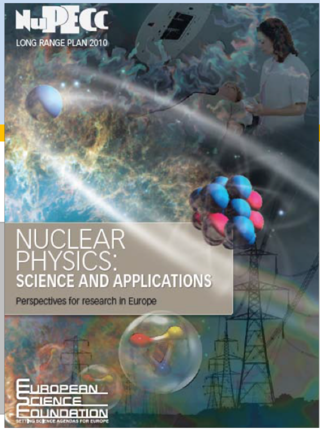
Facilities used by the Nuclear Physics Community

Exotic Nuclei and Radiactive Beams

- Introduction
- Exotic Nuclei :
    - Production modes
    - Separation
    - Identification
- Radioactive Beams
- References:

“The why and how of Radioactive beam Research”, Mark Huyse,
“In-flight separation of projectile fragments”, David Morrisey and Brad Sherril
“Isotope separation on line and post-acceleration”, P. Van Duppen
http://www.euroschoolonexoticbeams.be/site/pages/lecture_notes

Open Questions



NuPECC
LONG RANGE PLAN 2010
NUCLEAR PHYSICS:
SCIENCE AND APPLICATIONS
Perspectives for research in Europe
European Science Foundation

- ¿How a nucleus is formed from their constituents?

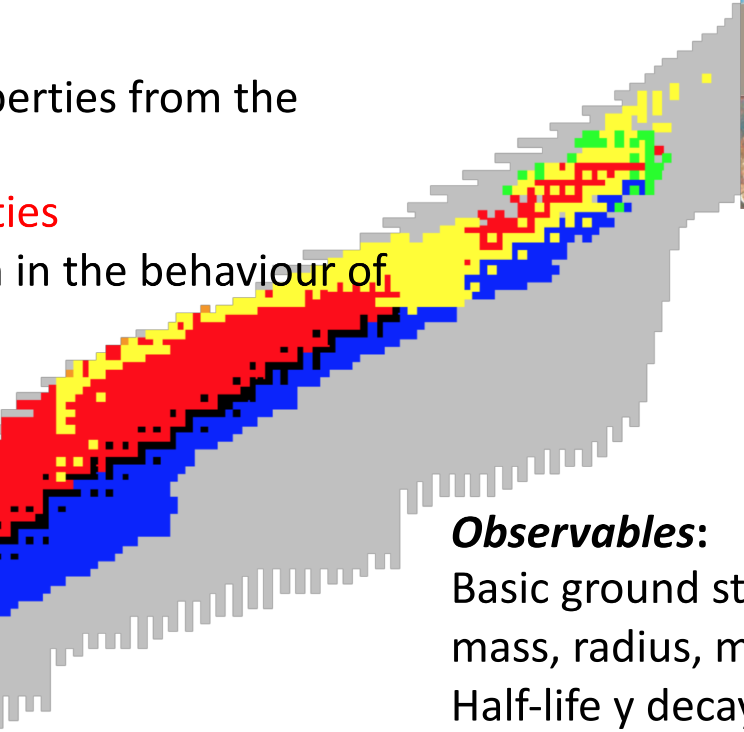
➢Strong force in nuclear medium

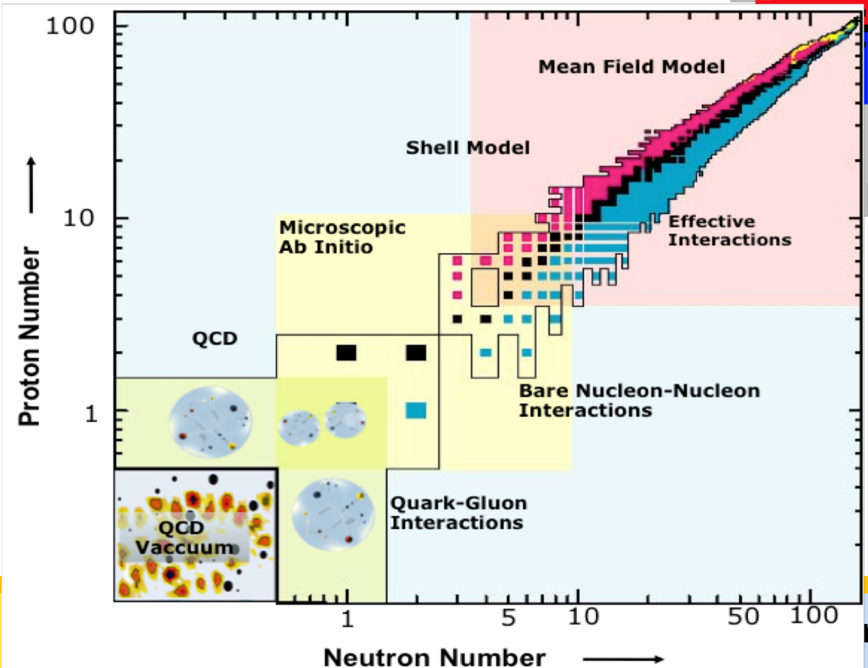
- ¿How to explain the collective properties from the individual behaviour?

➢Collective versus individual Properties

- ¿Why due we have regular pattern in the behaviour of nuclei?

➢Identification of Symmetries





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

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

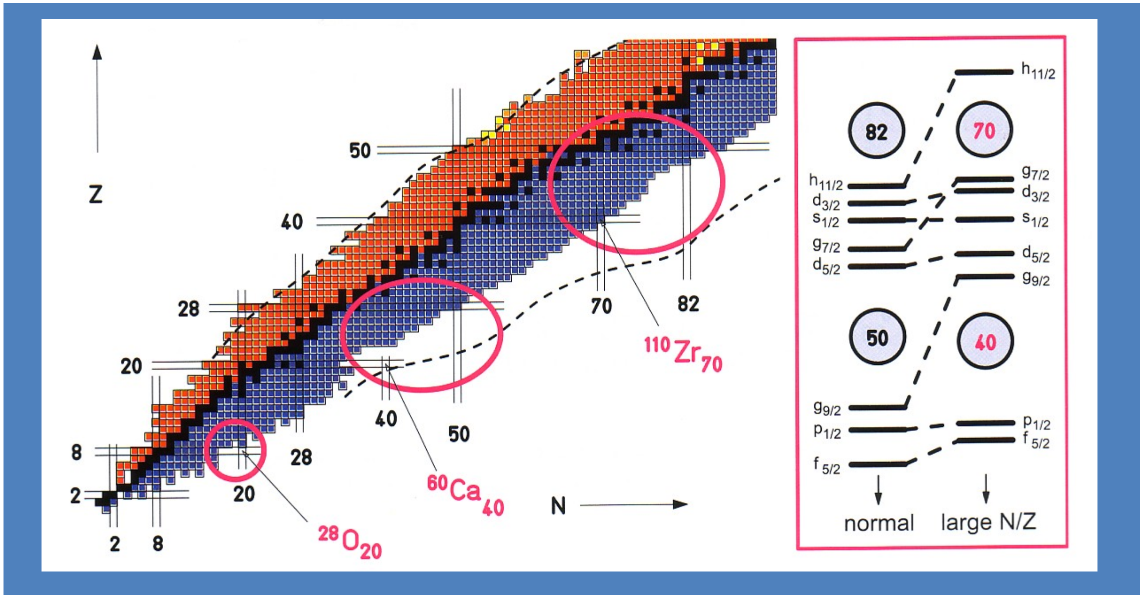
Why Study Exotic Nuclei?

Explore the different degrees of freedom of the system in
isospin, T,
in excitation energy, **E_x**,
spin, **J,**
level density, **ρ**

- Stringent test of Theoretical Models
- Observation of new decay modes
- Measurement of astrophysical interest
- Halo structure
- Evolution of shell structure

Challenges in producing exotic beams:

- Small interactions cross-section
- Isobaric contamination
- Very short life-times



Production Techniques:

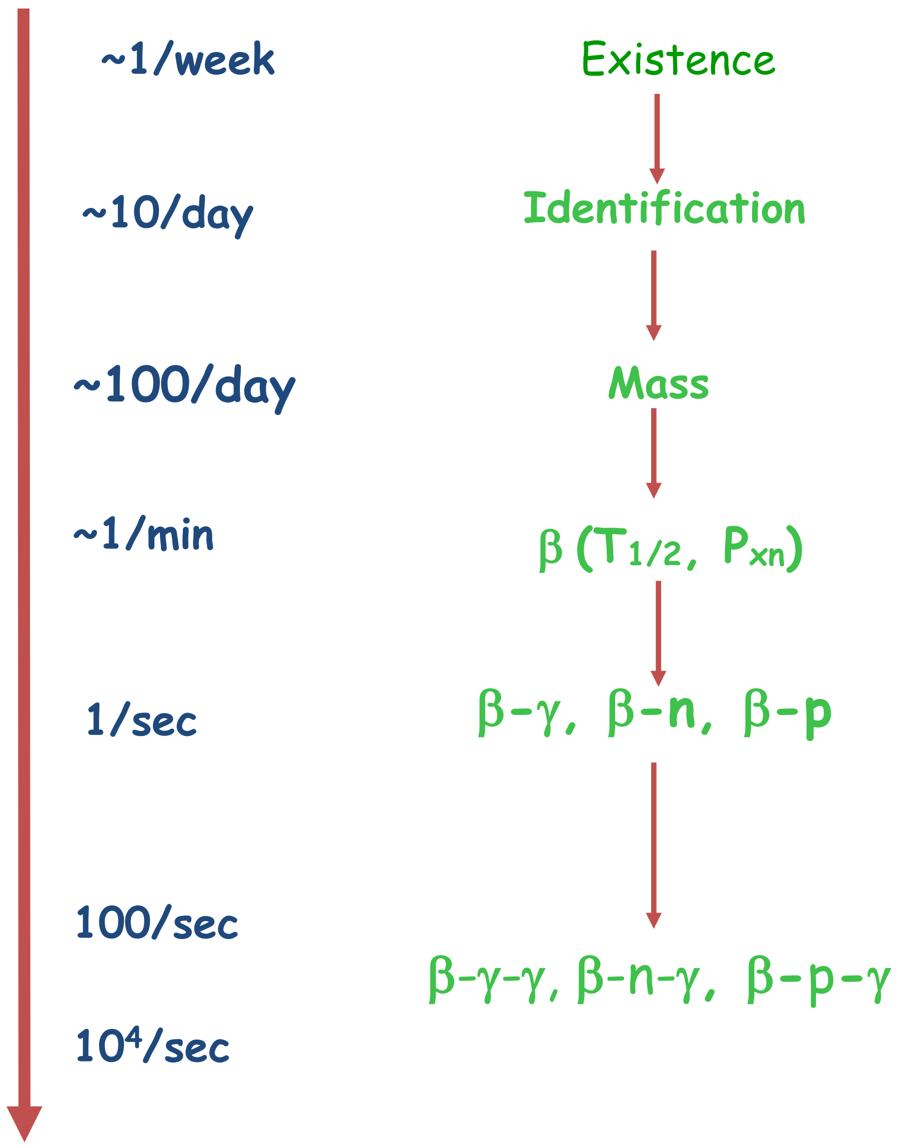
1. ISOL (Isotope On-line)
2. In-Flight

Production

The discovery of a new element/isotope depends of many factors:

- Production method: various mechanism of nuclear reactions.
- Efficient separation and transportation
- Detection method

Yield Requirements



Rate

~1/week

~10/day

~100/day

~1/min

1/sec

100/sec

10^4/sec

Access

Existence

Identification

Mass

β ($T_{1/2}$, P_{xn})

β-γ, β-n, β-p

β-γ-γ, β-n-γ, β-p-γ

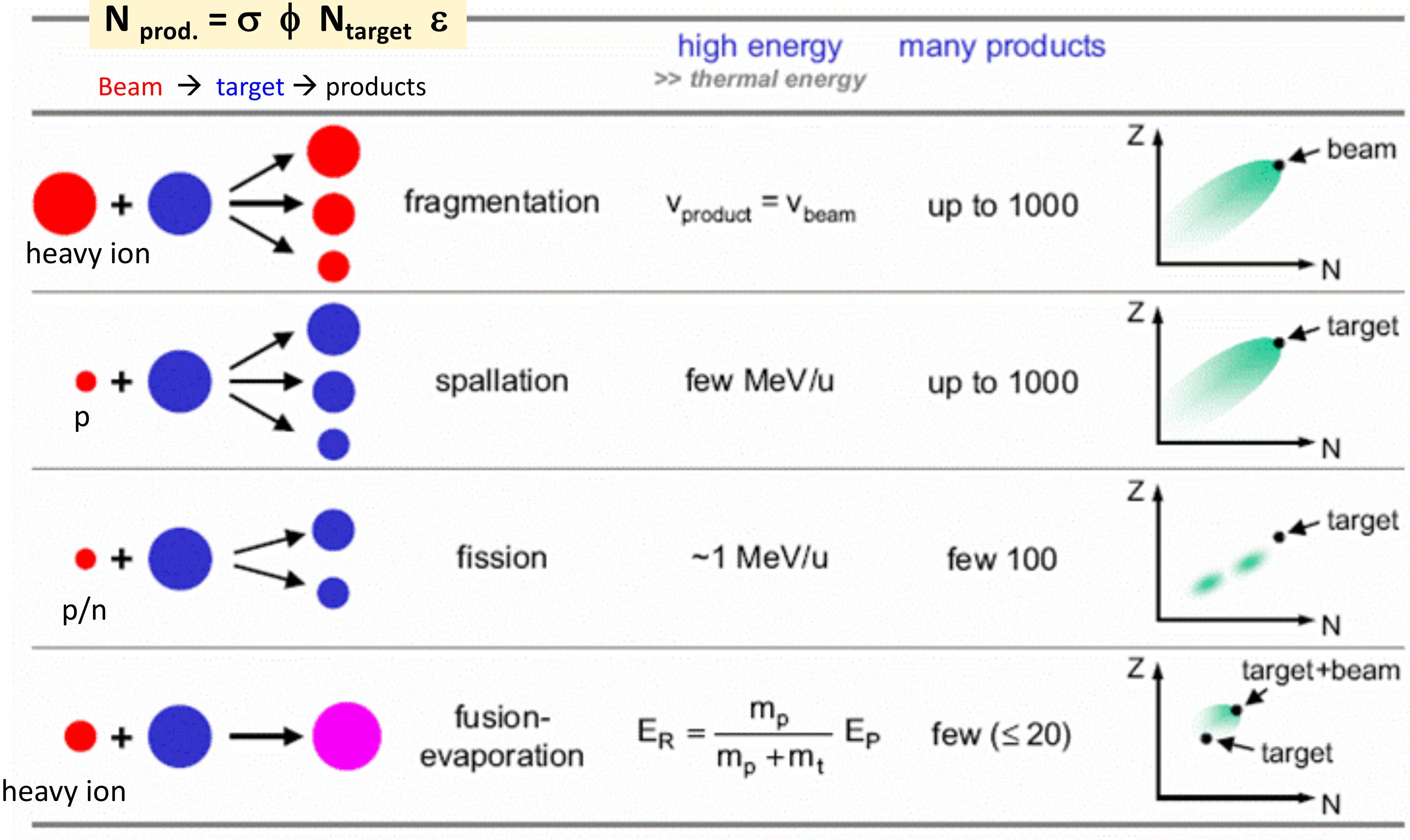
✓ β-decay gives first information of a new isotope.

✓ When the production is high ⇒ detailed structure information can be achieved.

Production Methods

$$N_{prod.} = \sigma\ \phi\ N_{target}\ \varepsilon$$

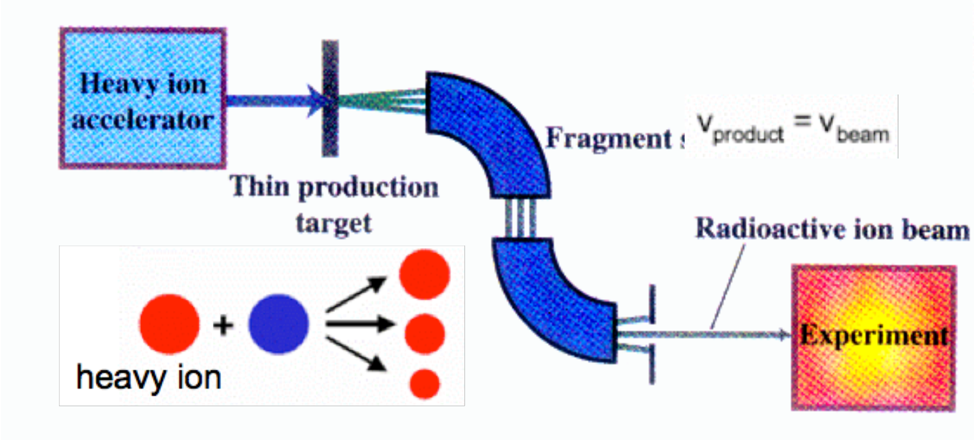
Beam → target → products

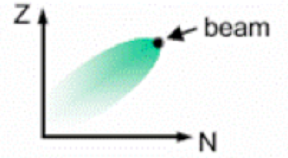


		high energy >> thermal energy	many products	
heavy ion	fragmentation	$v_{product} = v_{beam}$	up to 1000	beam
p	spallation	few MeV/u	up to 1000	target
p/n	fission	~1 MeV/u	few 100	target
heavy ion	fusion-evaporation	$E_R = \frac{m_p}{m_p + m_t} E_P$	few (≤ 20)	target+beam target

Production of Radioactive Beams

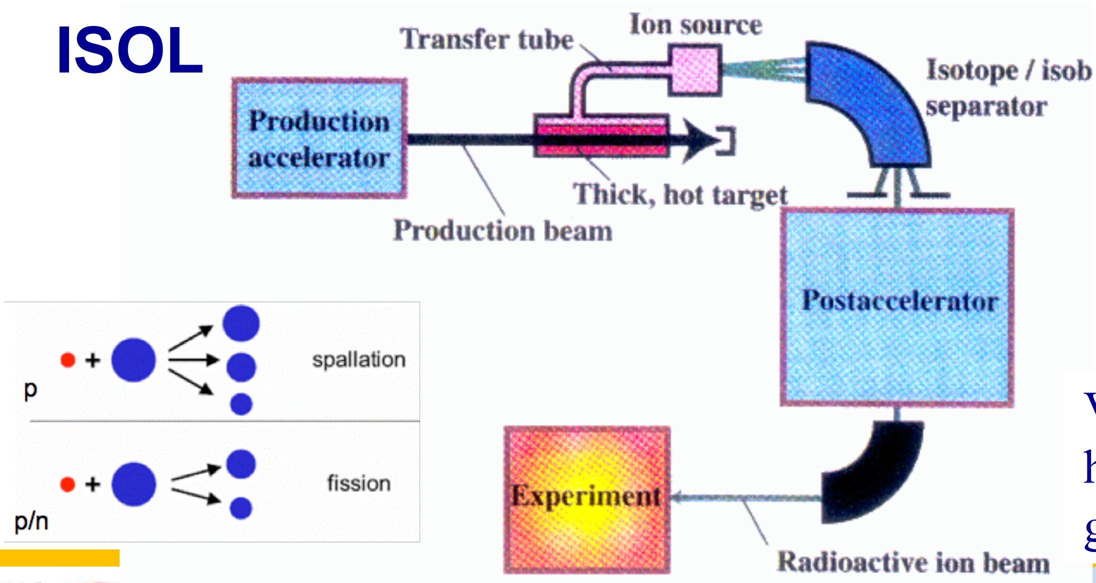
PROJECTILE FRAGMENTATION

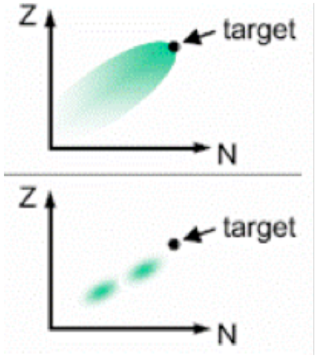




High energy,
large variety of species,
Short half-lives (μs),
cocktail beam

ISOL

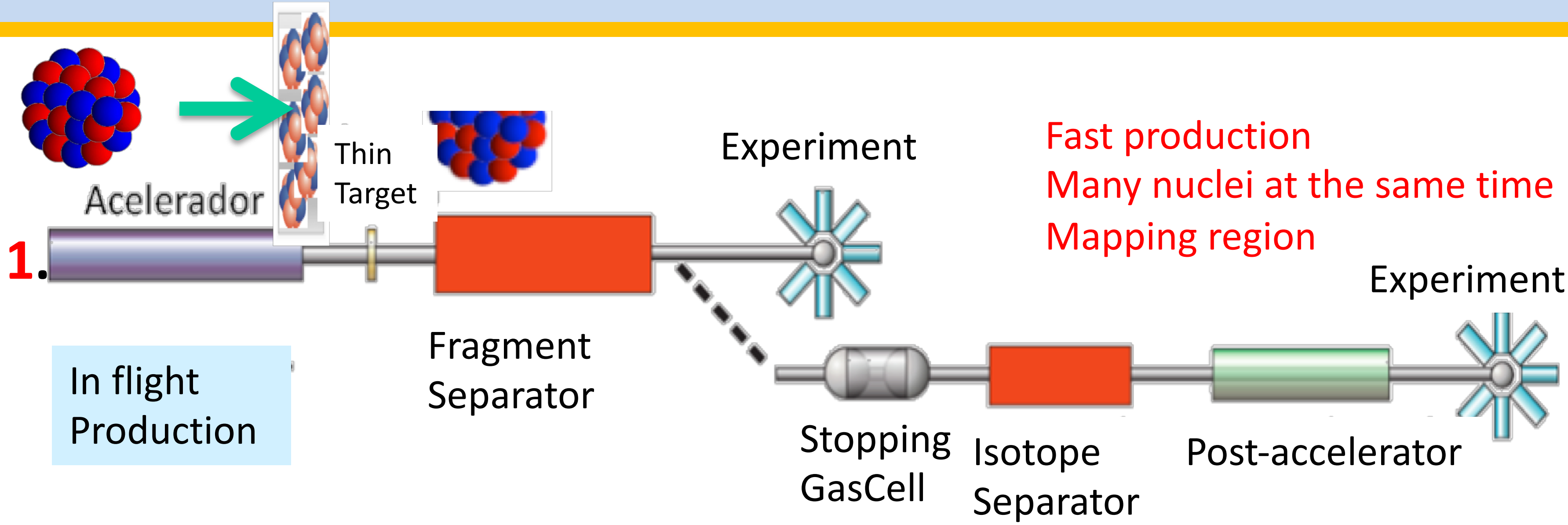




Variable energy,
high intensity,
good beam qualities

FAIR	1 GeV
GSI	400MeV/u
GANIL	50MeV/u
SPIRAL	10MeV/u
HIE – ISOLDE	10MeV/u
ISOLDE	0.06 MeV

Isotope production



1.

Acelerador

Thin Target

Experiment

Fragment Separator

Stopping GasCell

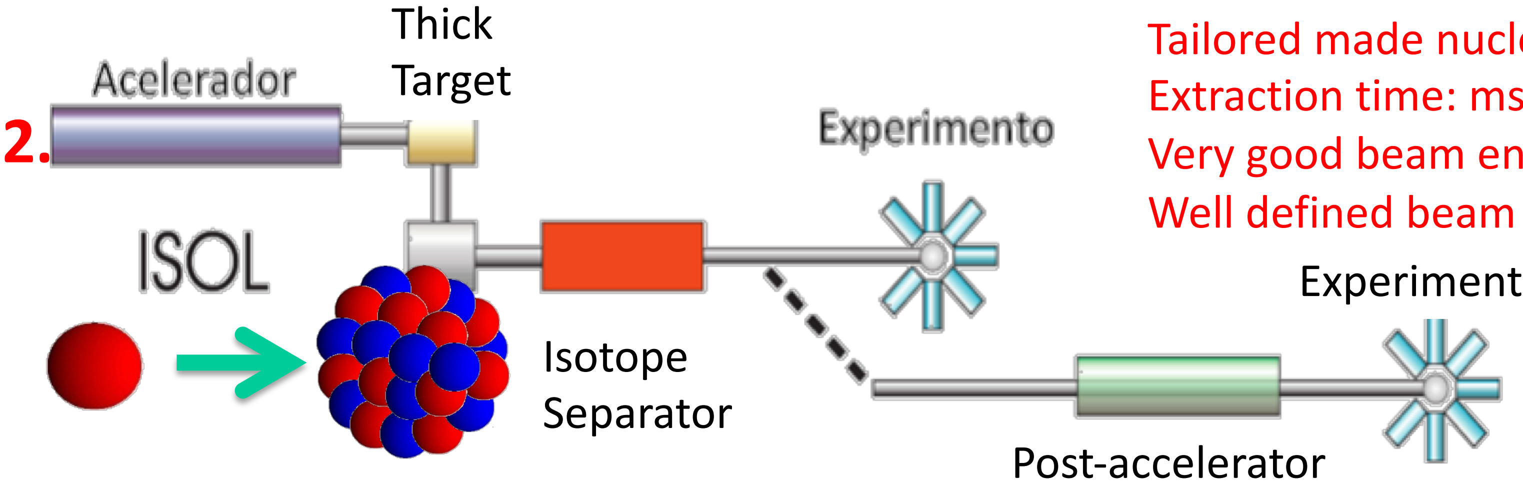
Isotope Separator

Post-accelerator

Experiment

In flight Production

Fast production
Many nuclei at the same time
Mapping region



2.

Acelerador

Thick Target

Experimento

ISOL

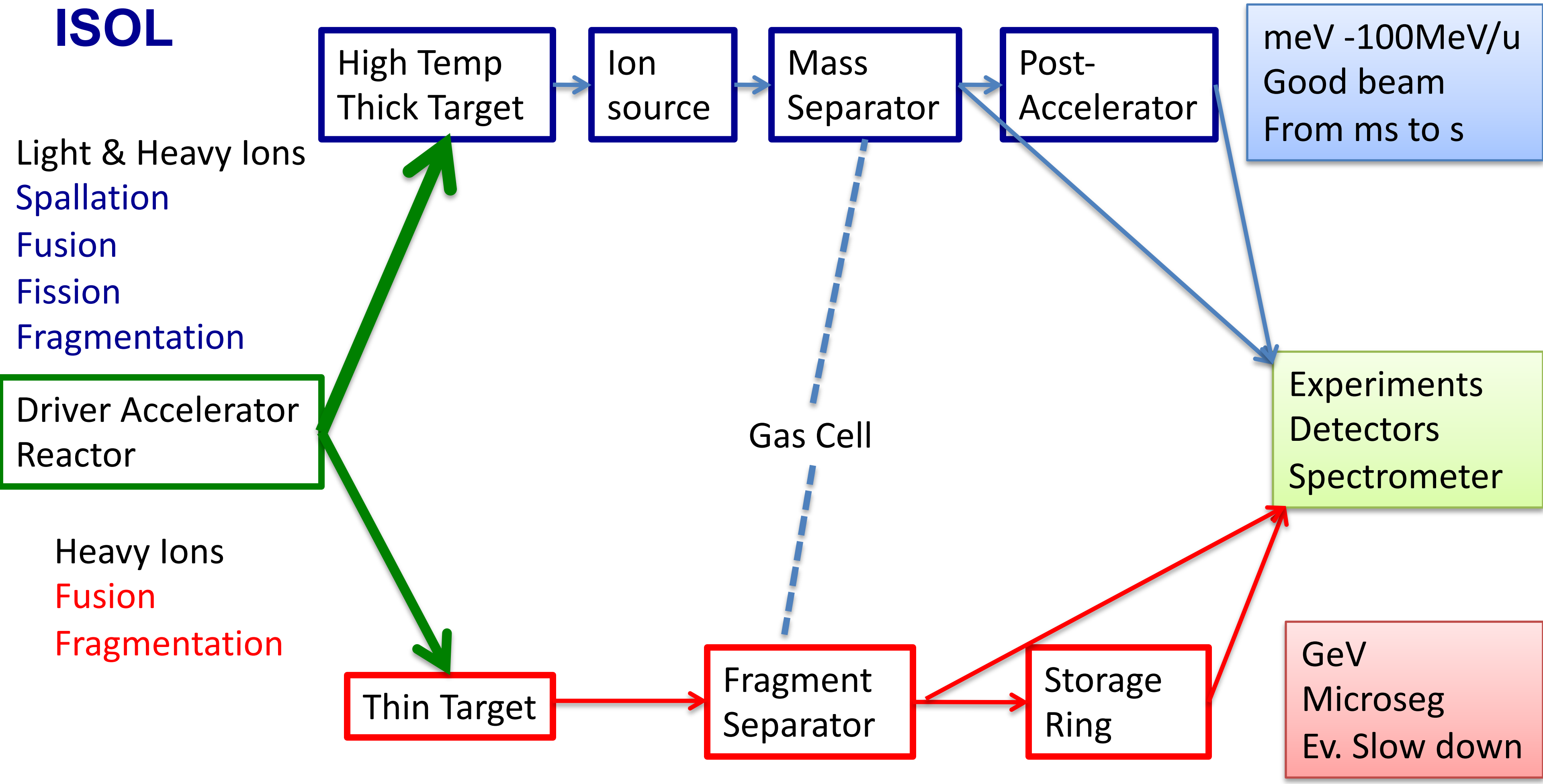
Isotope Separator

Experiment

Post-accelerator

Tailored made nuclei
Extraction time: ms – s
Very good beam energy resolution
Well defined beam optics

Production Methods



ISOL

High Temp Thick Target → Ion source → Mass Separator → Post-Accelerator

meV -100MeV/u
Good beam
From ms to s

Light & Heavy Ions
Spallation
Fusion
Fission
Fragmentation

Driver Accelerator
Reactor

Gas Cell

Experiments
Detectors
Spectrometer

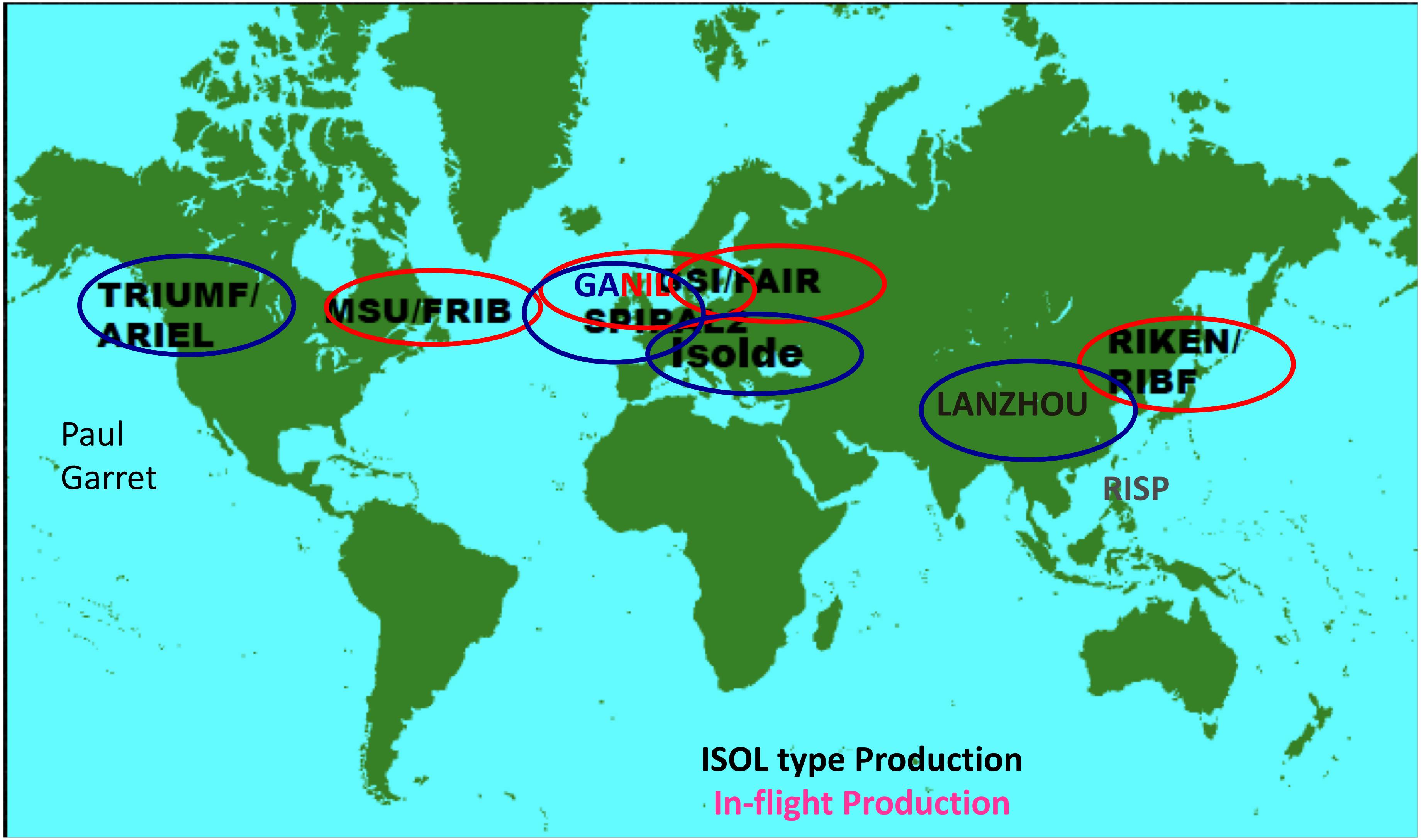
Heavy Ions
Fusion
Fragmentation

Thin Target → Fragment Separator → Storage Ring

GeV
Microseg
Ev. Slow down

PROJECTILE FRAGMENTATION

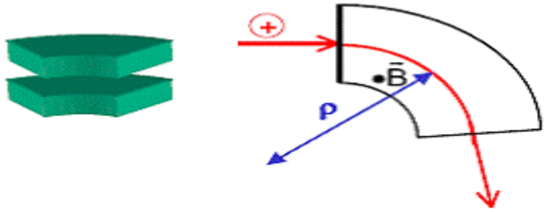
RIB Facilities in the World



Paul
Garret

Separation at High Energy

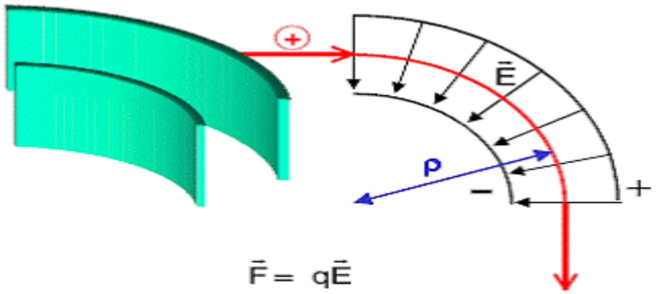
magnetic dipole



$\vec{F} = q\vec{v} \times \vec{B}$

$B\rho = \frac{mv}{q} \quad [T \cdot m]$

electric dipole



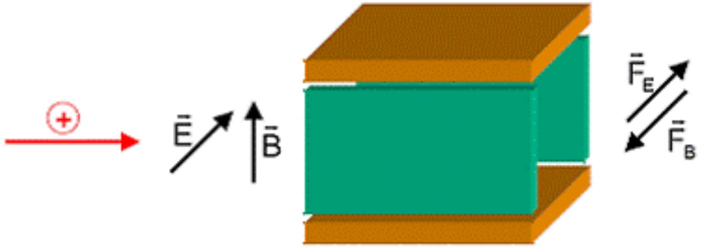
$\vec{F} = q\vec{E}$

$E\rho = \frac{mv^2}{q} \quad \left[\frac{J}{C}\right]$

Part with same charge, mass and v ➔same rigidity Bρ

velocity filter

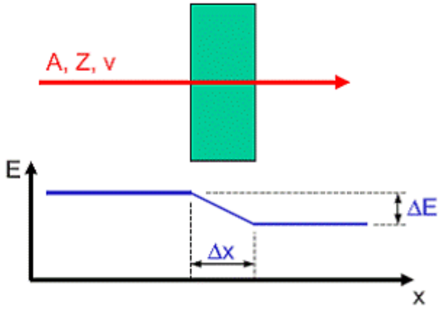
Wien filter, E-cross-B filter



charged particles with velocity $v = \frac{E}{B}$ are not deflected

Need Wien-vel-Filter to separate in velocity

Energy degrader



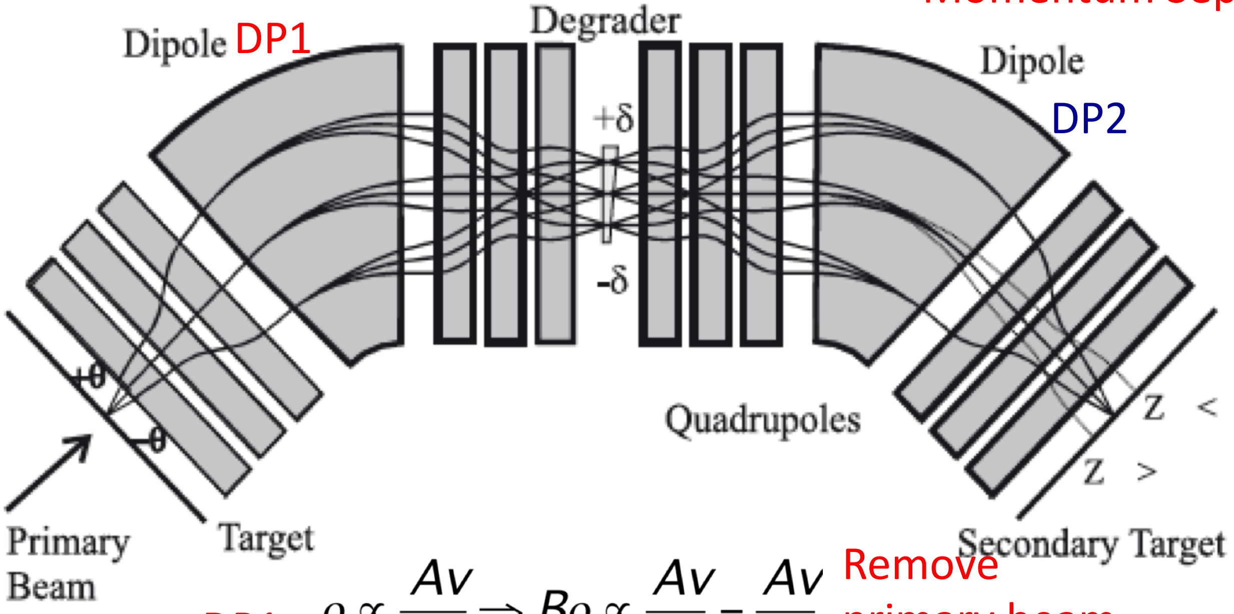
stopping power $S \equiv -\frac{dE}{dx} \propto \frac{Z^2}{v^2} \propto \frac{A\,Z^2}{E}$

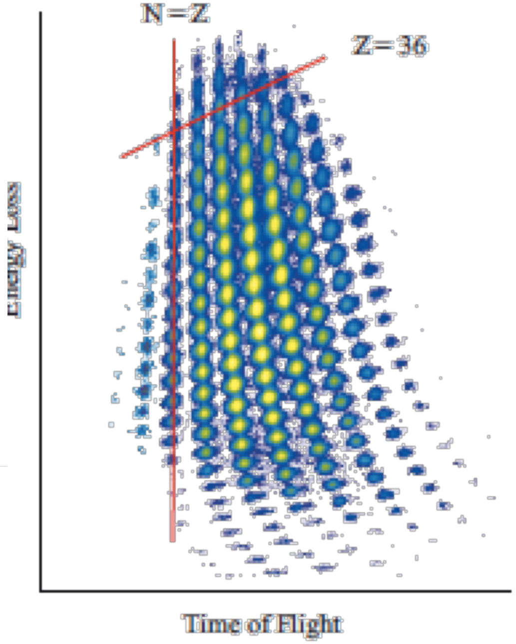
→ straggling (spread) in energy and angle

Fragment Separator - FRS

A/Z separation

Momentum Separation





DP1 $\rho \propto \frac{Av}{QB} \Rightarrow B\rho \propto \frac{Av}{Q} = \frac{Av}{Z}$

Remove primary beam 10^{12} ➔ 10^{8}

Degrader $\propto \frac{AZ^2}{E}$

Degrader + DP2 $\propto \frac{A^3}{Z^2}$

Reduction 10^{8} ➔ 10^{6}

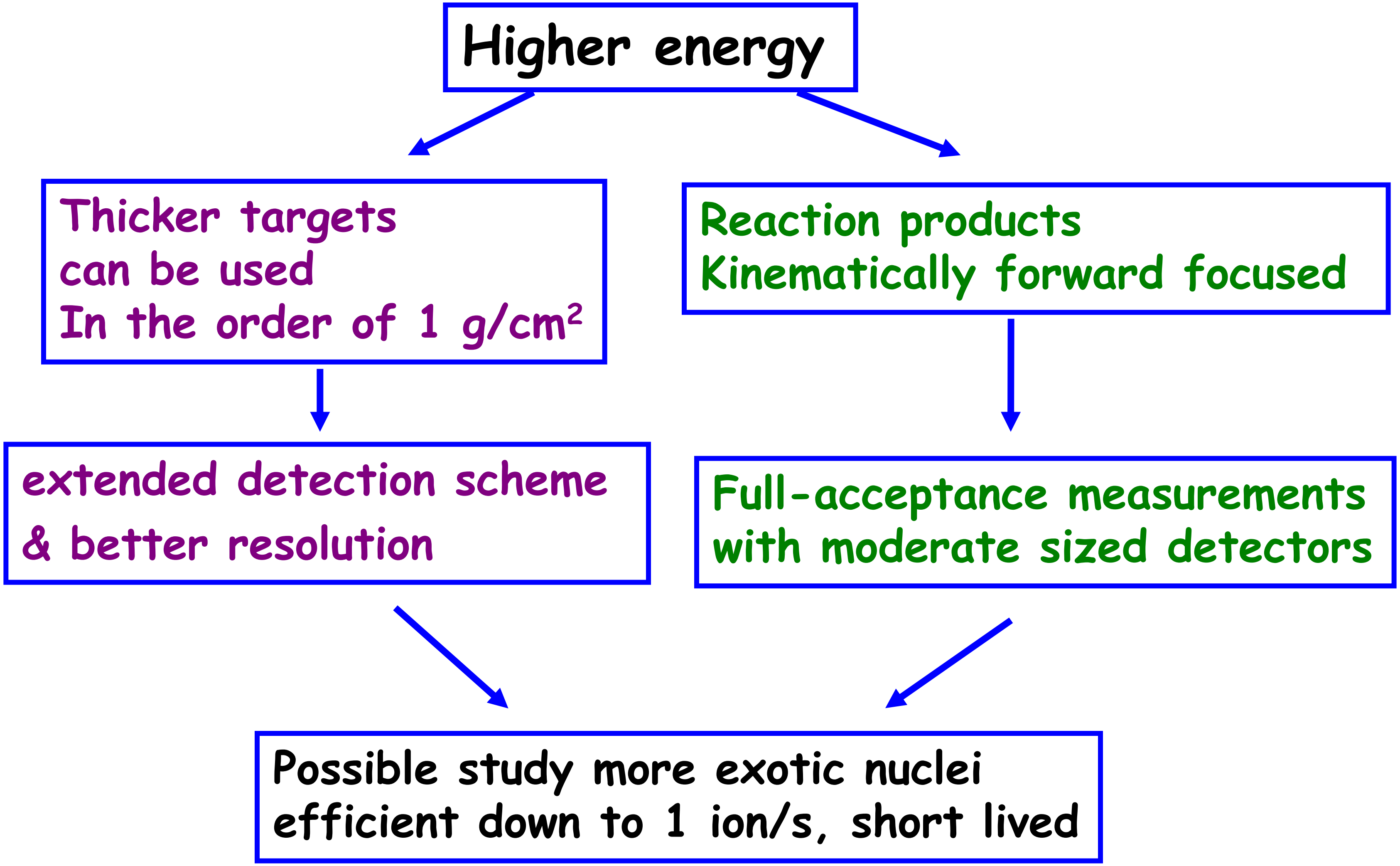
$$v_2^2 = v_1^2 - d\,\frac{Z^2}{Z+N}$$

$$v_2 = v_1\,\frac{(B\rho)_2}{(B\rho)_1}$$

Energy loss $\propto Z^2$

Tvol (Taget - detector)= $\frac{d}{v} \propto \frac{A}{Z}$

In flight method



Higher energy

Thicker targets
can be used
In the order of 1 g/cm^2

Reaction products
Kinematically forward focused

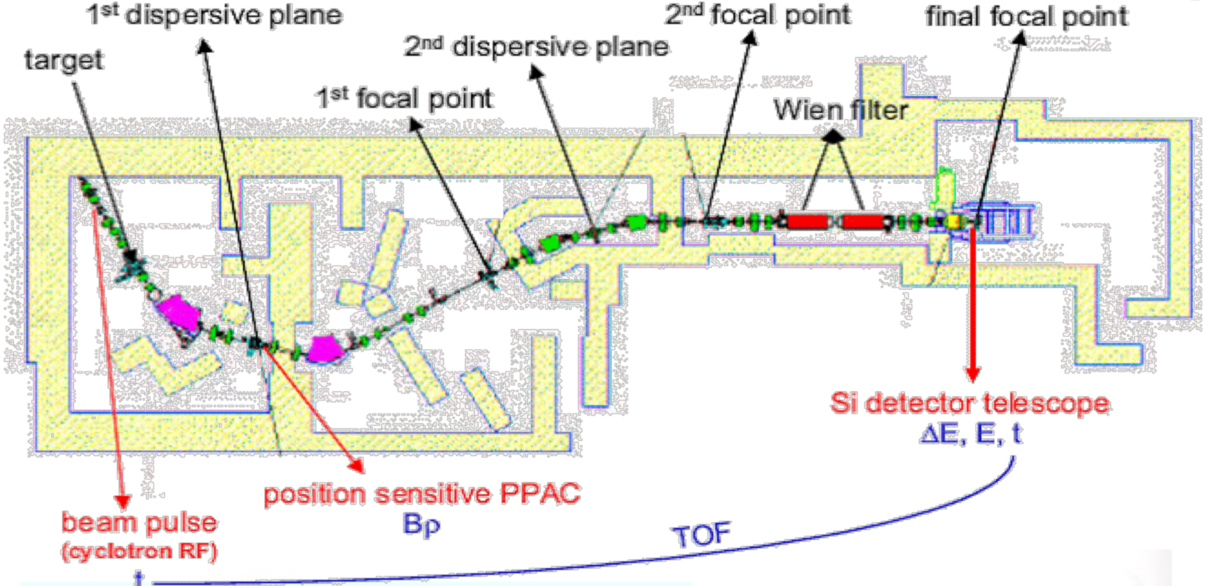
extended detection scheme
& better resolution

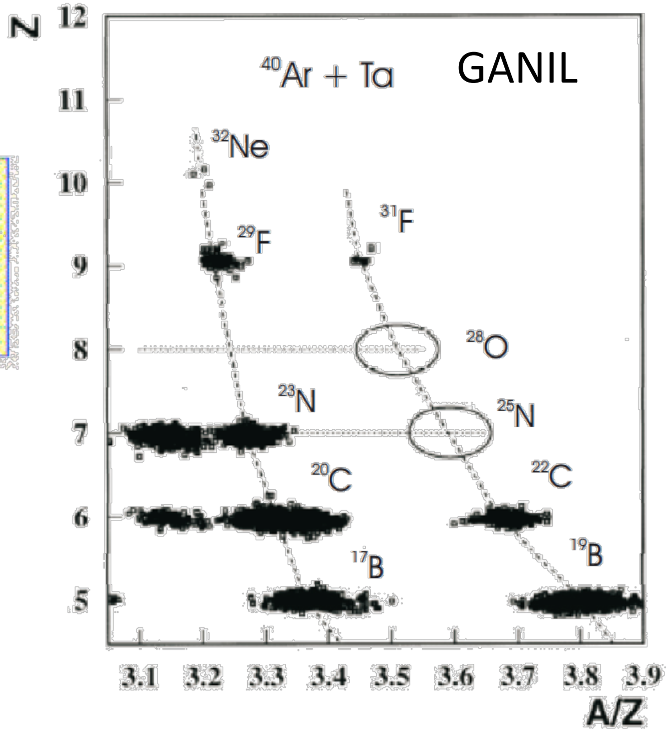
Full-acceptance measurements
with moderate sized detectors

Possible study more exotic nuclei
efficient down to 1 ion/s, short lived

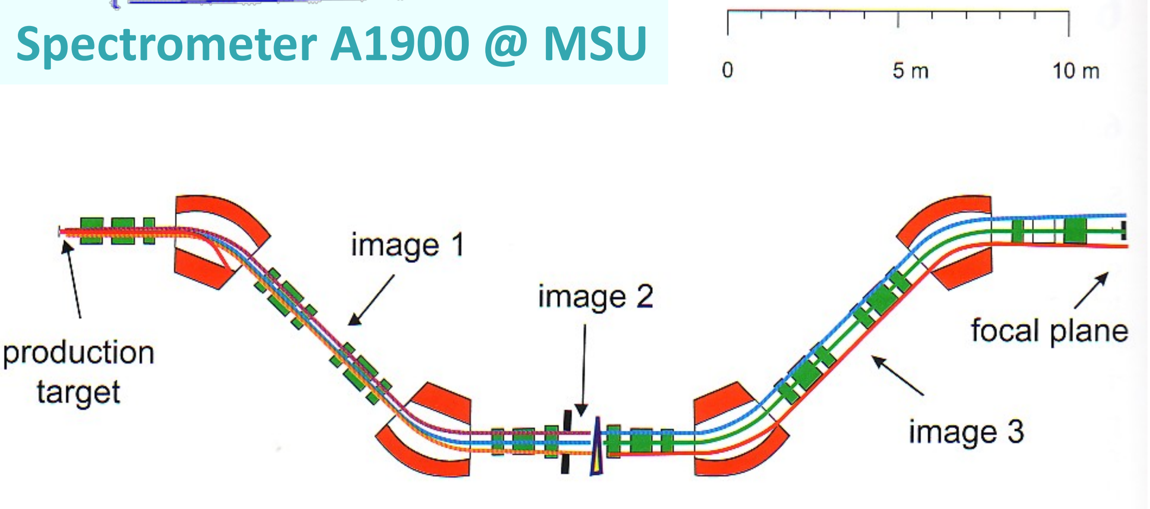
Different Spectrometer

Spectrometer LISE @ GANIL



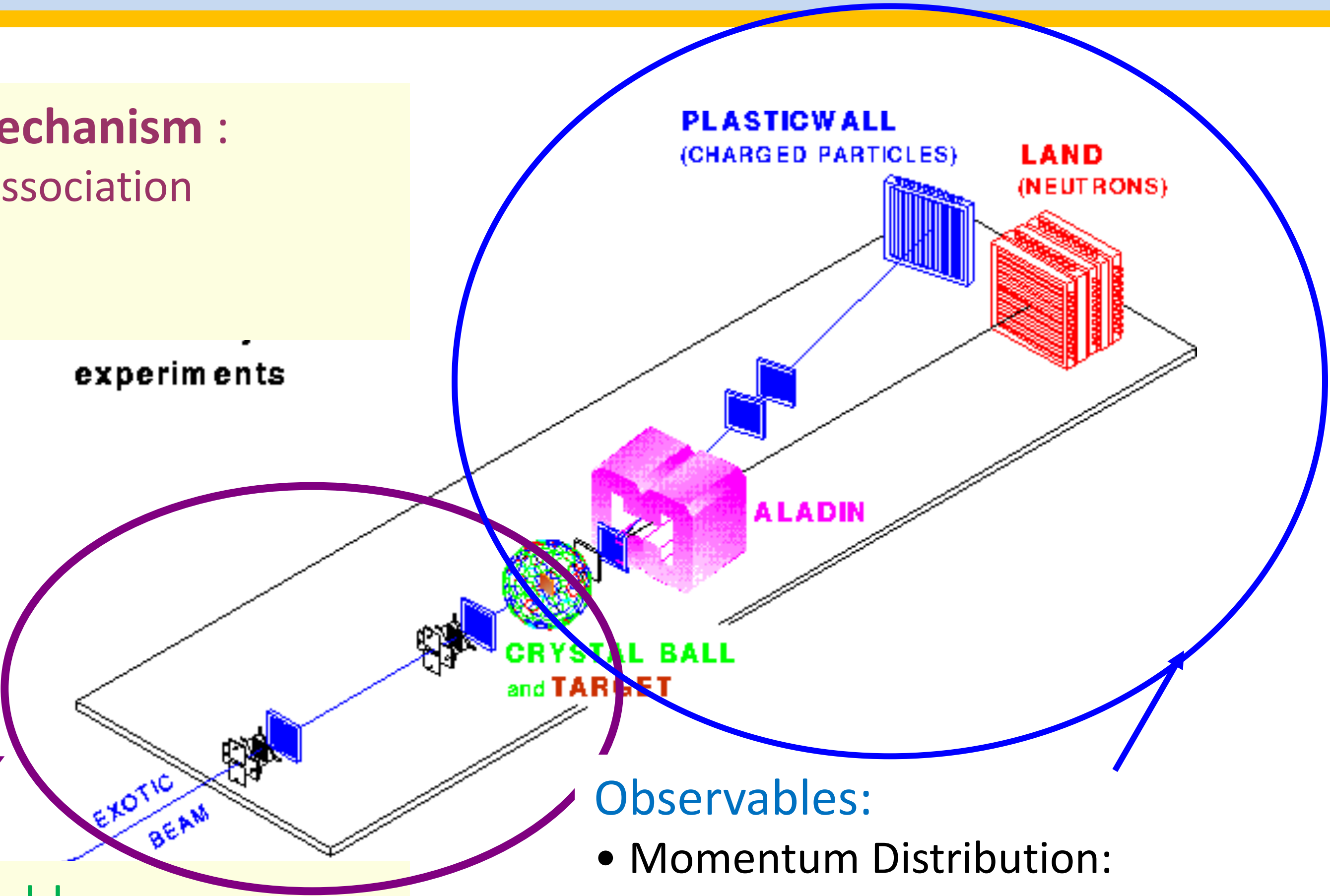


Spectrometer A1900 @ MSU



Reaction at High Energy @GSI → R3B @ FAIR

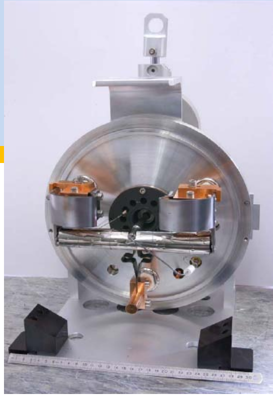
Reaction Mechanism :
- Coulomb dissociation
- Difraction
- Absortion

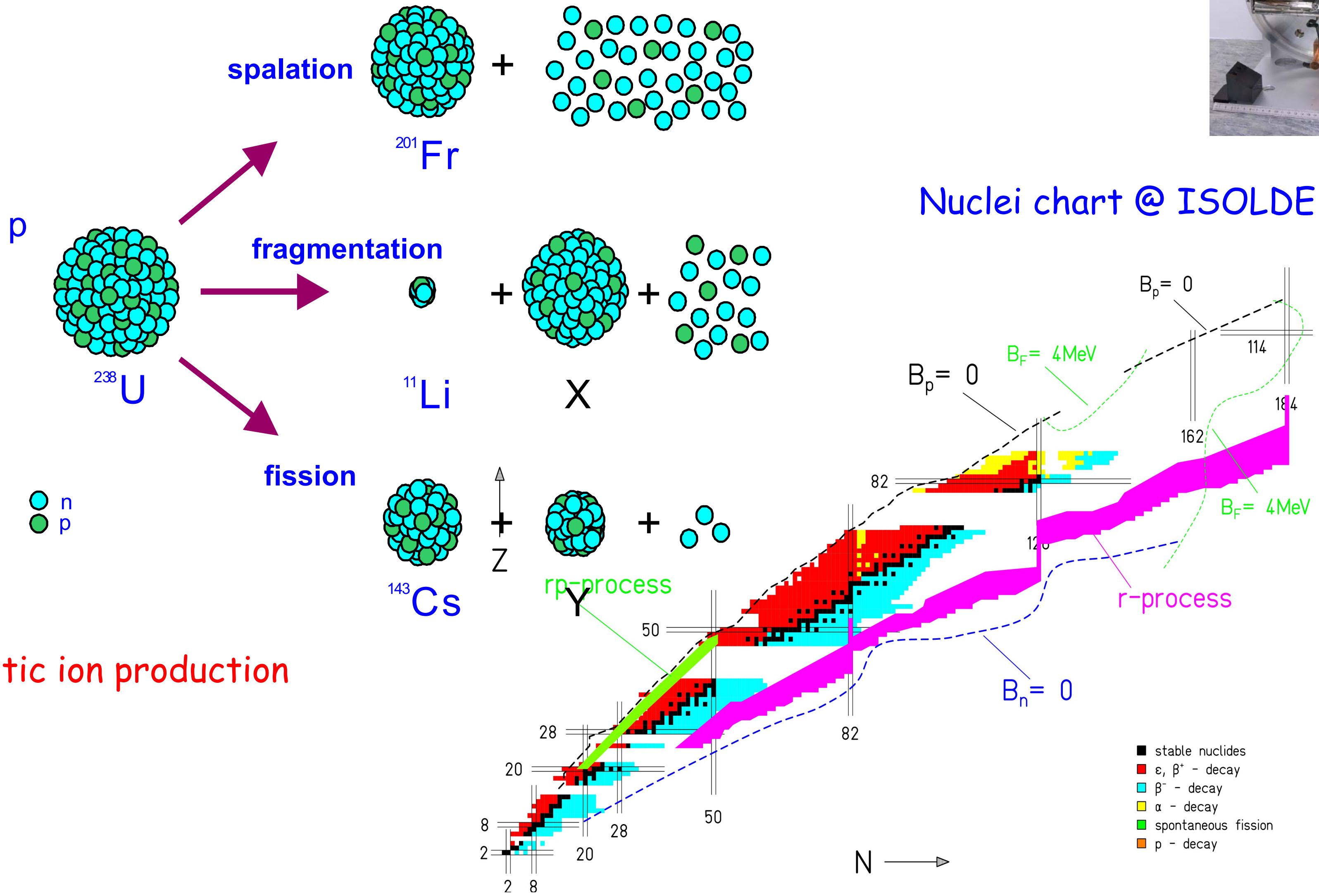


Experimental Variable:
- beam energy 30 → 700 MeV/A
- Secondary Target material: C → Pb
- Secondary Beam ^{6}He → ^{22}Ne

Observables:
- Momentum Distribution:
  - neutron
  - Charged fragment
- Invariable Mass
- Angular correlations

ISOL Method: Isotope production





Nuclei chart @ ISOLDE

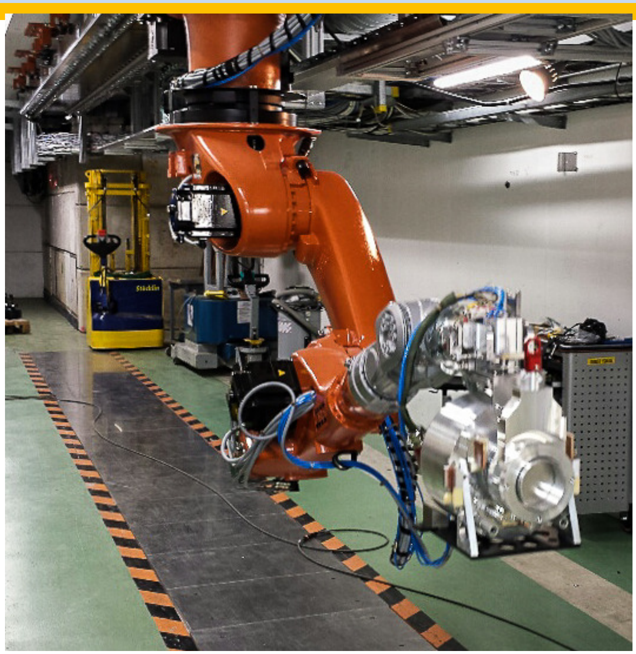
Exotic ion production

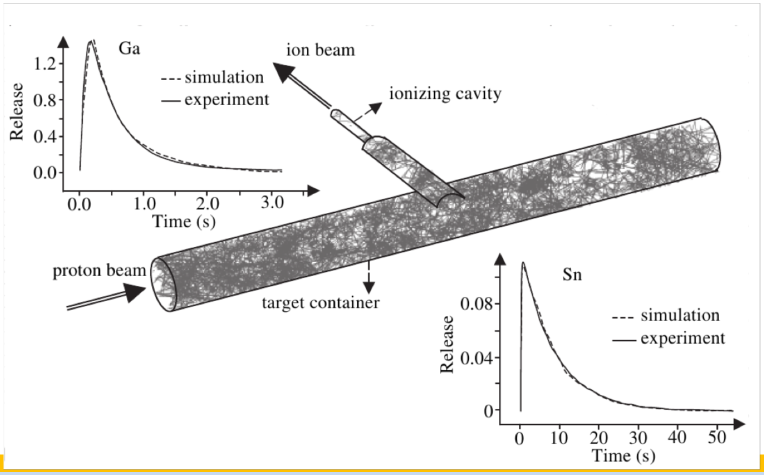
Target – Ion-source matrix: a chemical laboratory

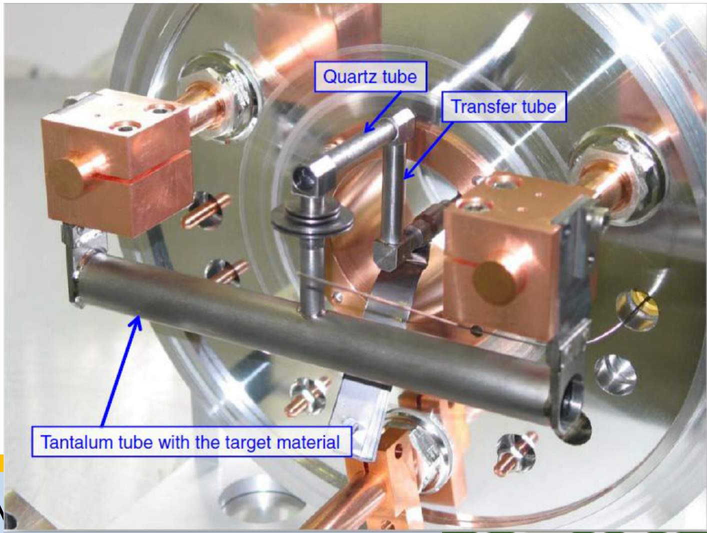
- Main challenge: extracting the $10^{-1} – 10^{12}$ nuclei produced in the reaction from the 10^{23} nuclei in the target
- Targets:

  UCx, SiC, Ta, LaCx, CaO, ZrO….

- The diffusion into the ion source is controlled by the target and transfer line temperature



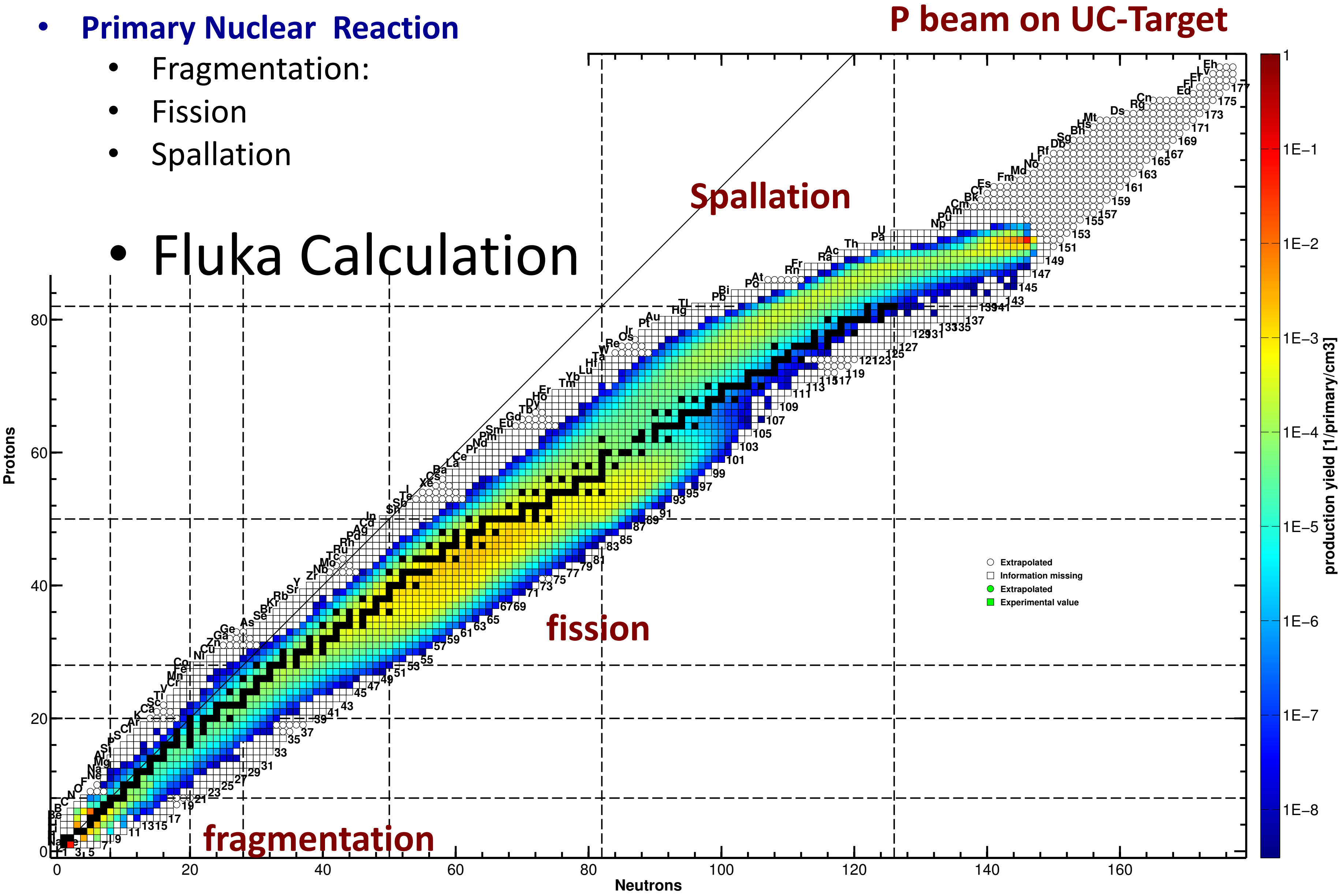




Production of Radiactive Beams @ ISOL Facilities

- **Primary Nuclear Reaction**
  - Fragmentation:
  - Fission
  - Spallation

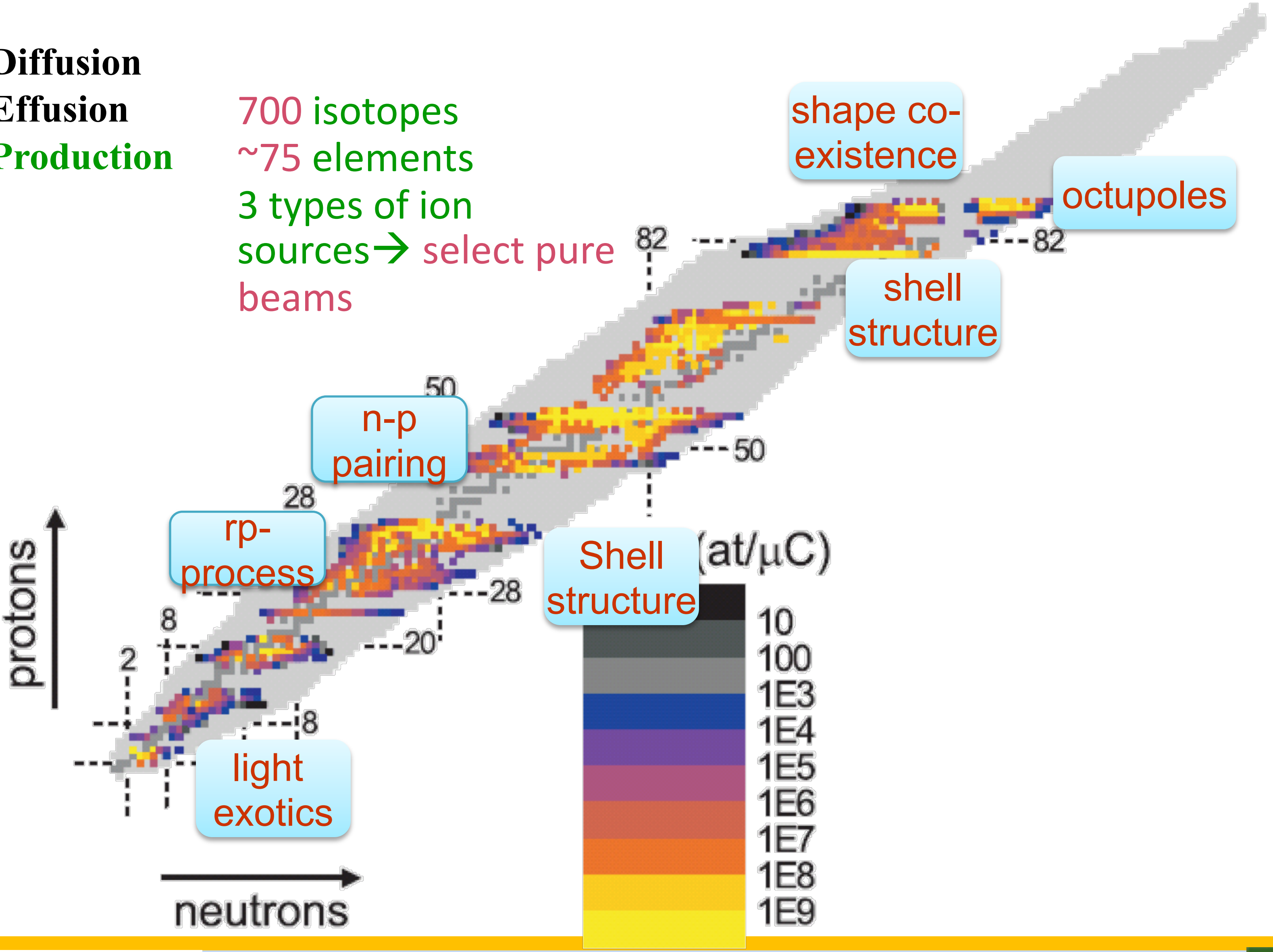
- Fluka Calculation



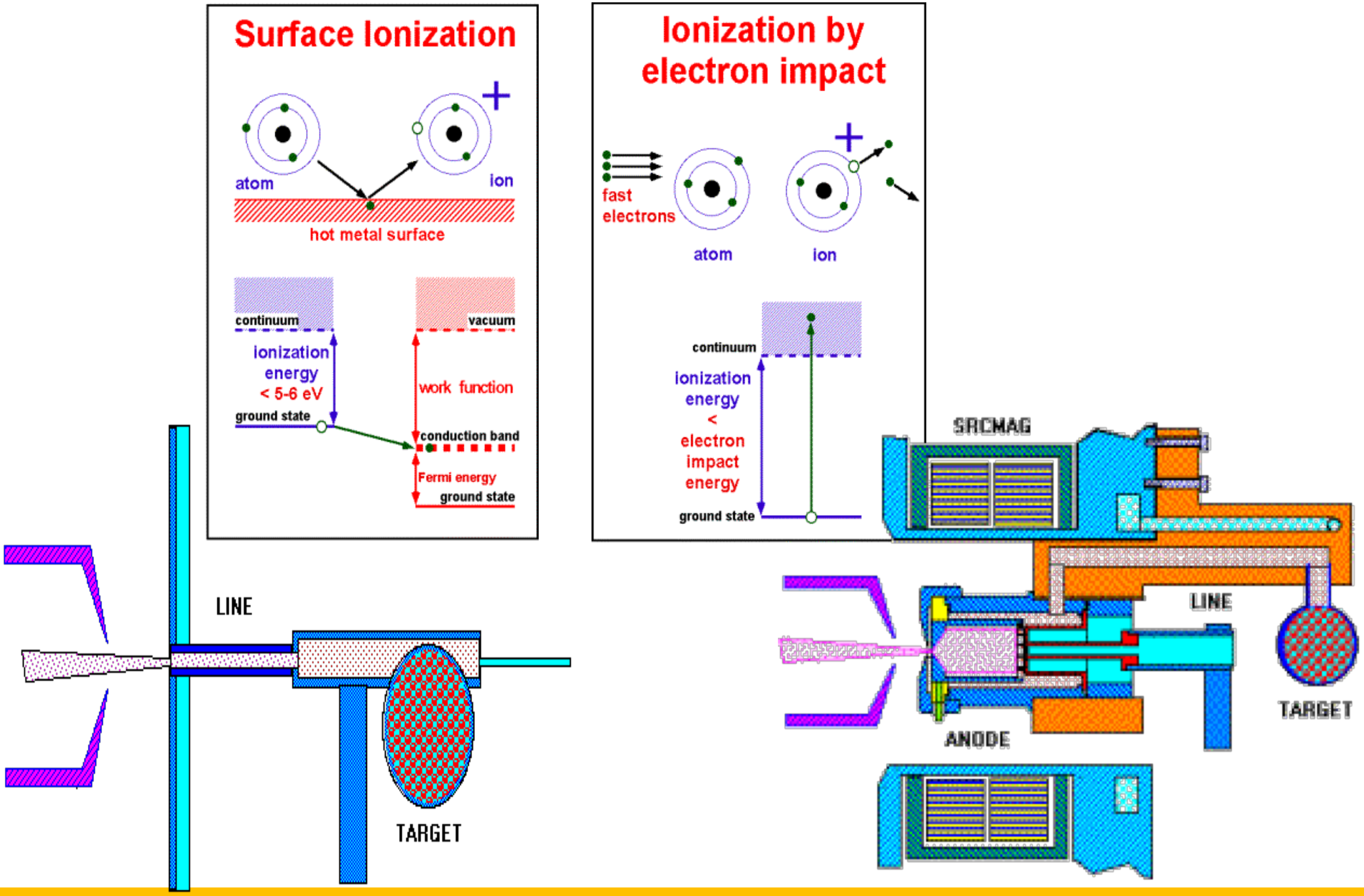
ISOLDE Main potential

- **Diffusion**
- **Effusion**
- **Production**

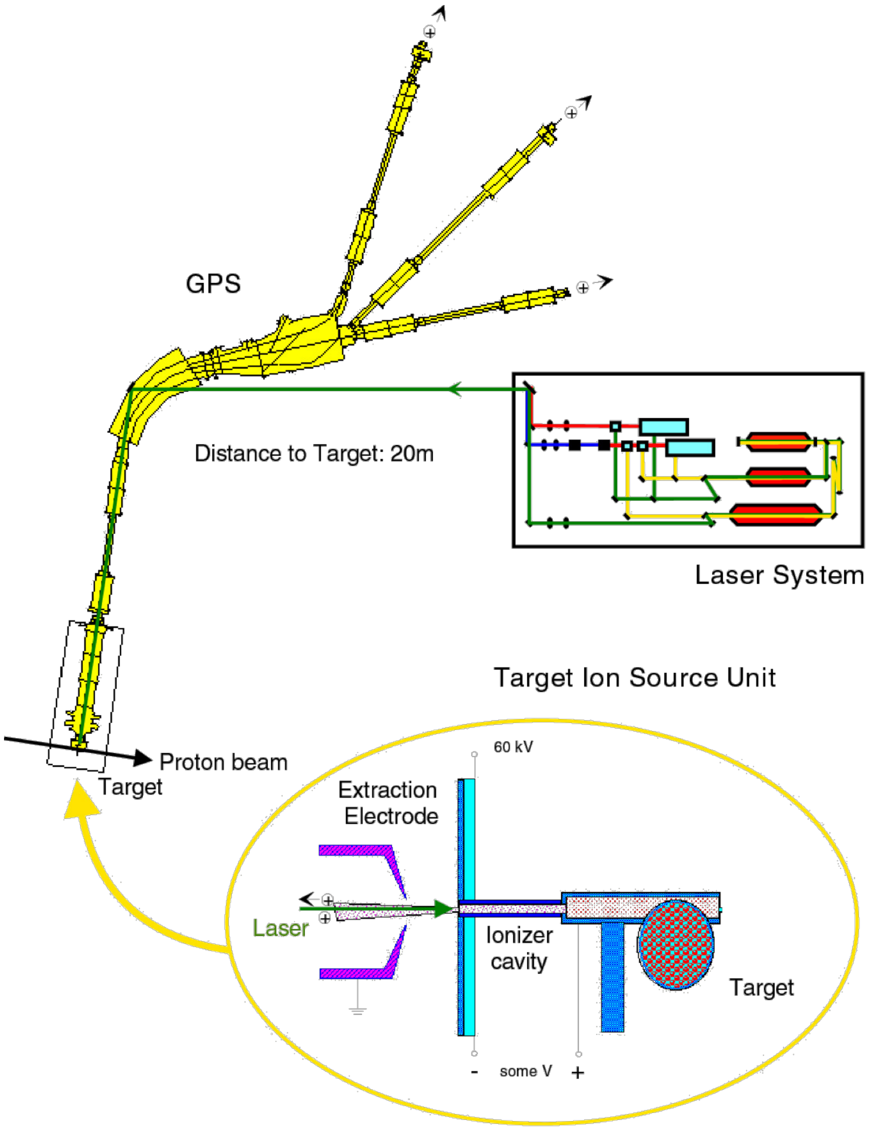
700 isotopes
~75 elements
3 types of ion sources→ select pure beams

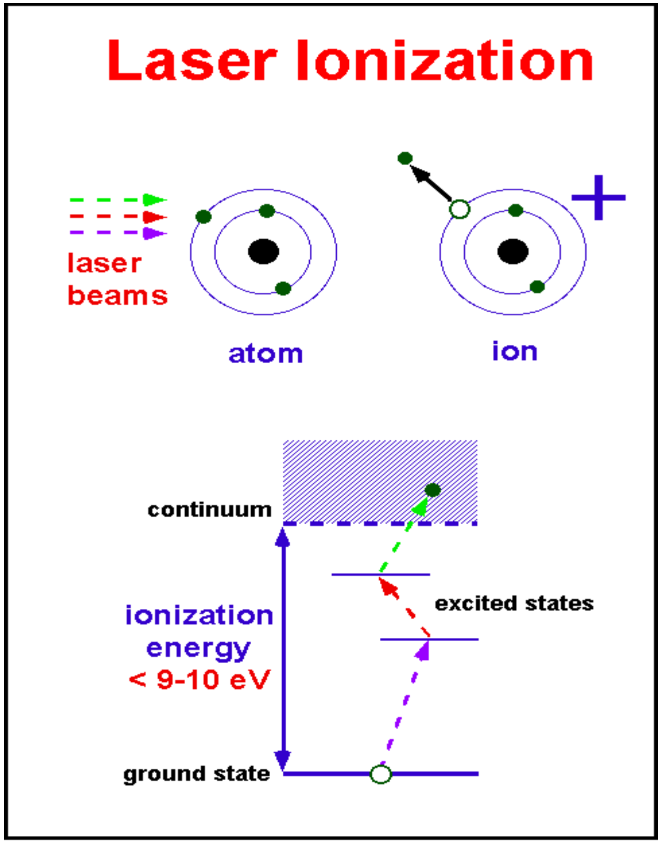


Surface & plasma ionization



Laser Ionization source

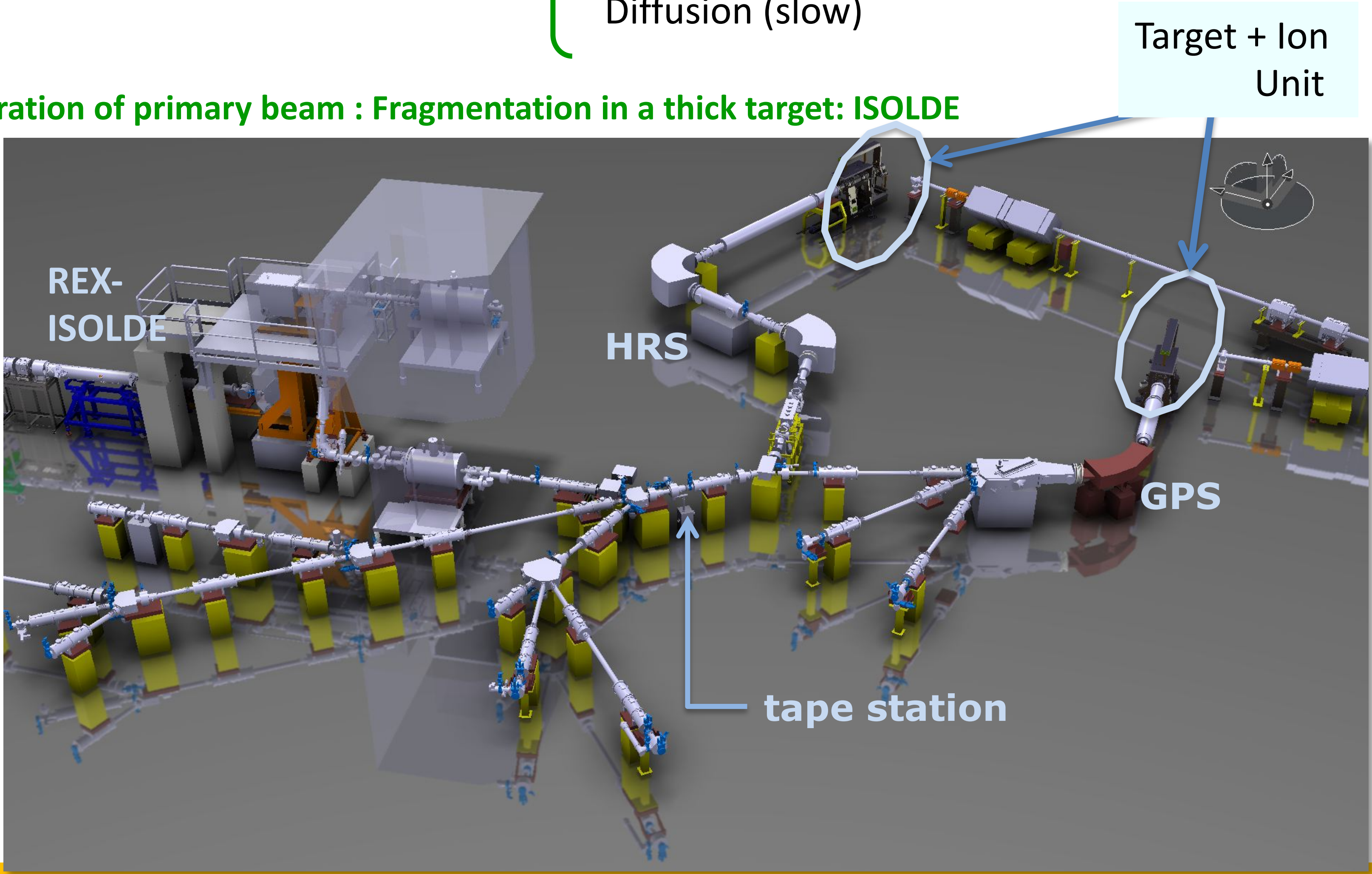




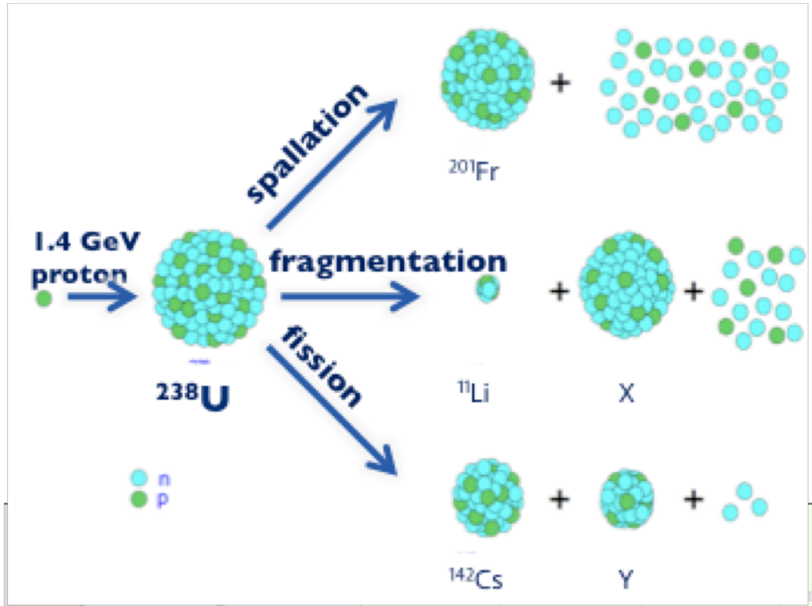
Separation @ ISOL

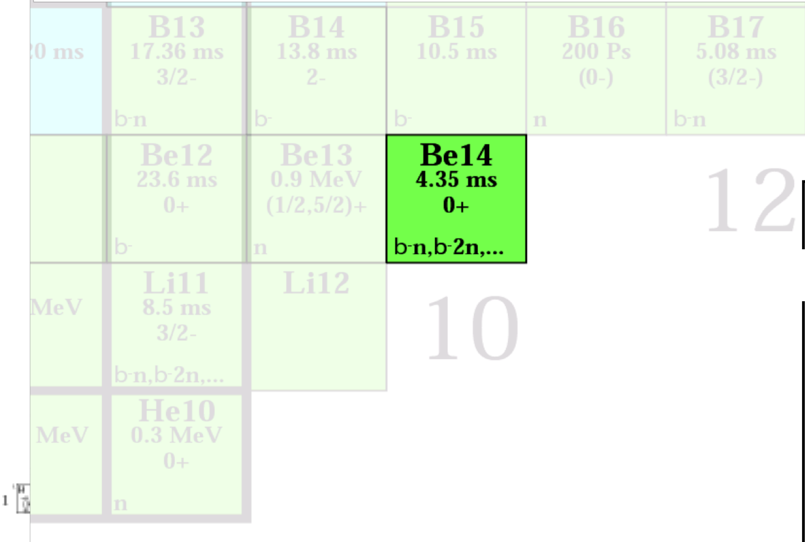
The produced ions must leave the target:
- Recoil Energy (fast)
- Diffusion (slow)

Separation of primary beam : Fragmentation in a thick target: ISOLDE



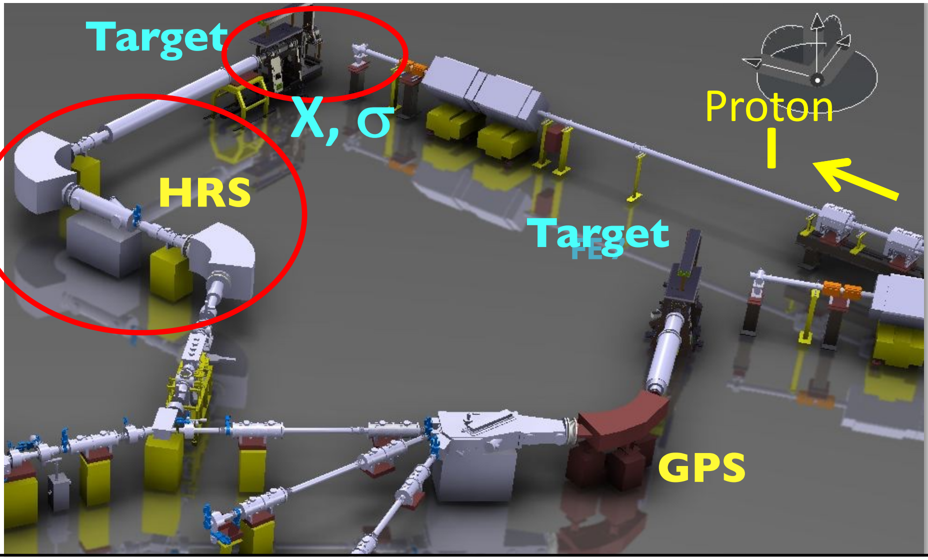
Production and Selection @ ISOLDE

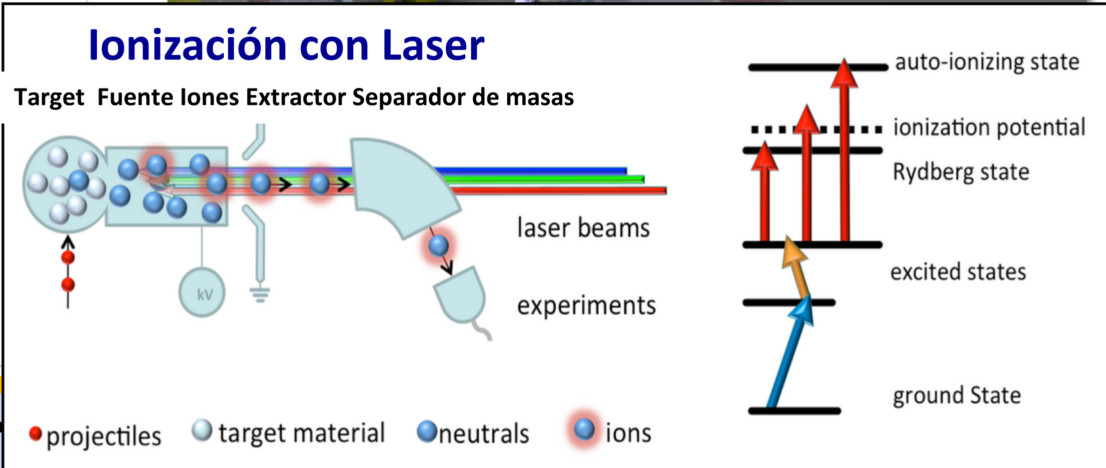




0 ms	B13 17.36 ms 3/2- b-n	B14 13.8 ms 2- b-	B15 10.5 ms b-	B16 200 Ps (0-) n	B17 5.08 ms (3/2-) b-n	B1
	Be12 23.6 ms 0+ b-	Be13 0.9 MeV (1/2,5/2)+ n	Be14 4.35 ms 0+ b-n,b-2n,...		12	
MeV	Li11 8.5 ms 3/2- b-n,b-2n,...	Li12	10			
MeV	He10 0.3 MeV 0+ n					

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





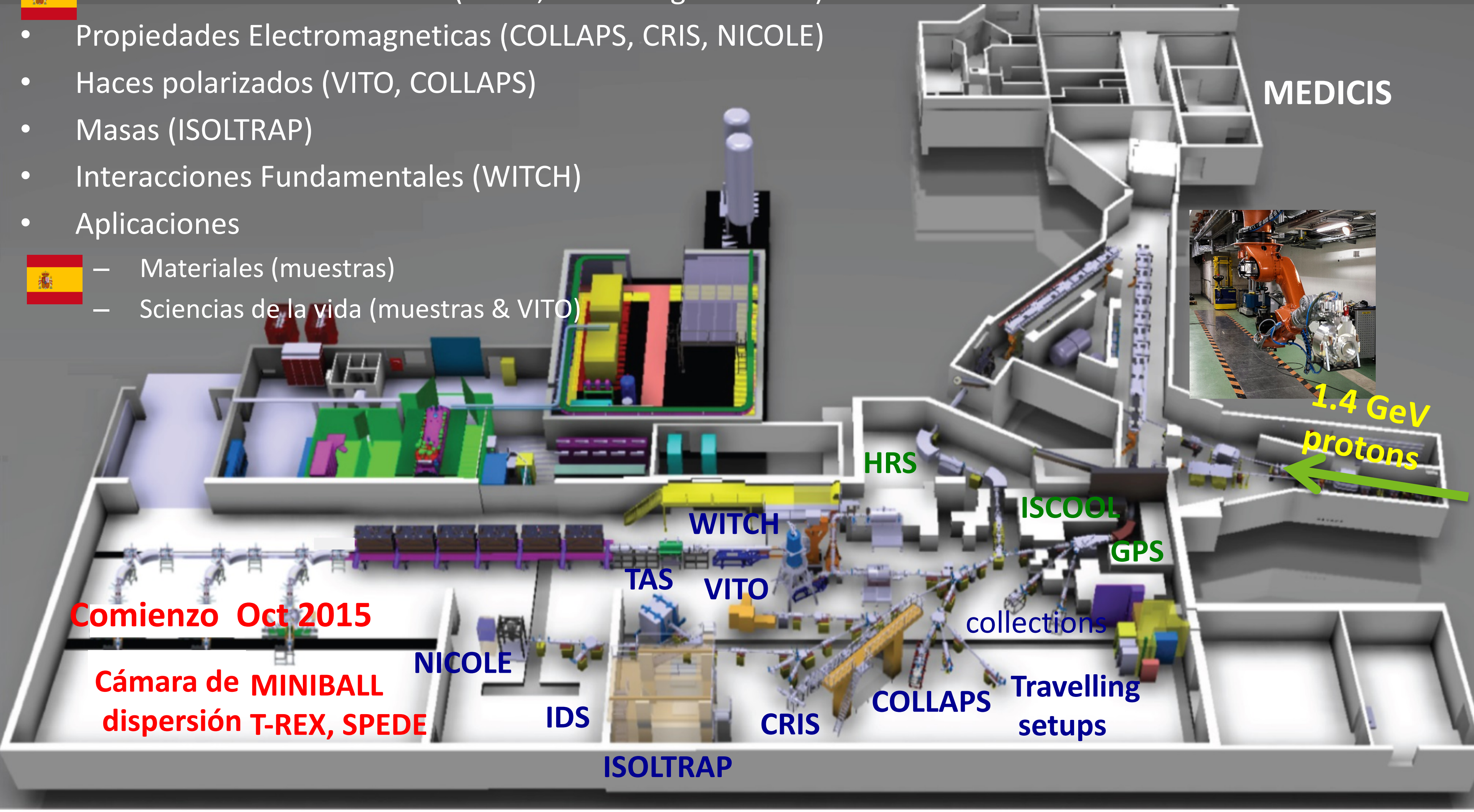
Ionización con Laser

Target Fuente Iones Extractor Separador de masas

● projectiles ○ target material ● neutrals ● ions

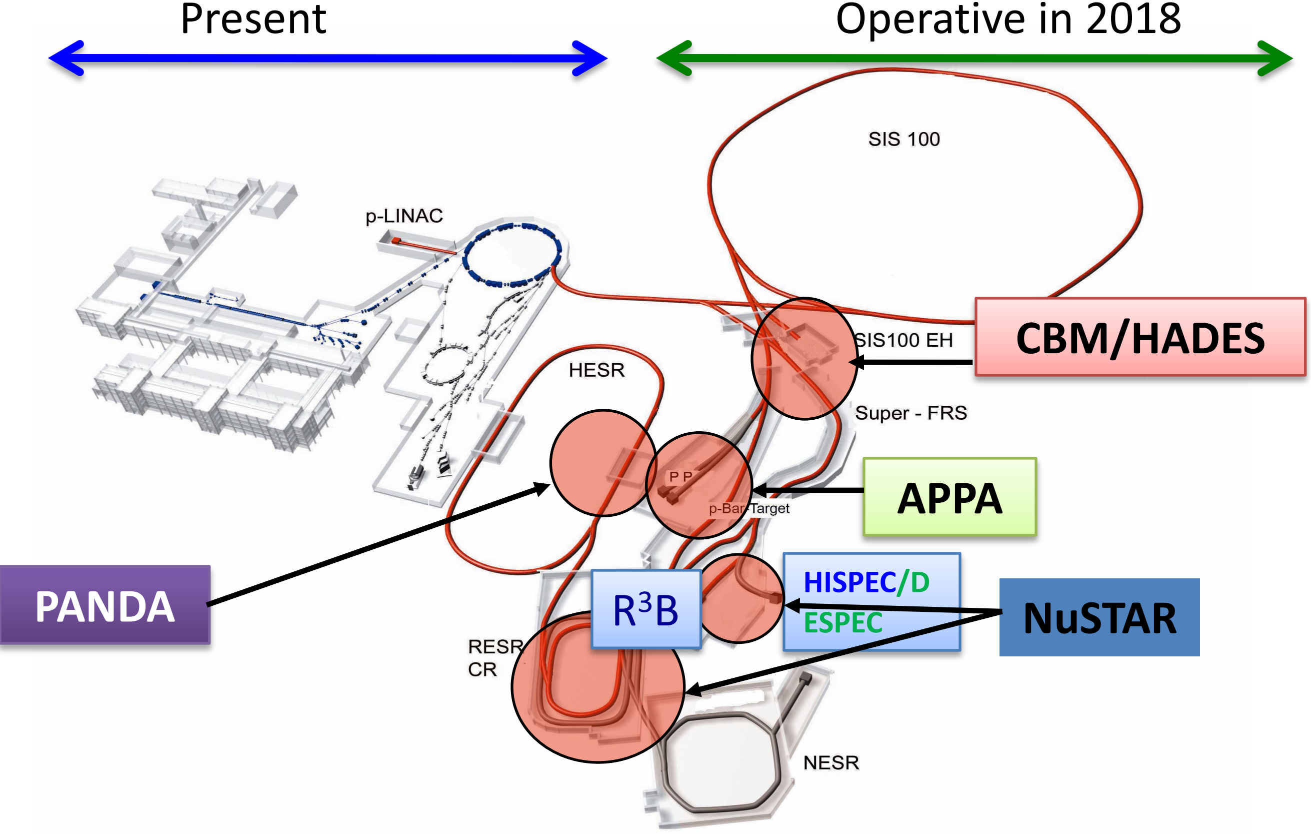
ISOLDE

- Desintegración beta (IDS, TAS,..)
- Excitacion Coulombiana (MINIBALL+ CD + SPEDE)
- Reacciones de transferencia (T-REX, Scattering Chamber)
- Propiedades Electromagneticas (COLLAPS, CRIS, NICOLE)
- Haces polarizados (VITO, COLLAPS)
- Masas (ISOLTRAP)
- Interacciones Fundamentales (WITCH)
- Aplicaciones
  - Materiales (muestras)
  - Sciencias de la vida (muestras & VITO)



— Haces Post-acelerados (5.5 MeV/u)   — Exp. de baja energía (30-60kV)   — Maquina

Fair : Facility of Antiprotons and Ion Research



Present

Operative in 2018

CBM/HADES

APPA

PANDA

R^{3}B

HISPEC/D

ESPEC

NuSTAR

All the Spanish experimental groups participate in the project

The company FAIR started 4th October 2010

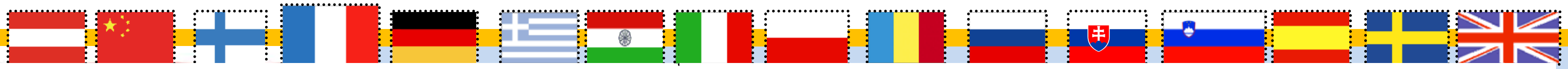
- CIEMAT
- IEM (CSIC)
- IFIC (CSIC)
- Universidad Complutense de Madrid
- Universidad de Granada
- Universidad de Huelva
- Universidad Politécnica de Cataluña
- Universidad de Salamanca
- Universidad de Santiago de Compostela

-Universidad de Sevilla

--Universidad de Vigo

✓ **Nuclear Structure and Astrophysics: NUSTAR**

- R3B, HISPEC/DESPEC, EXL/ELISe, MATS
- 11 research groups

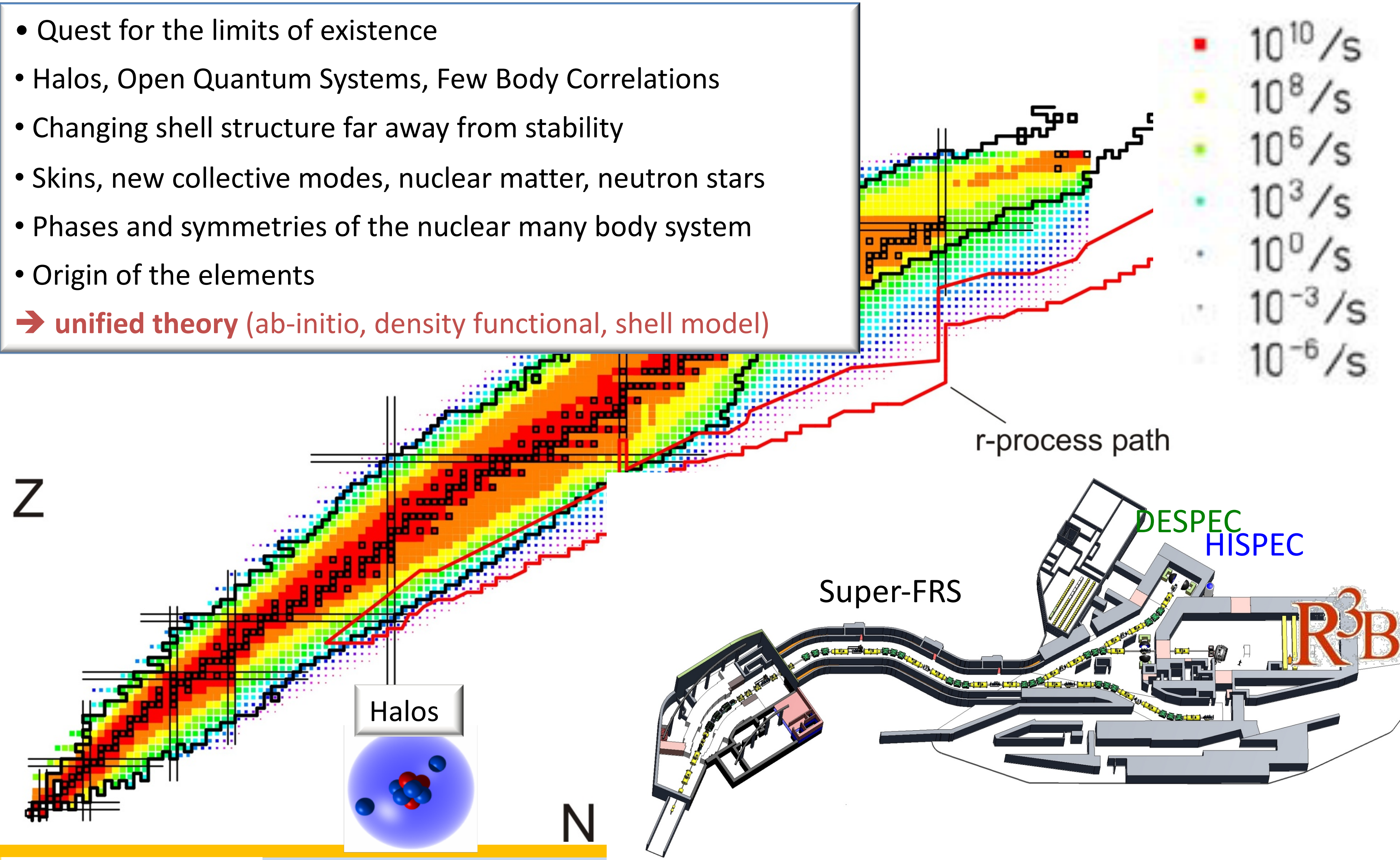


Austria China **Finland** **France** Germany Greece **India** Italy **Poland** **Romania** **Russia** ›lovakia **Slovenia** **Spain** **Sweden** **U K**

Central Topics for NuSTAR at FAIR

- Quest for the limits of existence
- Halos, Open Quantum Systems, Few Body Correlations
- Changing shell structure far away from stability
- Skins, new collective modes, nuclear matter, neutron stars
- Phases and symmetries of the nuclear many body system
- Origin of the elements

➔ **unified theory** (ab-initio, density functional, shell model)



HISPEC & DESPEC @ FAIR

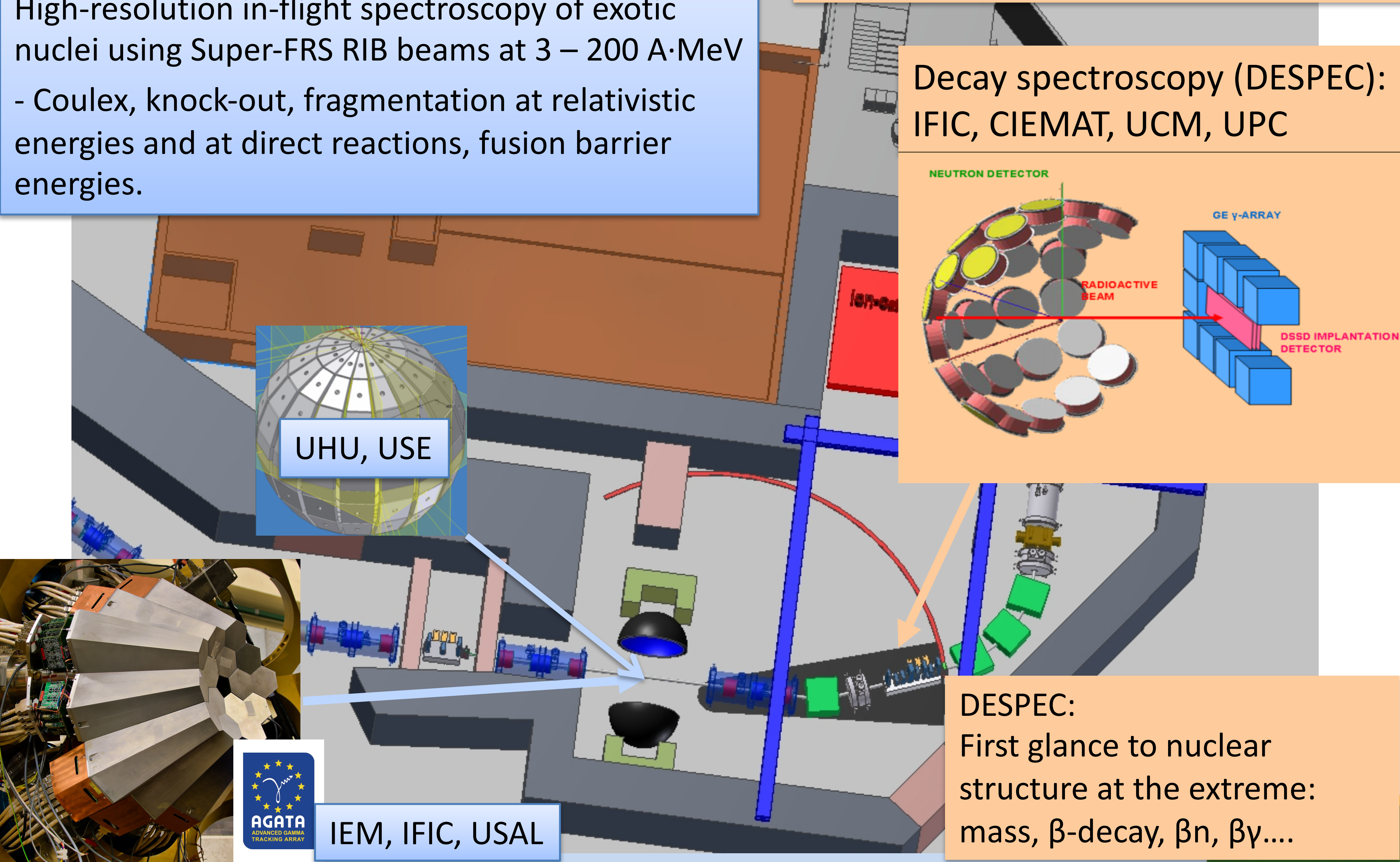
HISPEC:

High-resolution in-flight spectroscopy of exotic nuclei using Super-FRS RIB beams at 3 – 200 A·MeV

- Coulex, knock-out, fragmentation at relativistic energies and at direct reactions, fusion barrier energies.

Precision Mass Measurements (MATS
UGR

Decay spectroscopy (DESPEC):
IFIC, CIEMAT, UCM, UPC

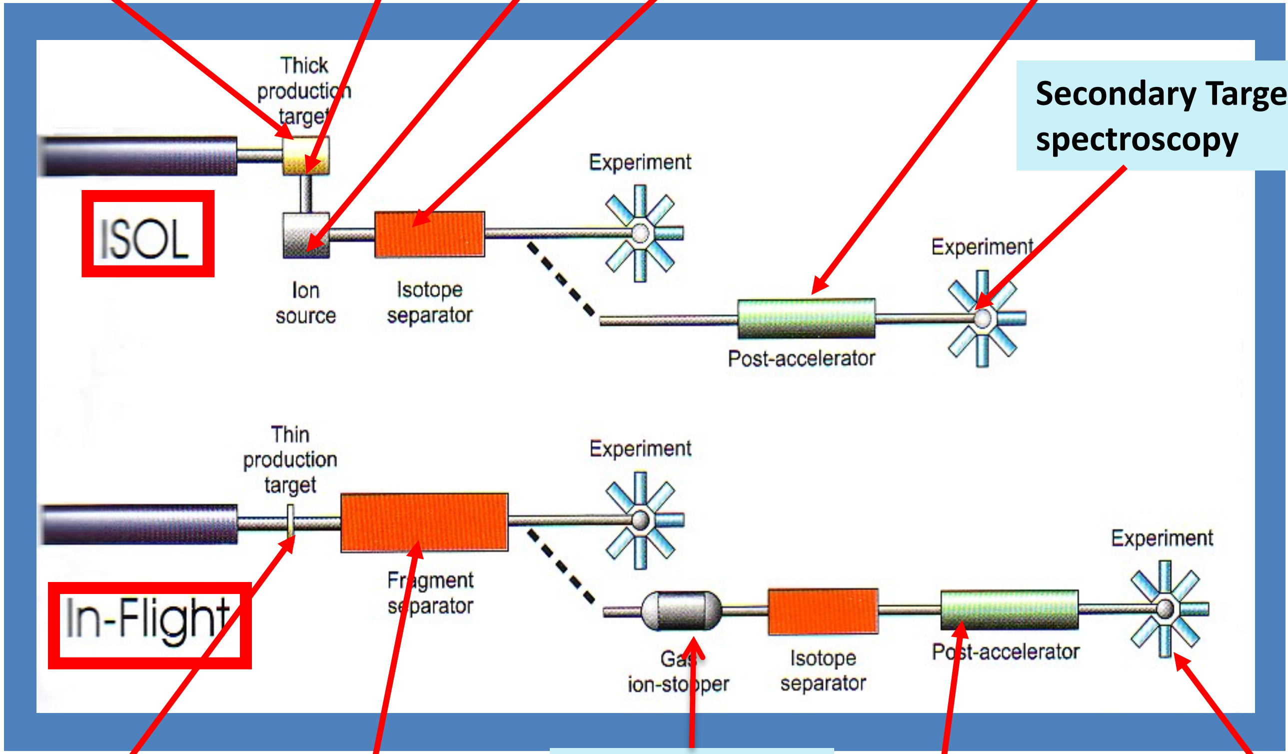


UHU, USE

IEM, IFIC, USAL

DESPEC:
First glance to nuclear structure at the extreme: mass, β-decay, βn, βγ….

Summary: Two production Methods



Primary Target

extraction

ionisation

séparation

post-accelerator

Secondary Target spectroscopy

driver accelerator

driver accelerator
ions 100 MeV - 1 GeV/u

fragmentation / fission

Fragment Separator

De-acceleration

Post-accelerator

Secondary Target Spectroscopie