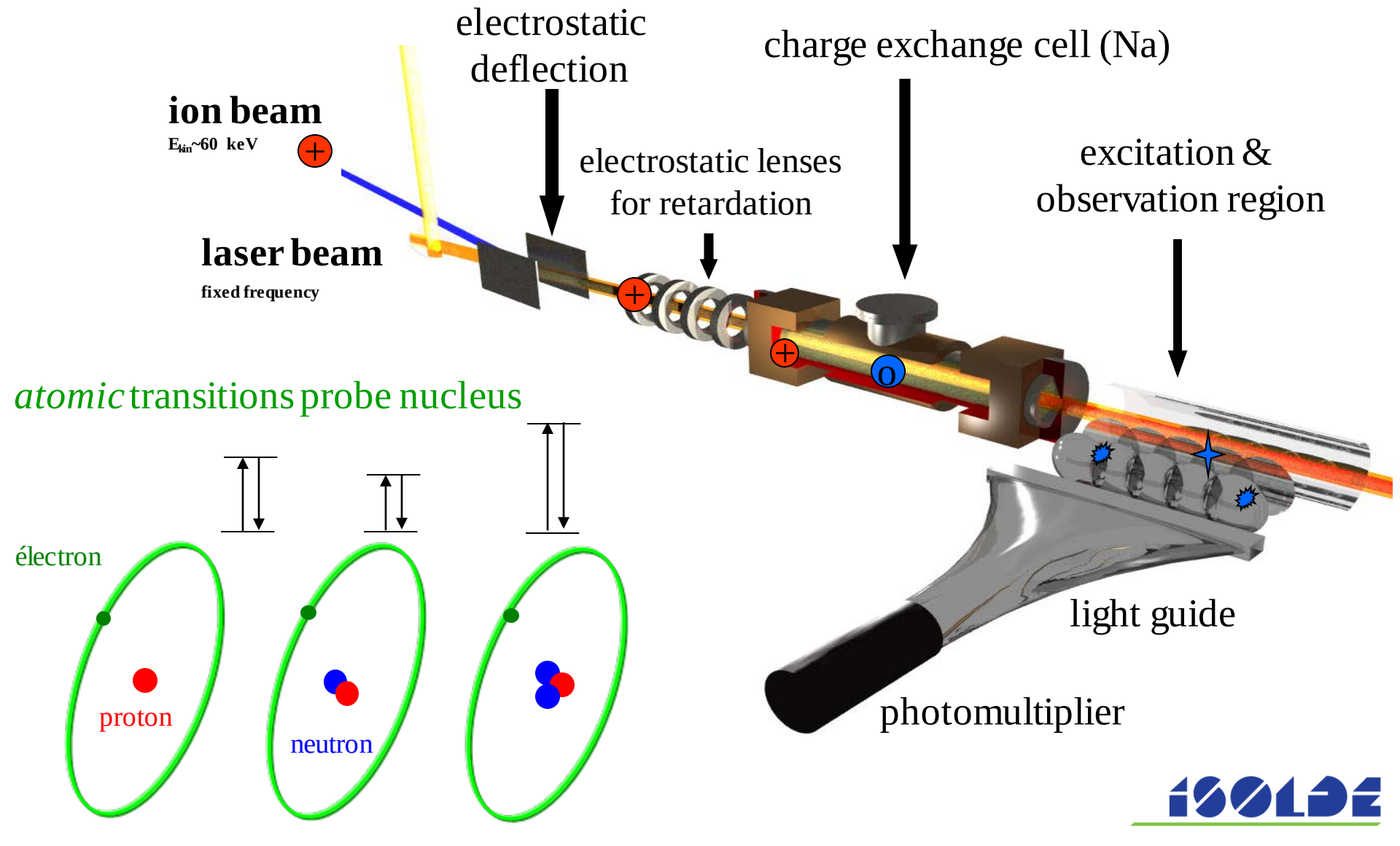



# IDS in the ISOLDE hall

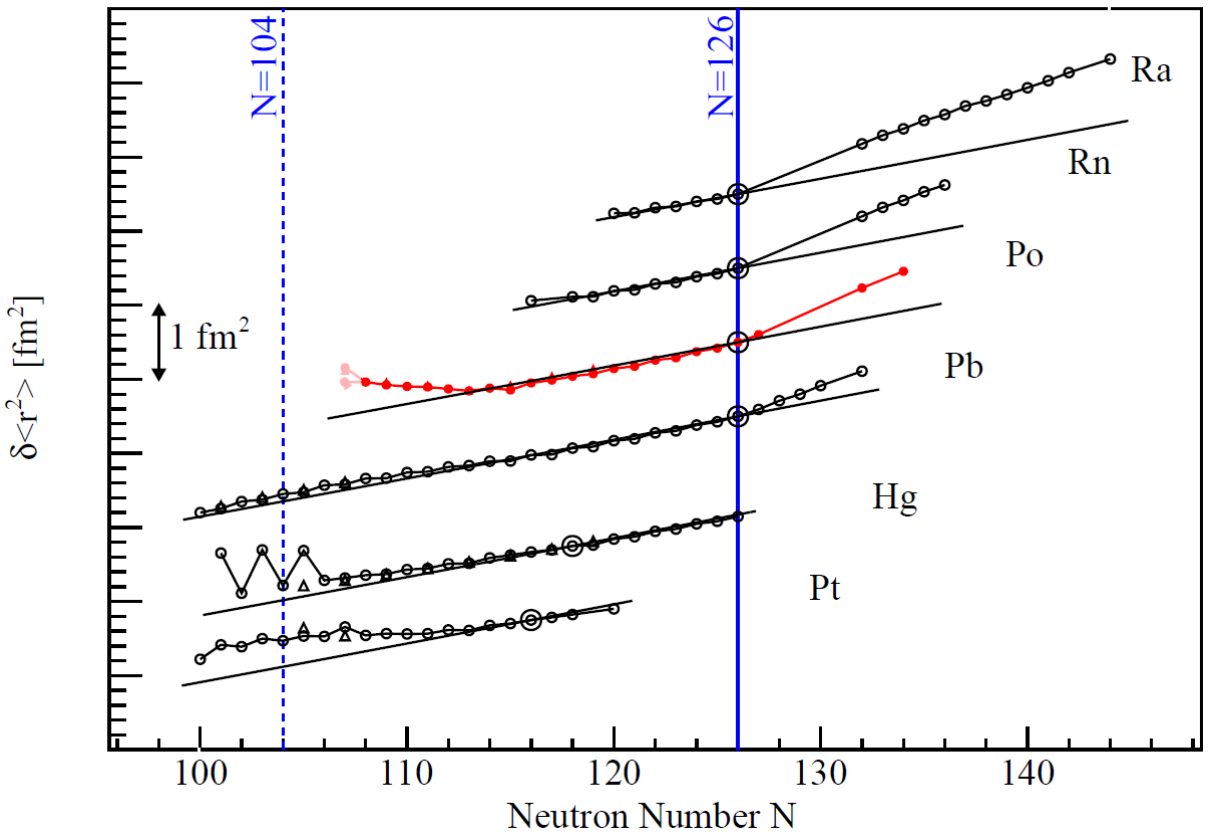


- Frame from Osiris IFIN Bucharest
- Tape station from KU Leuven
- 2 clovers from IFIN Bucharest
- 2 clovers from KU Leuven
- LaBr3 detectors from Madrid / IFIN Bucharest/ Milano collaboration

# Collinear laser spectroscopy



# Charge radii around lead



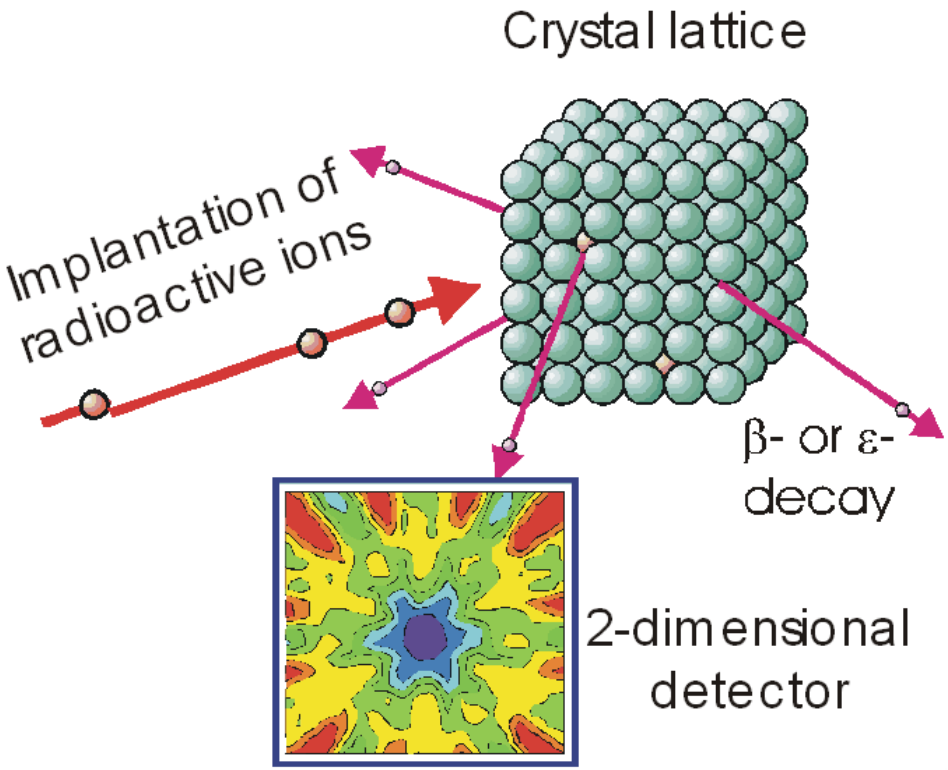

**Isotope shifts** measured with RILIS setup (part of data shown):

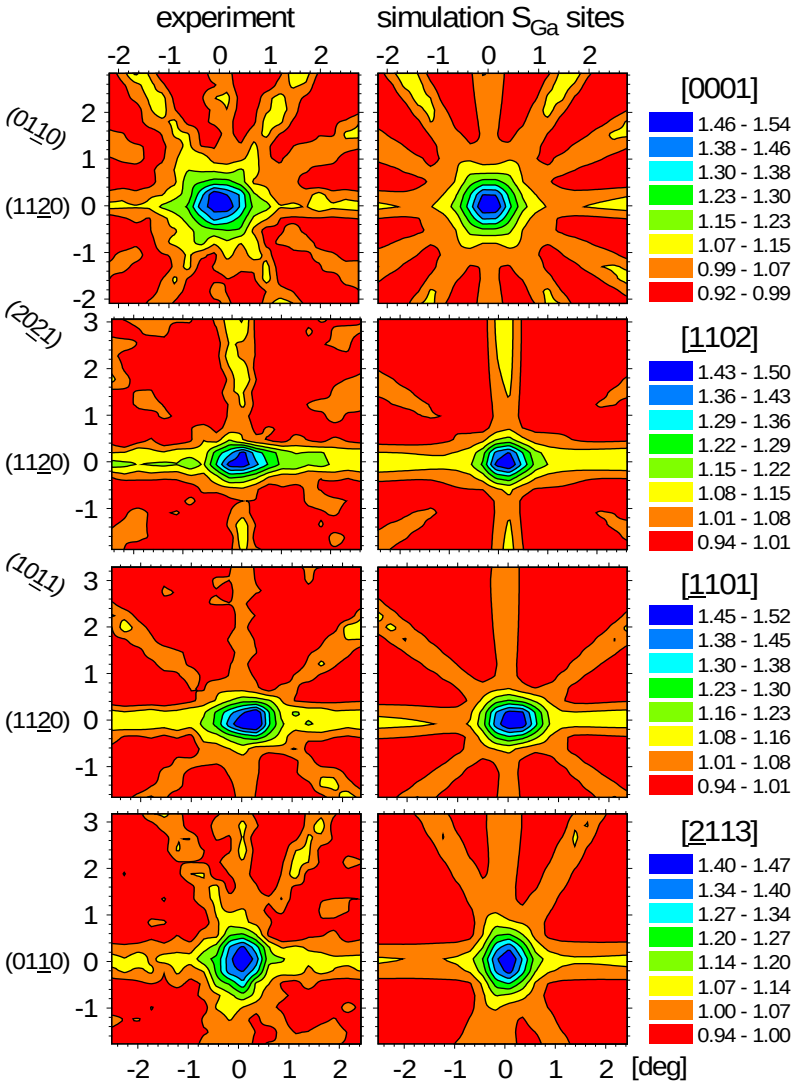
Regions of deformation visible


T.E. Cocolios et al., PRL 106 (2011) 052503
M. Seliverstov et al., EPJ A41(2009) 315
H. De Witte et al., PRL 98 (2007) 112502

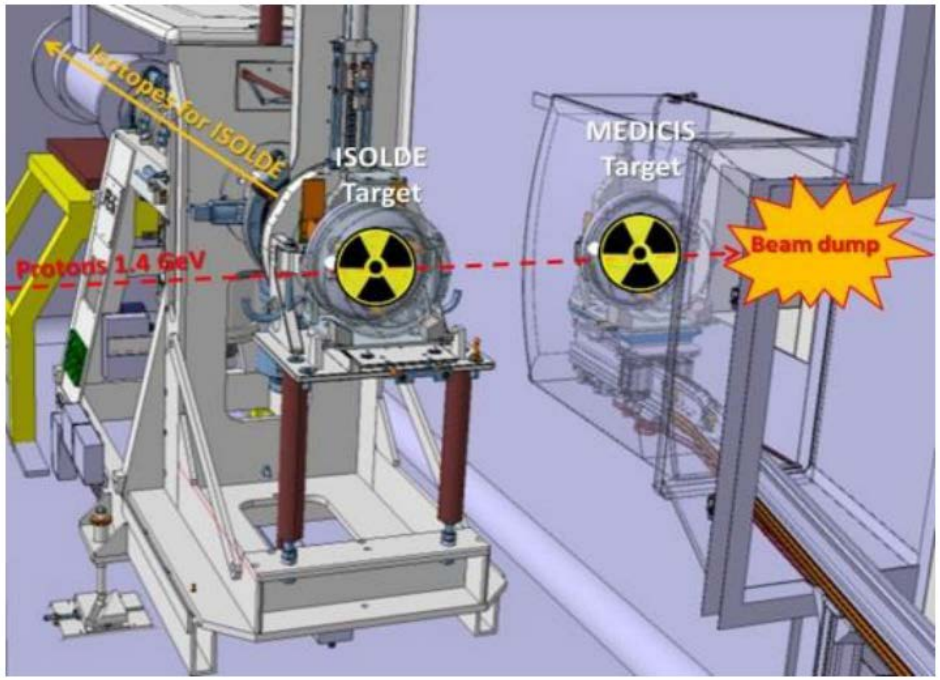
# Material science

- Emission channeling
  - Position of implanted ions

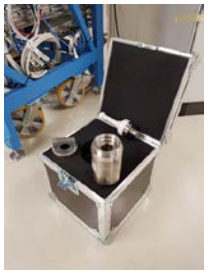


# MEDICIS: recycling protons for society

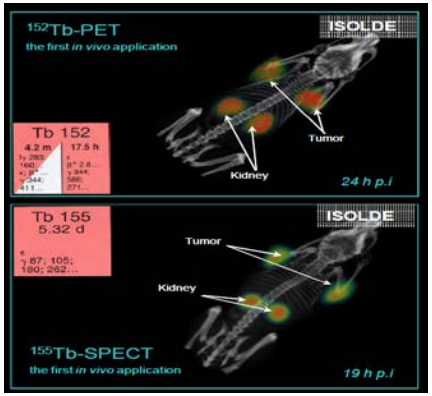



- Production of non-conventional radioisotopes for medical research
  - 80-90% of the proton beam goes through the ISOLDE target unaffected
  - Use these (free!) protons to create more radioisotopes



# Theranostics

**DiagNOSTICS** ← Target — MAB or PEPTIDE — Linker — Radioisotope → **THERApy**




## $\beta^+$-(positron) emissions

PET E(γ) = 511 keV

## γ-emissions

SPECT
100keV<E(γ)<200keV

## α-emitter

High LET, short distance in human tissue


## β-emitter

Low LET, long distance in human tissue

# ISOLDE at CERN

- Isotope Separator On Line
- Approved by CERN council 1964, first beam 1967
  - Initially used 600 MeV protons from SC
  - Now 1.4 GeV protons from PSB (soon 2 GeV ☺)
- A small facility with a big impact!
  - ~0.1% of the CERN budget
  - ~7% of the CERN scientists
  - ~50% of the CERN protons
- Run by international collaboration
  - CERN, BE, DE, DK, FI, FR, GR, IT, NO, PL, RO, SK, ZA, ES, SE, UK
  - ~50 staff/students/fellows
  - ~1500 users
- PAC → beamtime; typically one week 24/7

# Safety rules in the ISOLDE hall

- Don't touch anything!
- No food & drinks allowed, leave your bag here!
- Always follow the guide, don't wander off!
- Everyone must wear flat, closed or block-heeled shoes!
- It is allowed to take pictures!
- No entry for people:
  - Younger than 16
  - Who are pregnant
  - Who have devices sensitive to magnetic fields