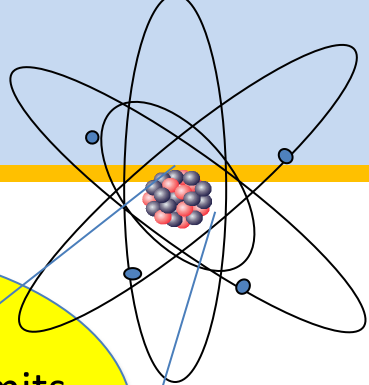
Production of Exotic Nuclei

Exotic Nuclei and Radiactive Beams

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

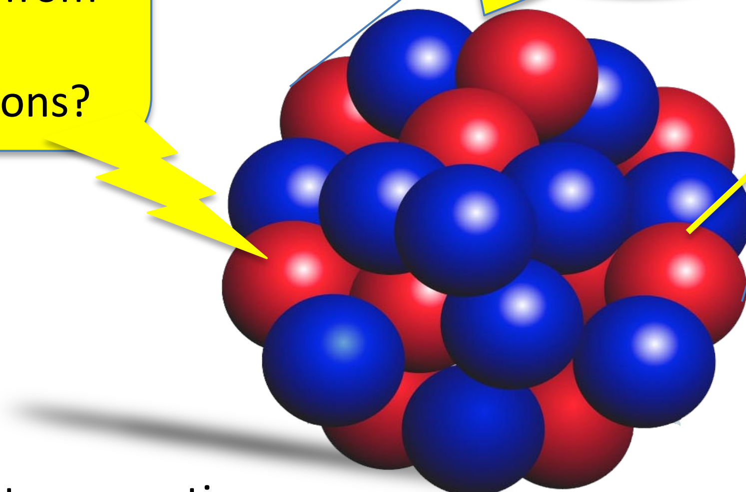
"The why and how of Radioactive beam Research", Mark Huyse,
"In-flight separation of projectile fragments", David Morrisey and Brad Sherril
"Isotope separation on line and post-acceleration", P. Van Duppen
http://www.euroschoolonexoticbeams.be/site/pages/lecture_notes

Open Questions in Nuclear Physics



What are the limits of nuclear stability?

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

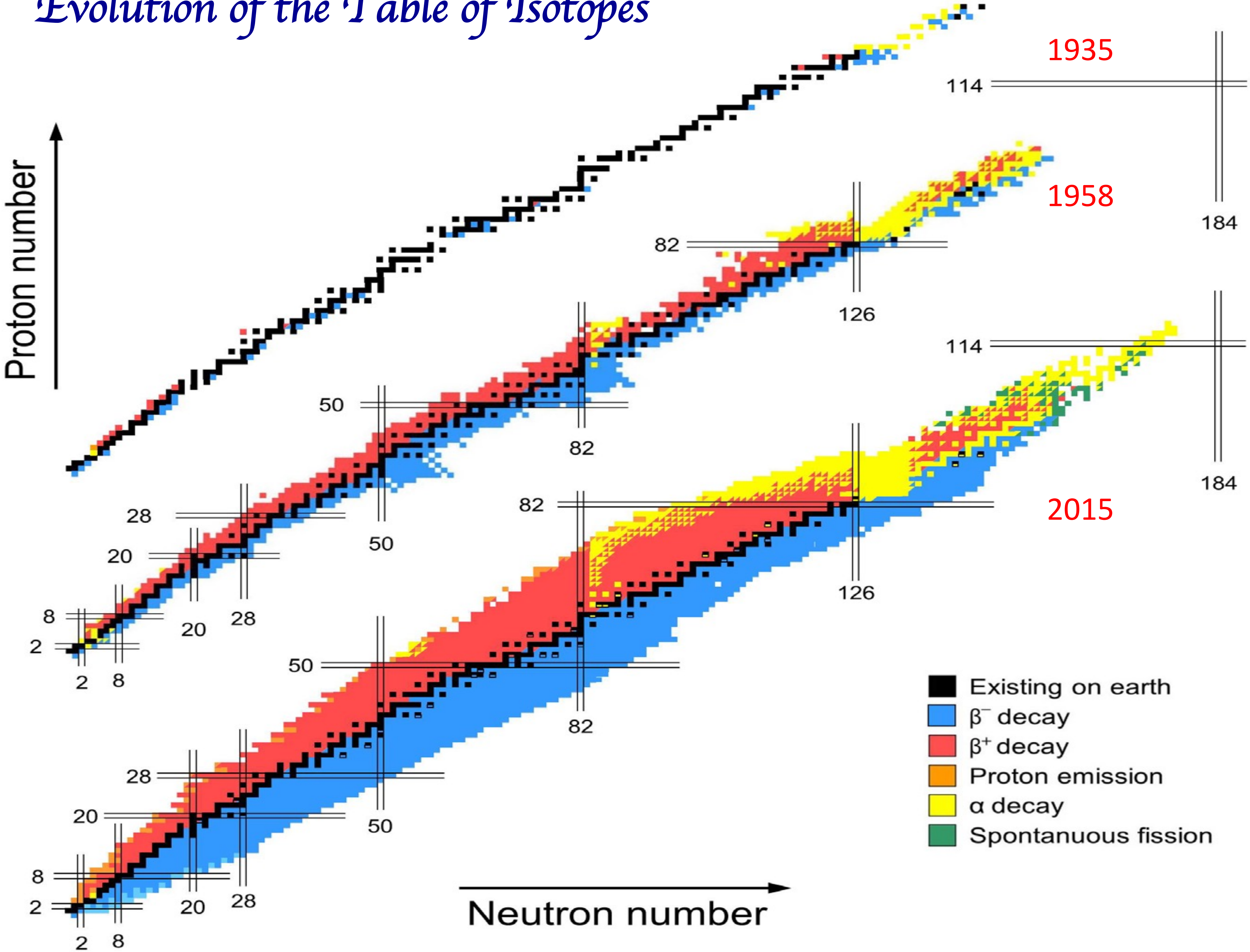


How and where in the Universe are the chemical elements produced?

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

After Nuclear Physics Long Range Plan 2017

Evolution of the Table of Isotopes



Production

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

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

Yield Requirements

Rate	Access
~1/week	Existence
~10/day	Identification
~100/day	Mass
~1/min	β ($T_{1/2}$, P_{xn})
1/sec	β-γ, β-n, β-p
100/sec	
10^4/sec	β-γ-γ, β-n-γ, β-p-γ

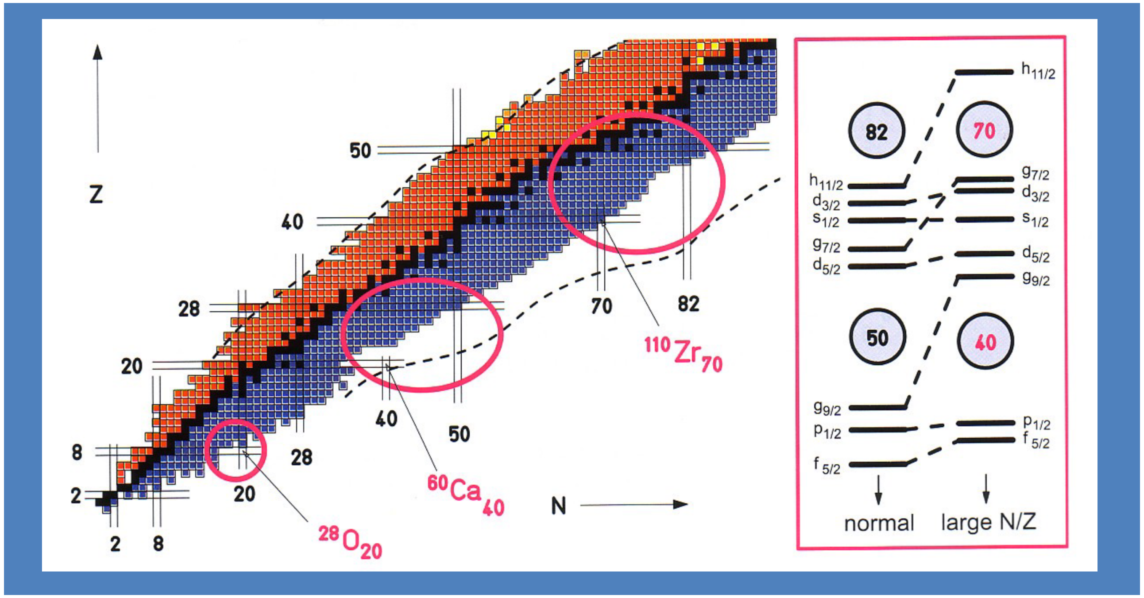
Z=107, 108, 109, … à GSI
Z < 40 GANIL, GSI, RIKEN, MSU

- ✓ β-decay gives first information of a new isotope.
- ✓ When the production is high ⇒ detailed structure information can be achieved.

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



Physics interest?

Correlations: Pairs,

influence of collective modes (Giant Resonances)

Inflence of halo or skin of neutrons

Extension of rare phenomena in the space of Z, N, J, Ex, superdeformation,

Study of: **Double magic nuclei**
Semi-magic nuclei
Region of shape transtions
Nuclei with N~Z
Nuclei with N >> Z, halo nuclei
Nuclei very deformed
Nuclei of astrophysical interest

Radiactive Beams: Possible Research Domains

de μeV à 100 keV {
- masses
- radius, shapes & moments
- decay properties

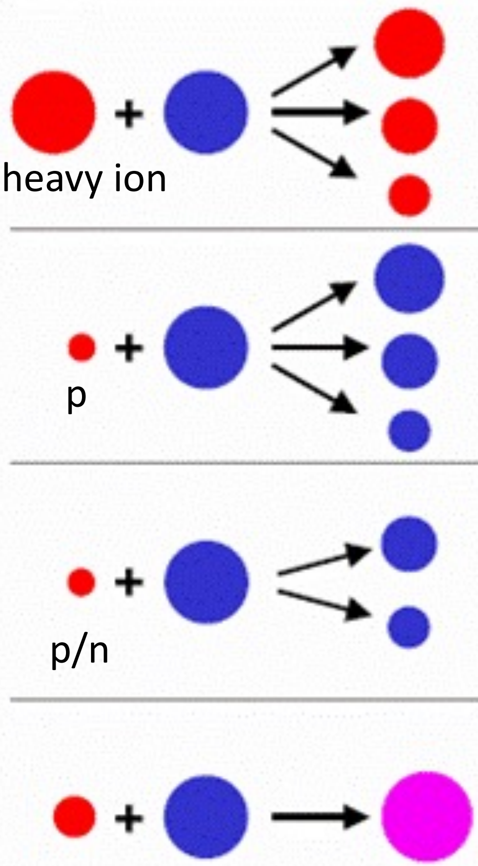
E < 1 MeV/u → astrophysics

de 1 à 10 MeV/u {
- Drip line phenomena
- Structure and excitation modes
- Tranfer and spectroscopic factors
- Heavy & Super-heavy nuclei

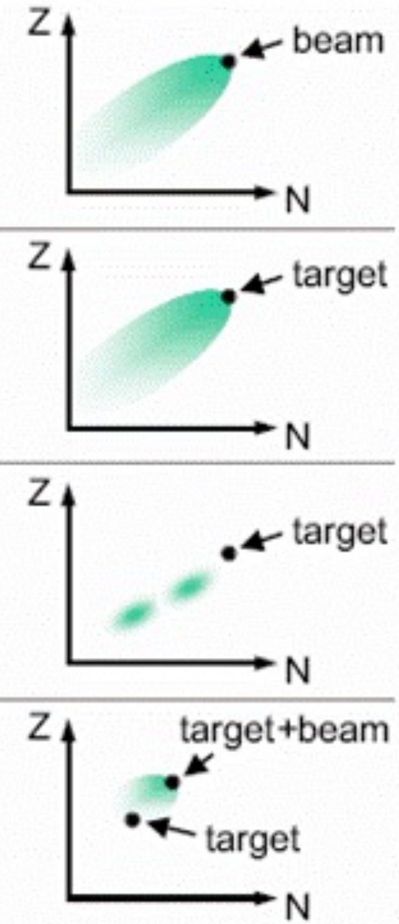
E < 100 MeV/u → Nuclear Matter

Production Methods

Beam → target → products



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



Production

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

- efficiency
- N of target nuclei/cm^2 ~ 1 - 100 g/cm^2
- Incoming particules/s ~ 10^8 - 10^{12} /s
- Cross Section

fusion – evaporation, @ GSI ^{54}Cr(4,7MeV/u) + ^{209}Bi → ^{263}107 *…

^{12}C + ^{56}Fe ou ^{16}O + ^{58}Ni … nuclei N~Z at Tandem energies

spallation p + La or U ou TH or W → $^{115-133}$Cs, A~20, 70 rates of 1 à 10^{11} at/s

transfer, 1 or several nucleons pick up, stripping…

inélastique ^{76}Ge (9 MeV/u) + Ta ou W → ^{62}Mn, $^{71-73}$Cu

fragmentation of target or projectile

p drip line Z < 30 @ GANIL

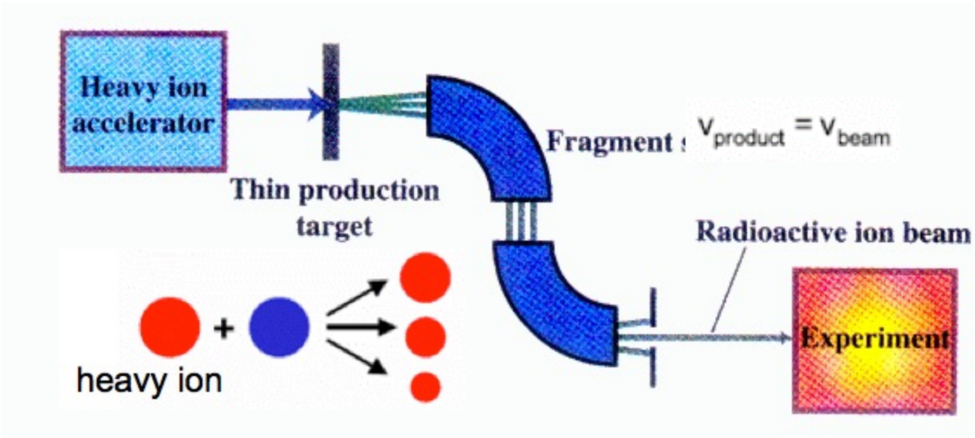
N-rich A~65 GSI , A~45 GANIL

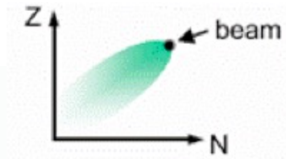
fission thermal ^{235}U, ^{239}Pu @ Grenoble ^{68}Fe, $^{71-74}$Ni, ^{79}Cu, $^{68-69}$Co

relativistic ^{235}U (750 MeV/u) + Pb → 50 NE products

Production of Radioactive Beams

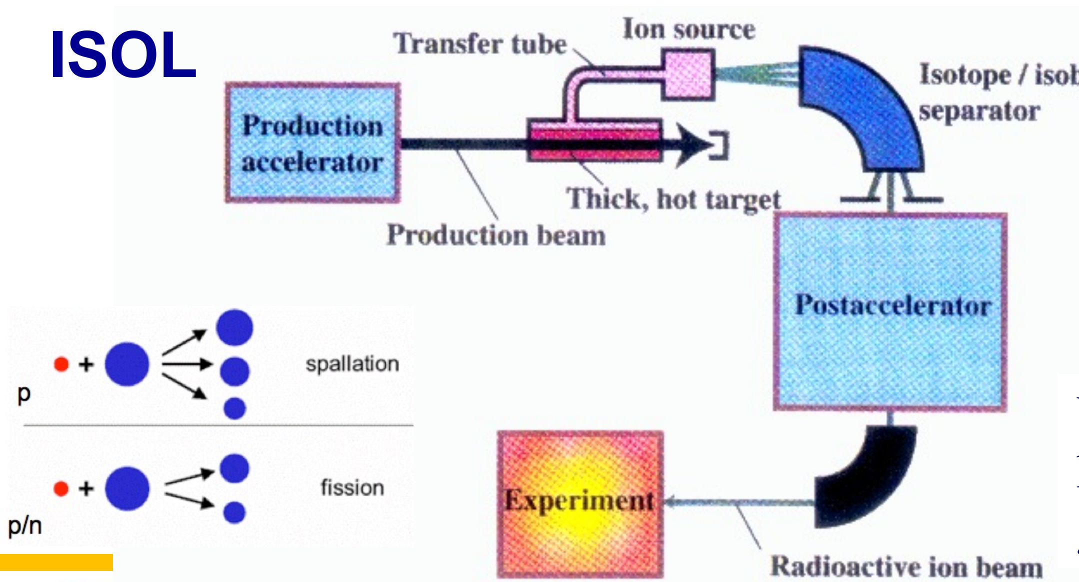
PROJECTILE FRAGMENTATION

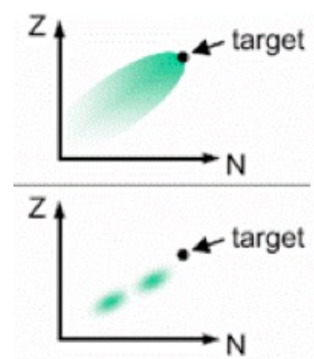




High energy,
large variety of species,
Short half-lives (μs),
cocktail beam

ISOL

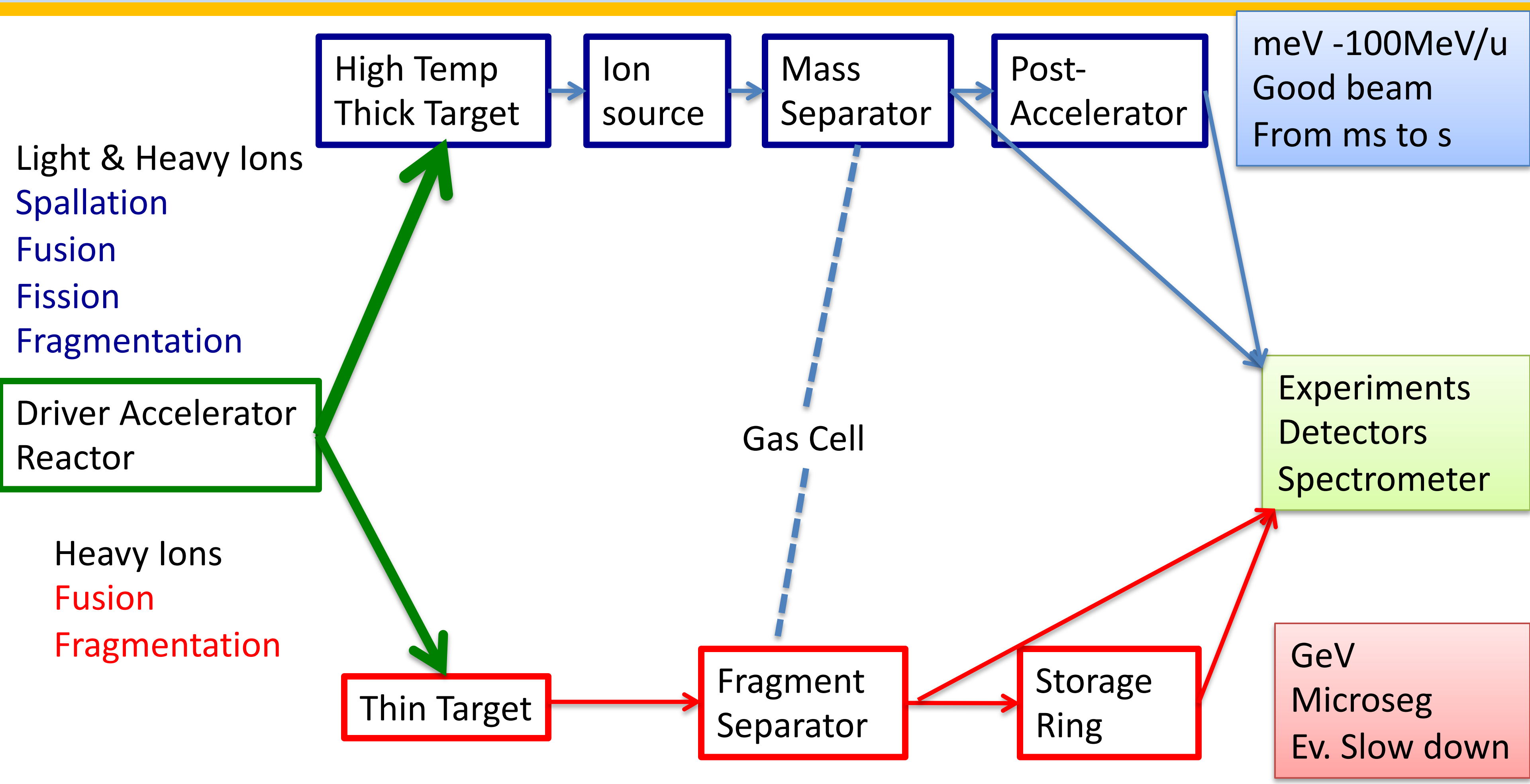




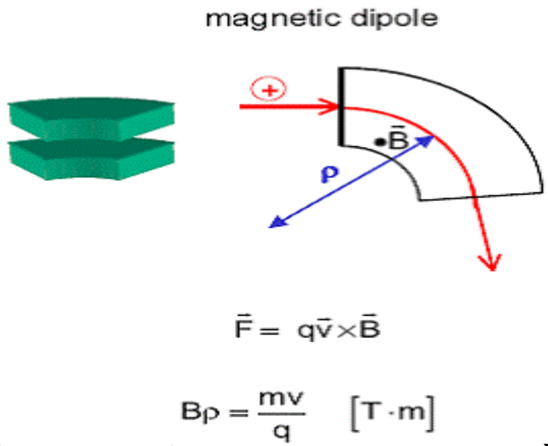
Variable energy,
high intensity,
good beam qualities

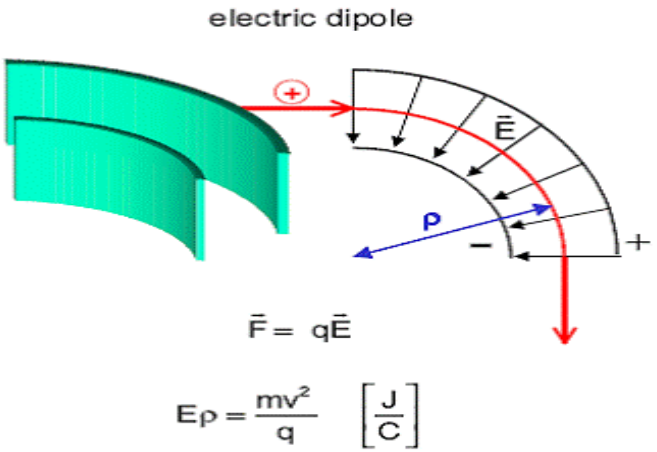
- FAIR — 1 GeV
- GSI — 400MeV/u
- GANIL — 50MeV/u
- SPIRAL — 14MeV/u
- HIE - ISOLDE — 10MeV/u
- ISOLDE — 0.06 MeV

Production Methods

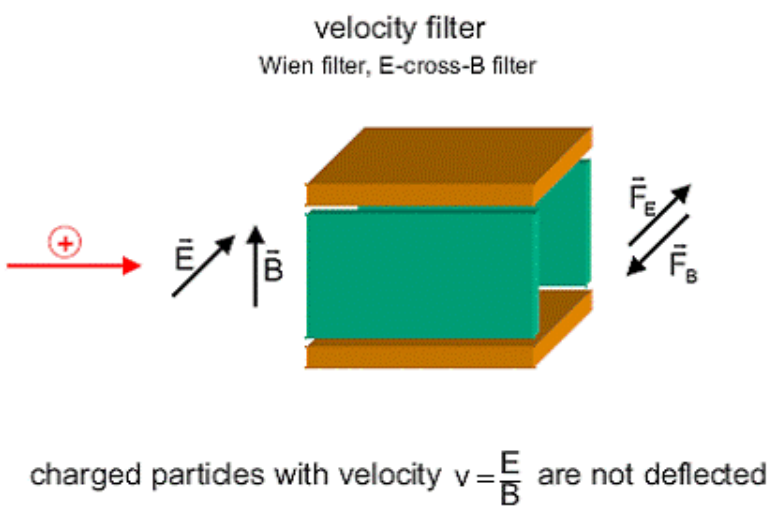


Separation at High Energy (See Talk by Teresa K)

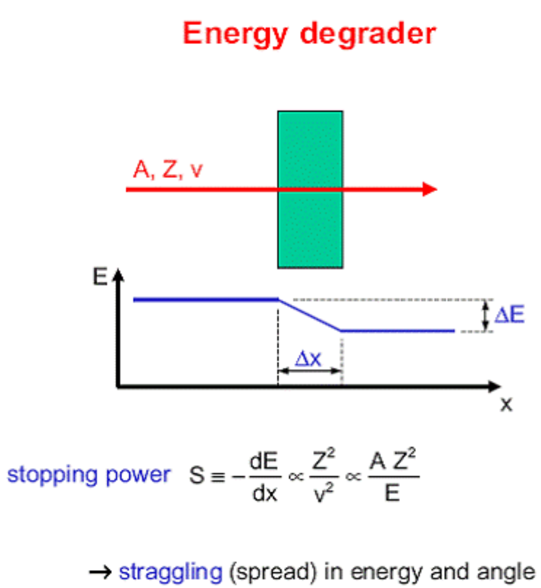




Part with same charge, mass and v ➔same rigidity Bρ



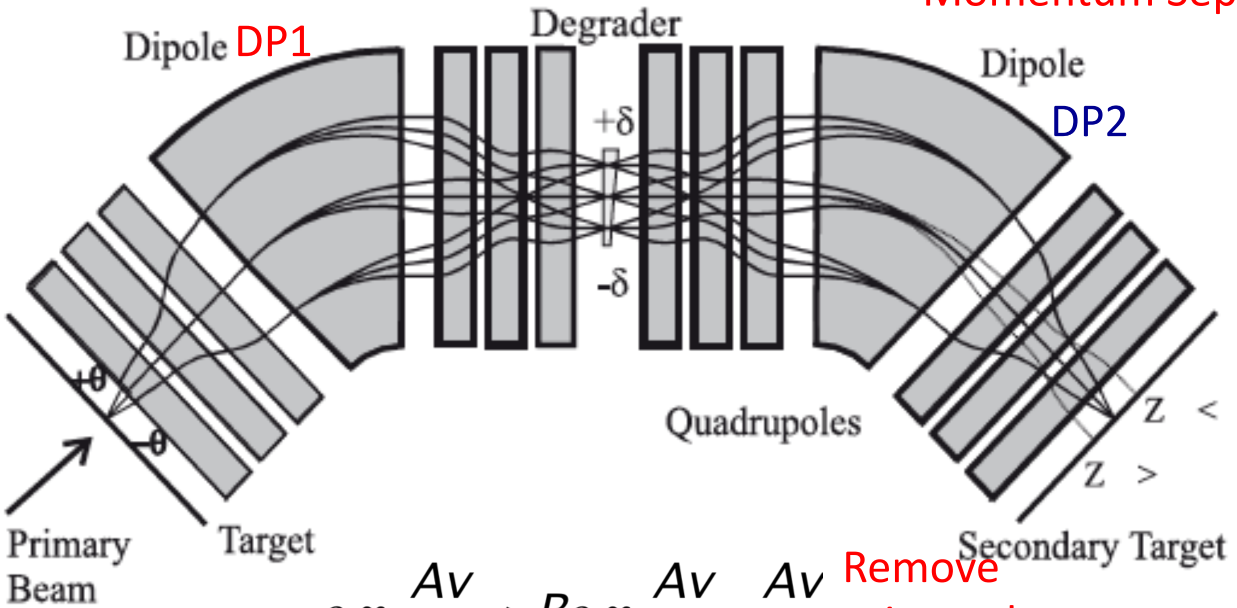
Need Wien-vel-Filter to separate in velocity

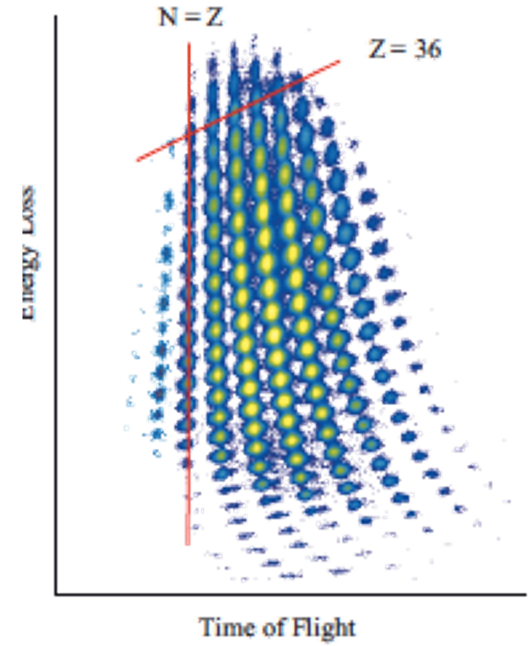


Fragment Separator - FRS

A/Z separation

Momentum Separation





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

Remove primary beam $10^{12} \rightarrow 10^{8}$

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

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

Reduction $10^{8} \rightarrow 10^{6}$

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

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

Energy loss $\propto Z^2$

T_{vol} (Target - 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

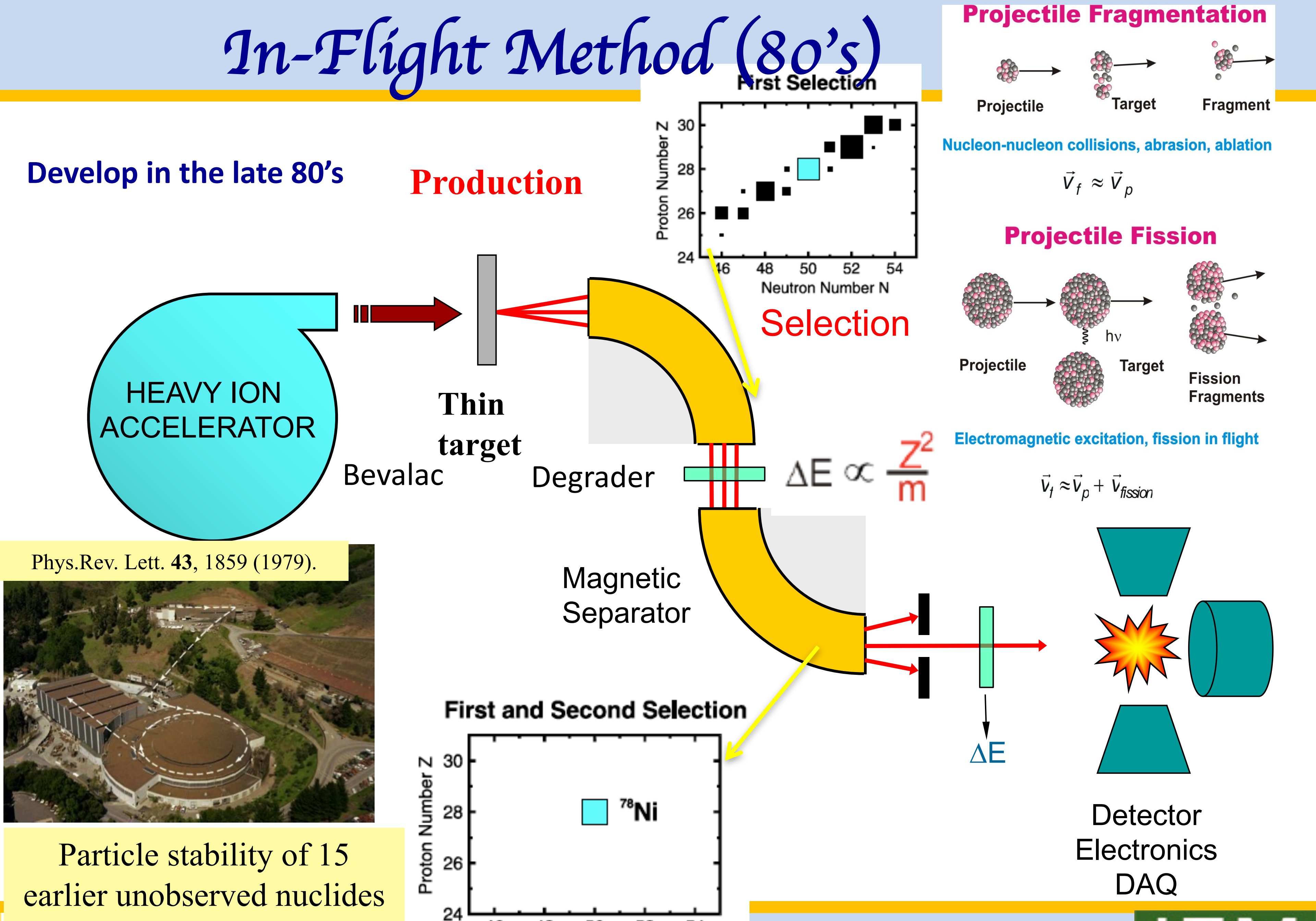
Reaction products
Kinematically forward focused

extended detection scheme
& better resolution

Full-acceptance measurements
with moderate sized detectors

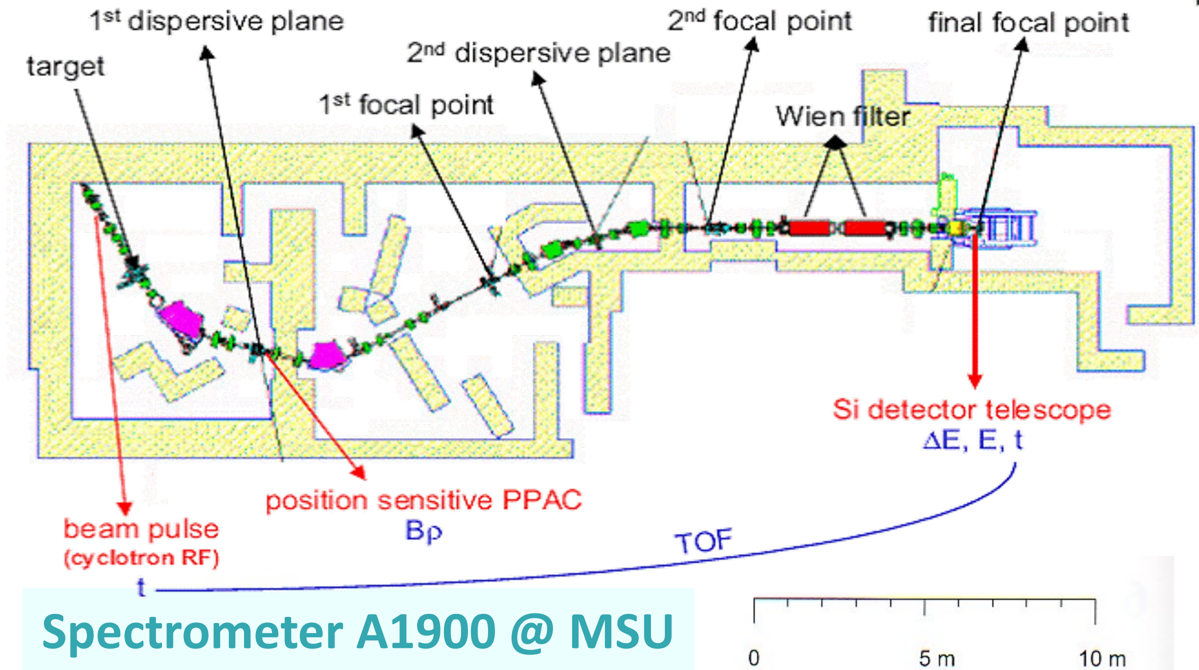
Possible study more exotic nuclei
efficient down to 1 ion/s, short lived

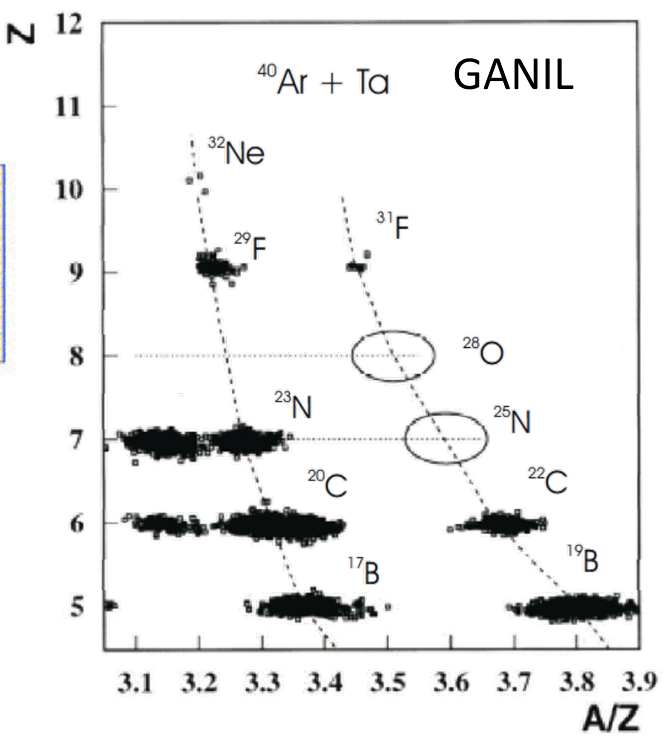
In-Flight Method (80's)



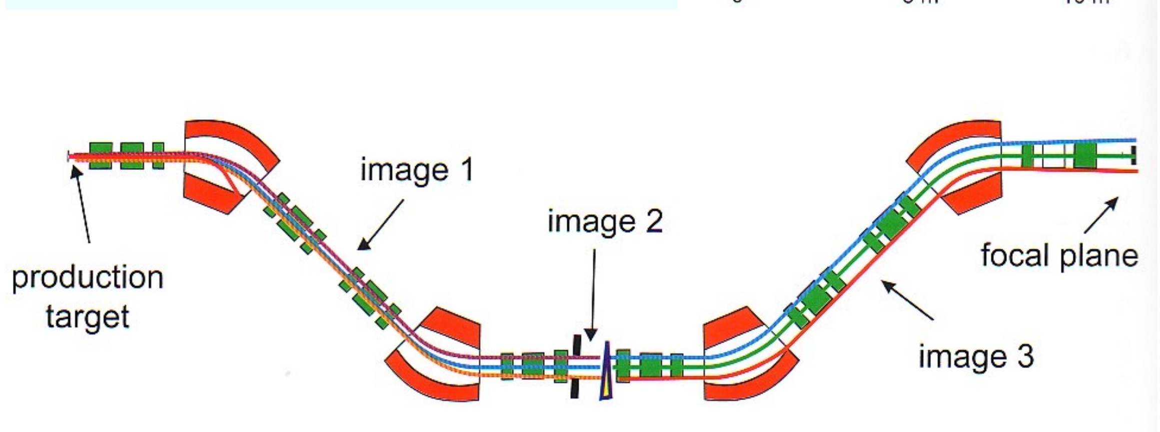
Different Spectrometer

Spectrometer LISE @ GANIL

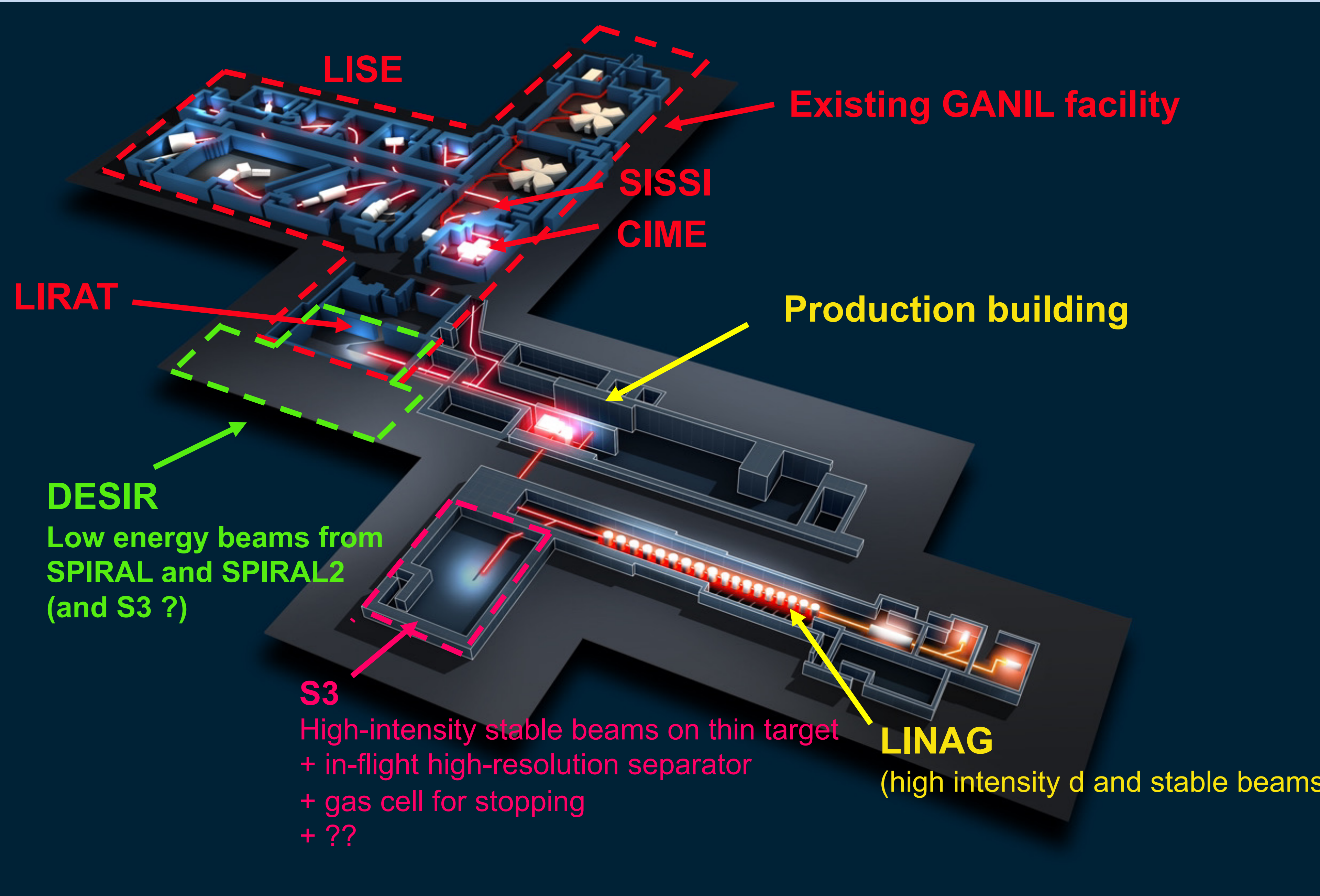




Spectrometer A1900 @ MSU

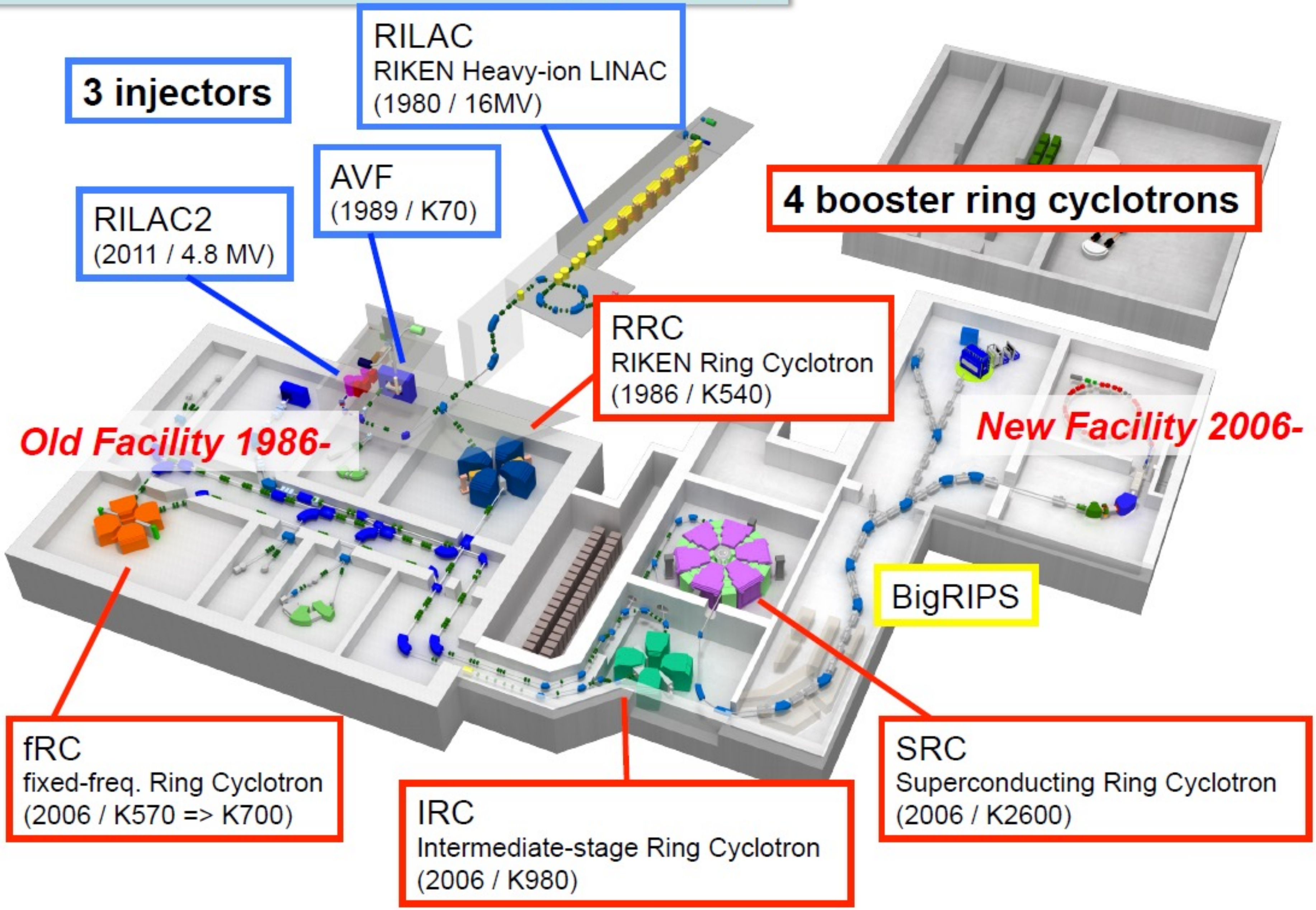


GANIL / SPIRAL 2



RIKEN RI Beam Factory (RIBF)

Y. Yano, NIM B261 (2007) 1009.

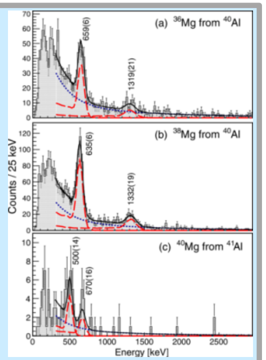


Steady increase of Beam Current @ RIKEN (Japan)

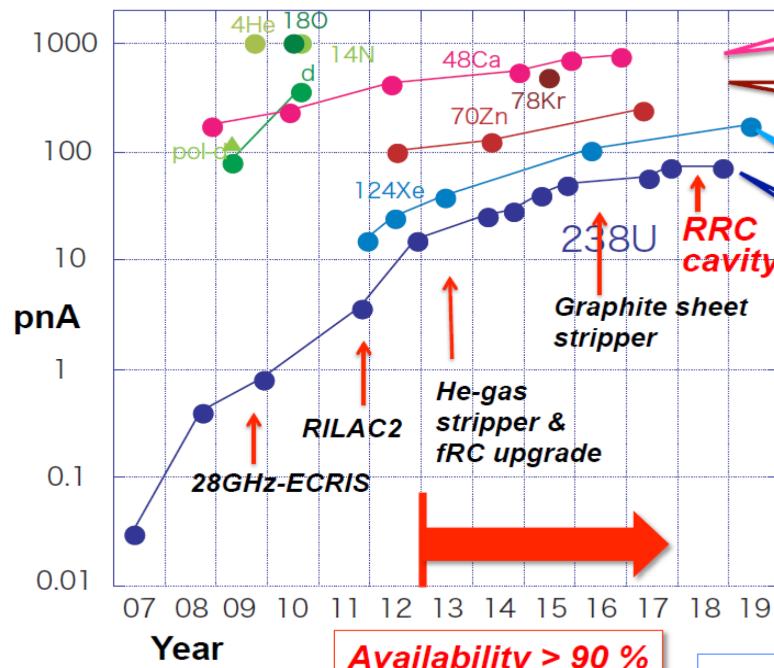
^{40}Mg (N=28) is largely deformed.

The origin is a mystery.

No theory can reproduces the data.



RIBF accelerator performance



Availability > 90 %

79 % in 2018…

^{48}Ca: 738 pnA => ***12.3 kW***

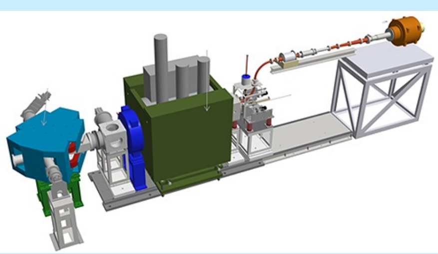
^{78}Kr: 486 pnA => ***13.1 kW***

^{124}Xe: 173 pnA => ***7.4 kW***

^{238}U: 72 pnA => ***5.9 kW***

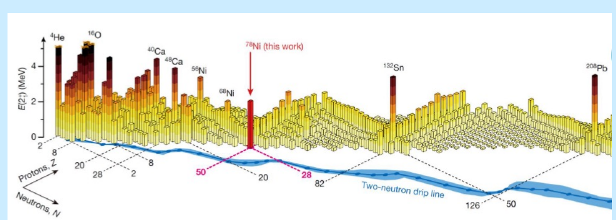
Quest for heavier super-heavies (Z=113) Success in producing and accelerating high intensity vanadium beam

- Cleared the way for producing element 119 – (2017)



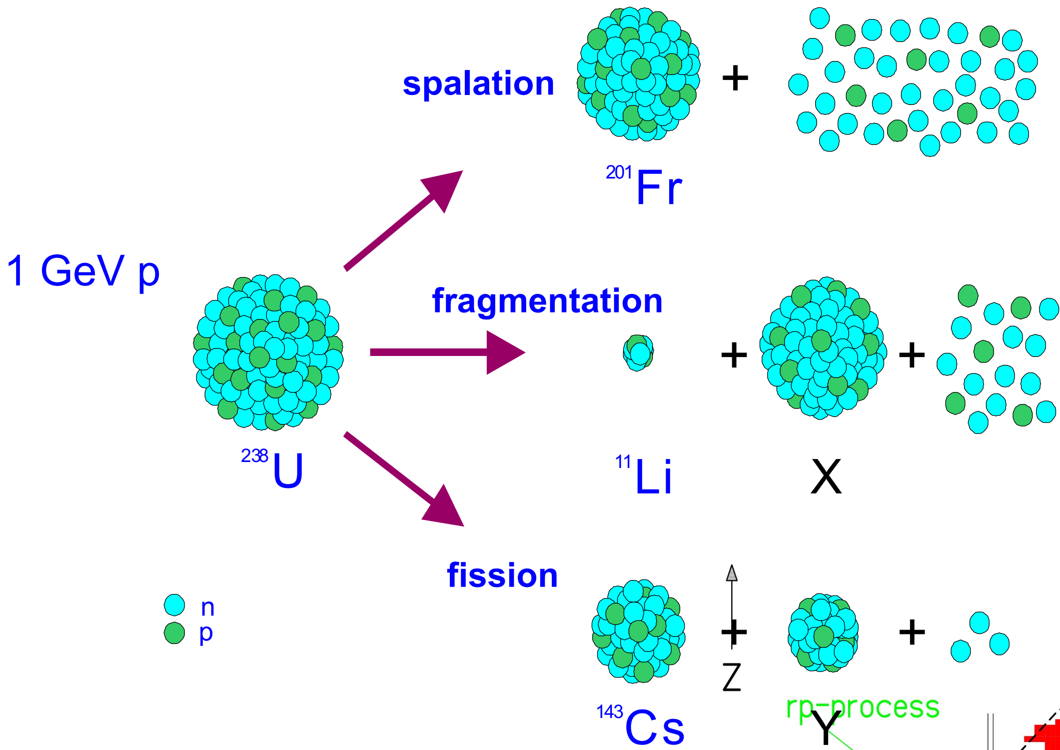
^{78}Ni (N=50) revealed as a doubly magic stronghold against nuclear deformation.

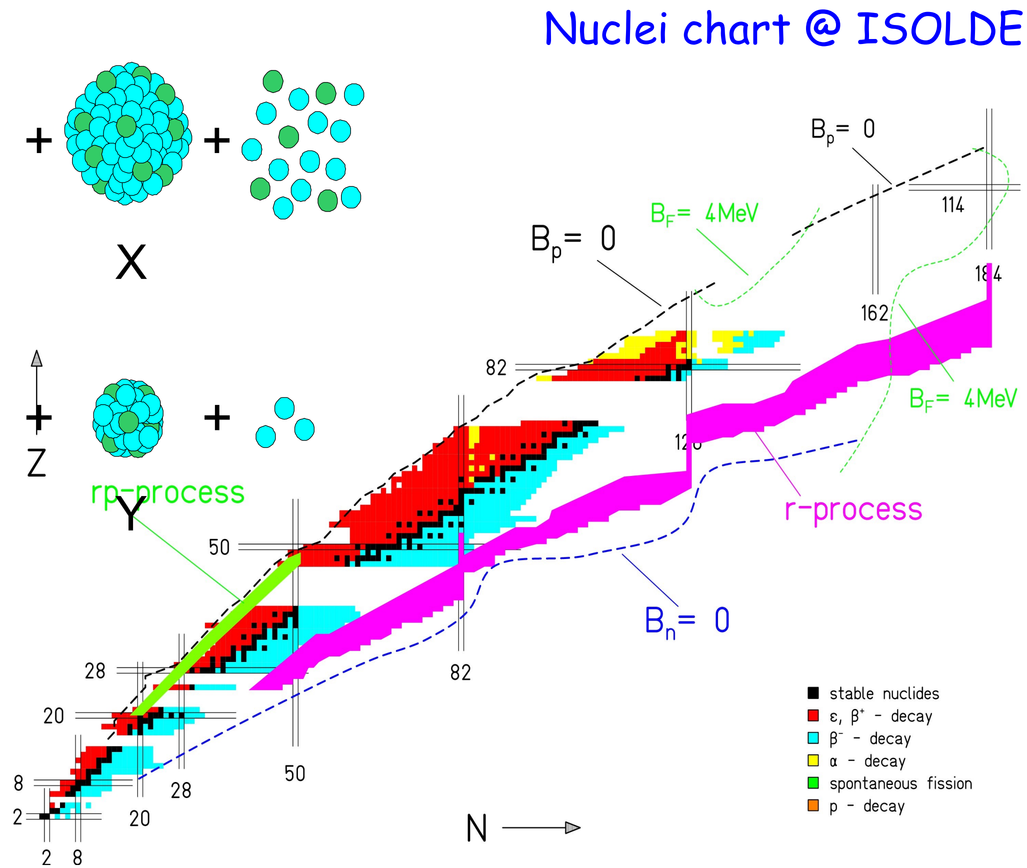
Taniuchi et al., Nature 569, 53 (2019)



73 new isotopes discovered at RIKEN's RI Beam Factory (2017)

Isotope production



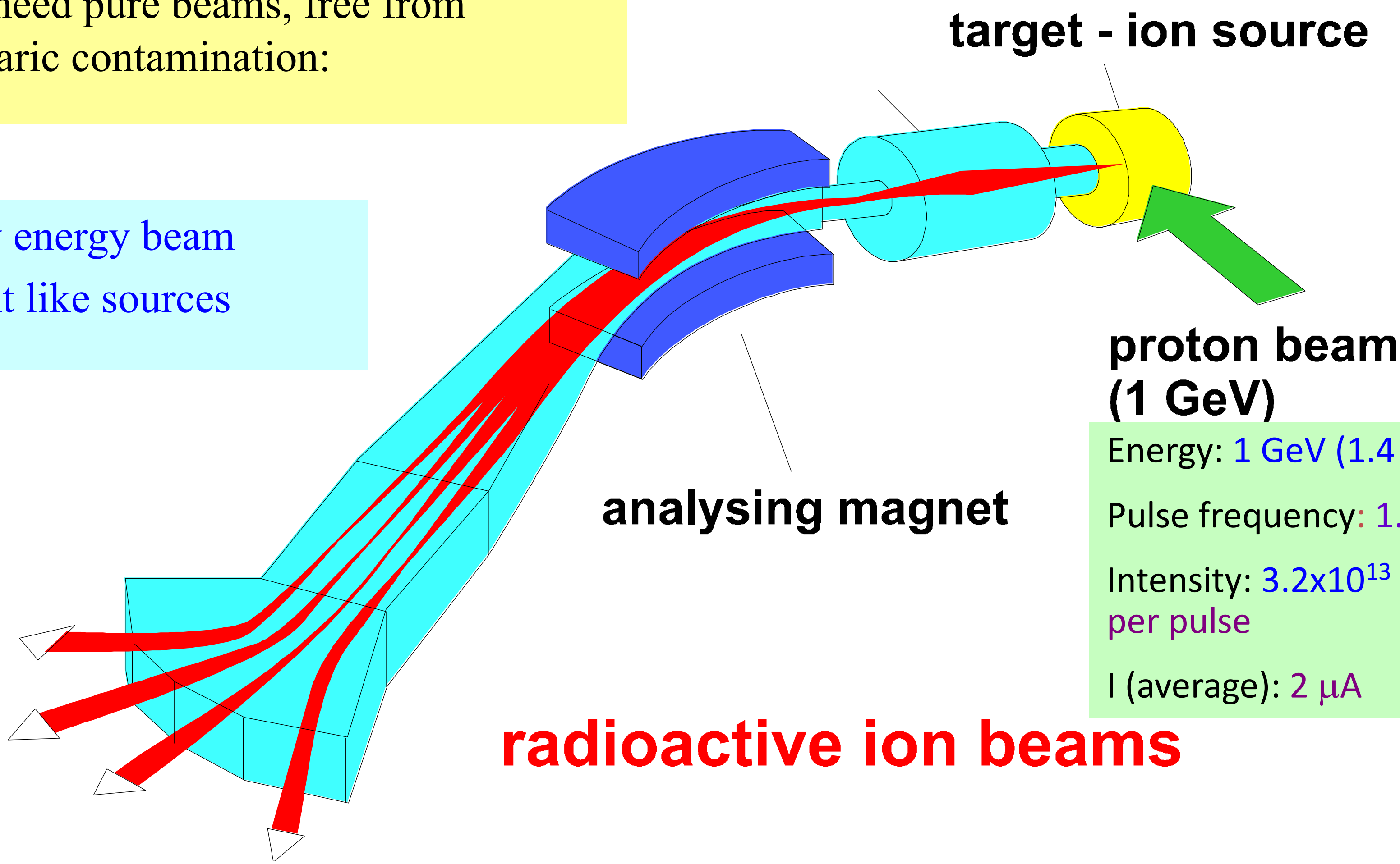


Exotic ion production

ISOLDE Isotope Separation On-Line

We need pure beams, free from isobaric contamination:

Low energy beam
Point like sources



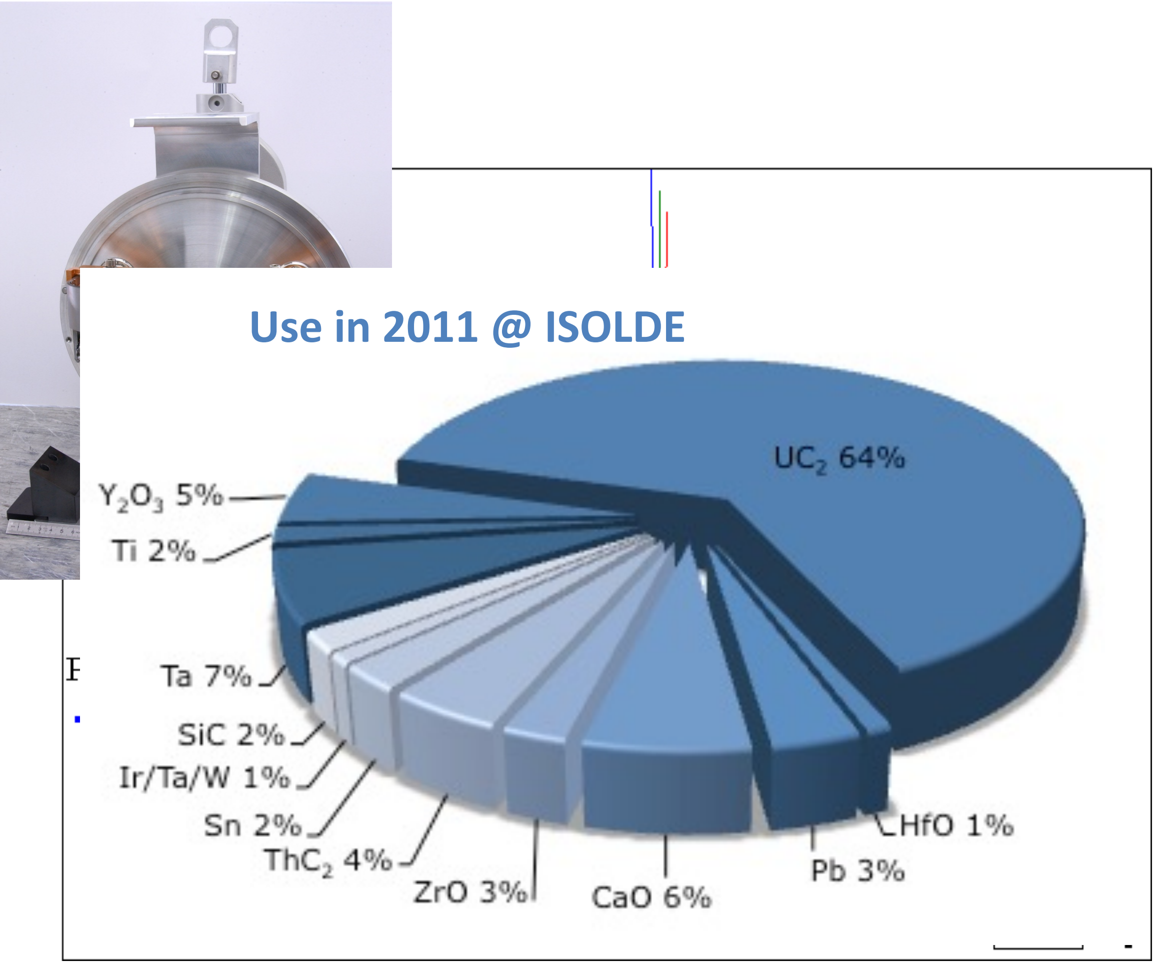
Energy: 1 GeV (1.4 GeV)

Pulse frequency: 1.2 s

Intensity: 3.2×10^{13} protons per pulse

I (average): 2 μA

Target – Ion-source matrix: a chemical laboratory



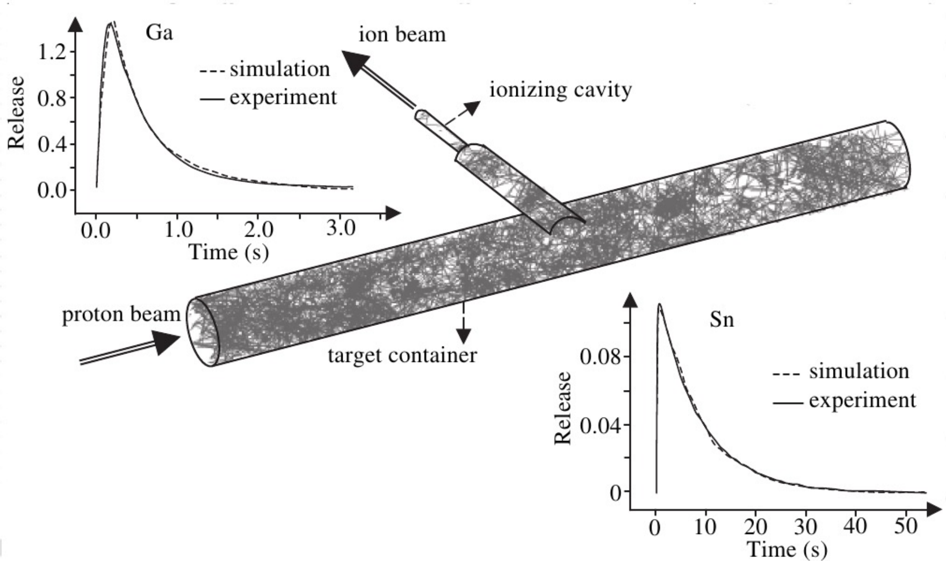
- **Container: 20 x 2 cm cylinder of Ta**
- **Material:**
  - **Liquid** **La, Pb, Sn**
  - **Metal foil/powder** **Nb, Ti,**
  - **Oxides** **CaO, MgO**
  - **Carbides** **SiC, UC, ThC**
- **Ion-source**
  - **Surface**
  - **Plasma**
  - **Laser**
- **Fluorination** **CF4 or SF6**

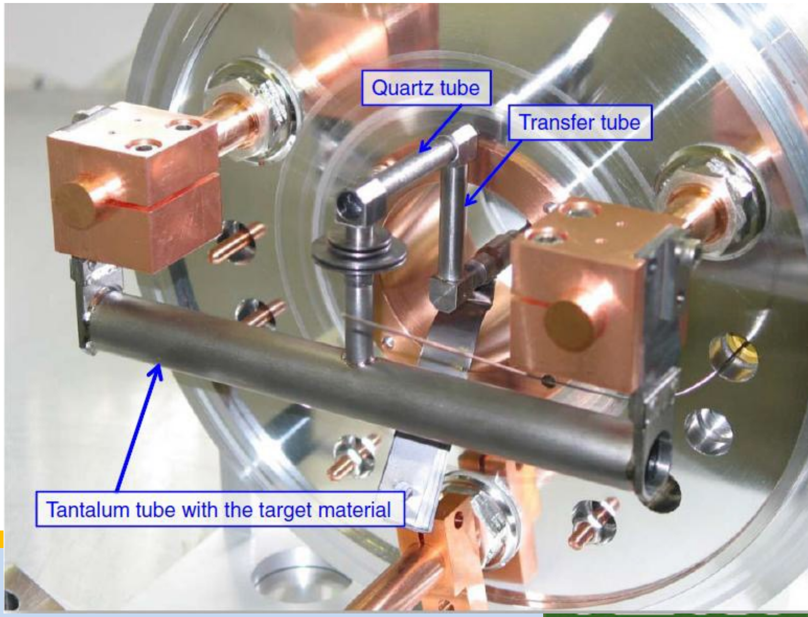
ISOLDE Targets

- 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



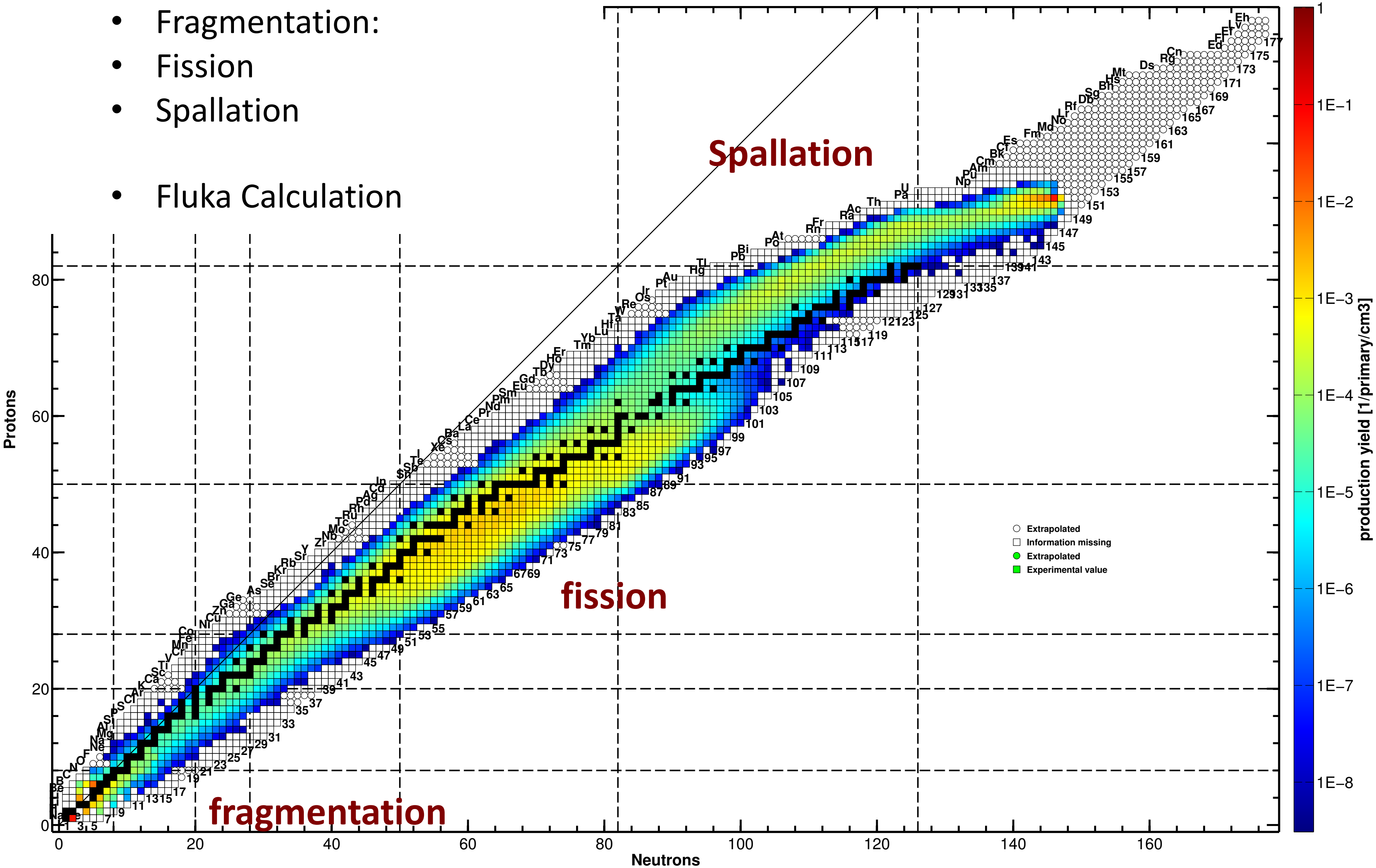


Monte Carlo Simulation of ISOLDE production

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

  - Fluka Calculation

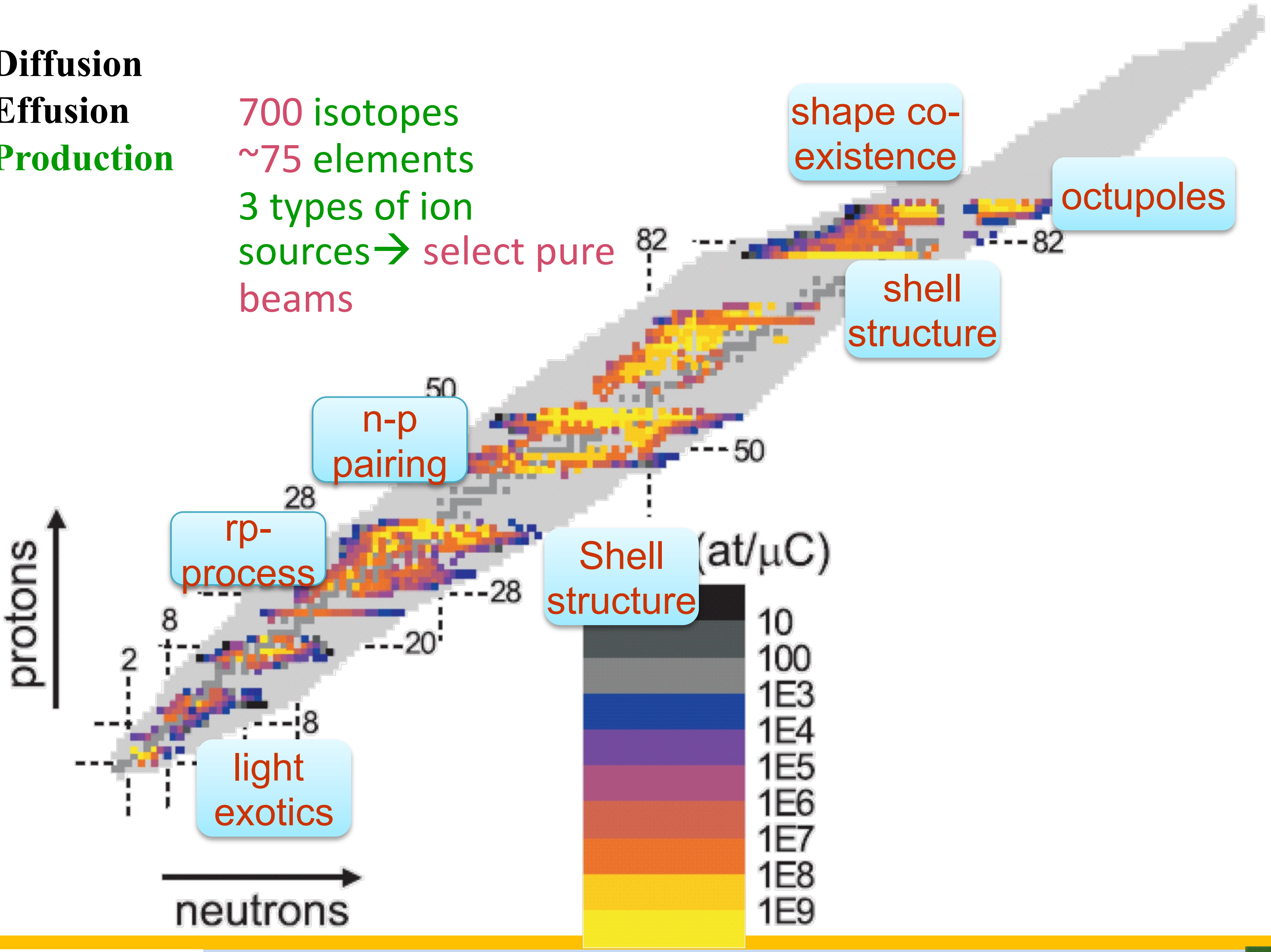
P beam on UC-Target



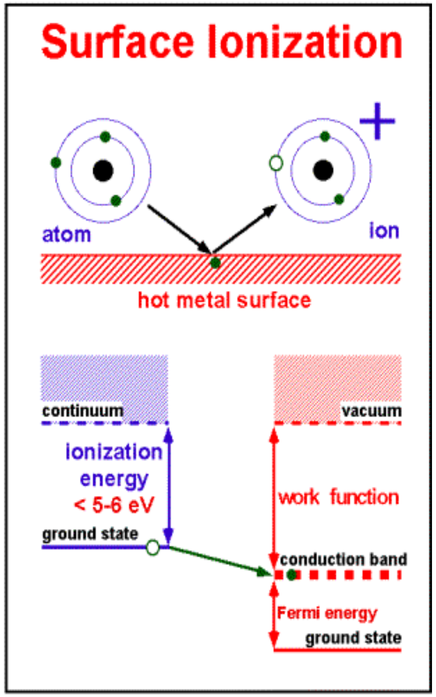
ISOLDE Main potential

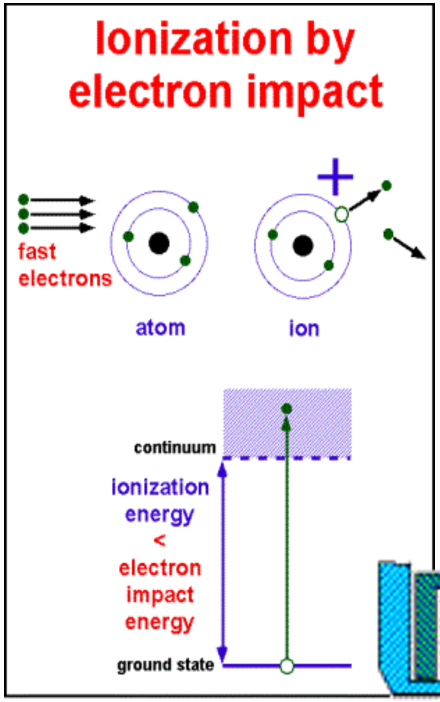
- **Diffusion**
- **Effusion**
- **Production**

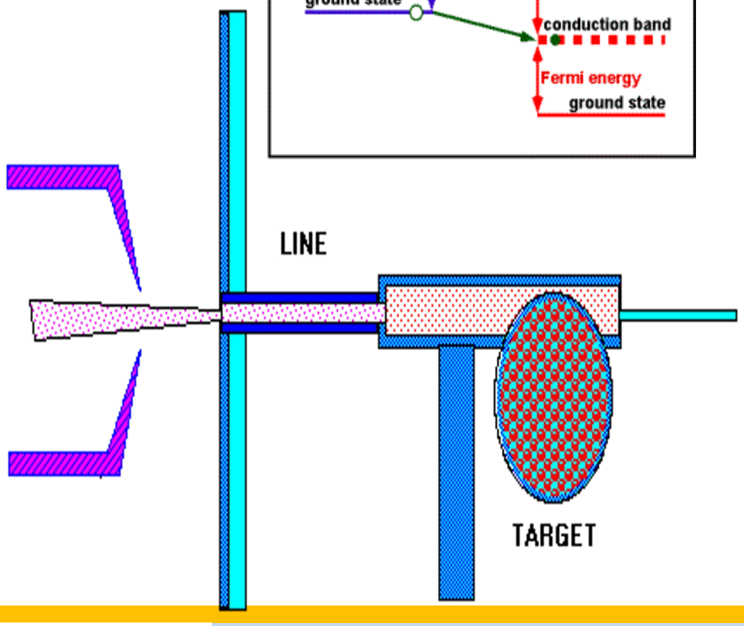
700 isotopes
~75 elements
3 types of ion sources→ select pure beams

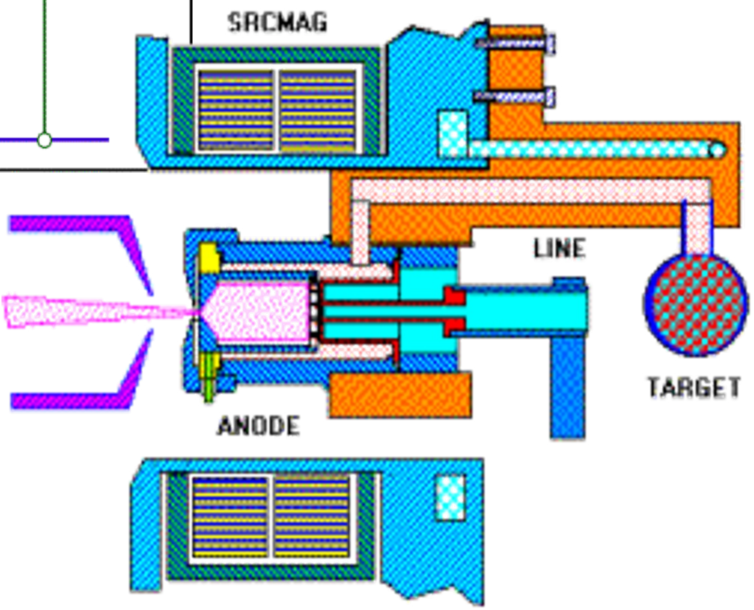


Surface & plasma ionization



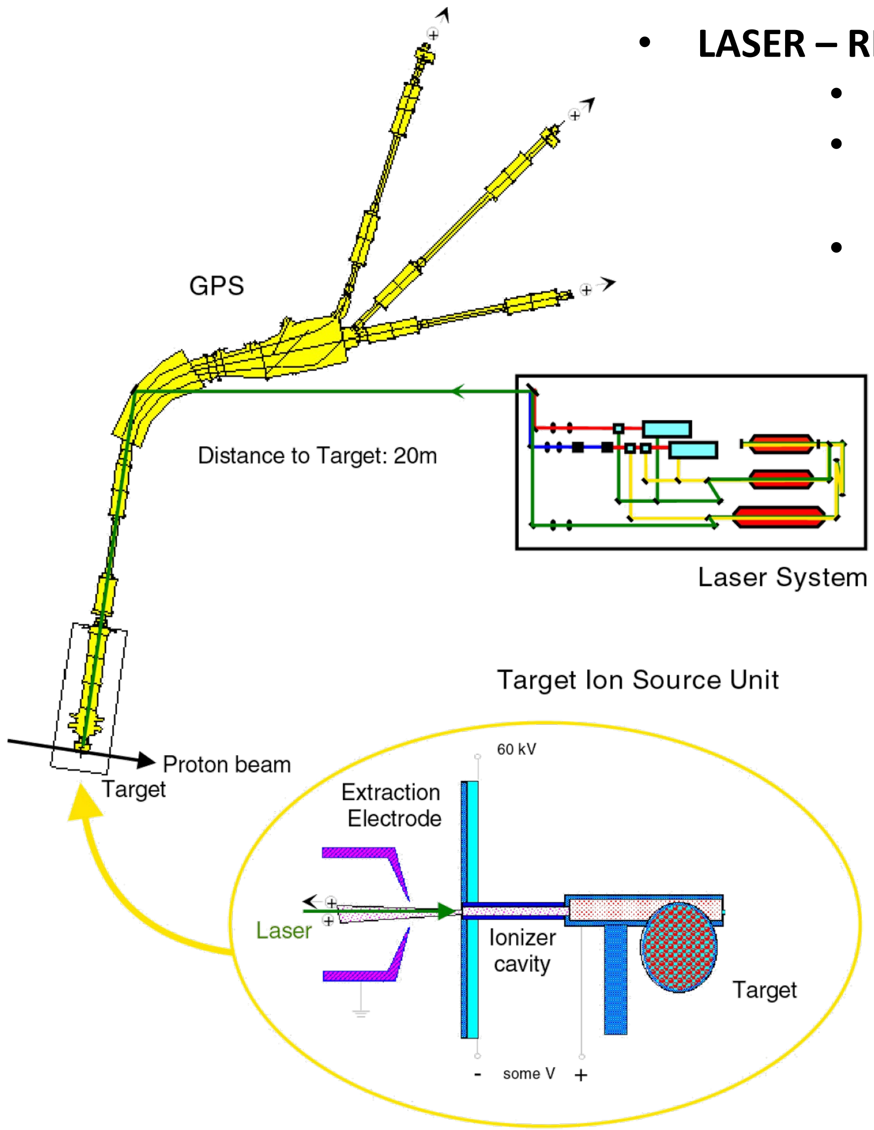


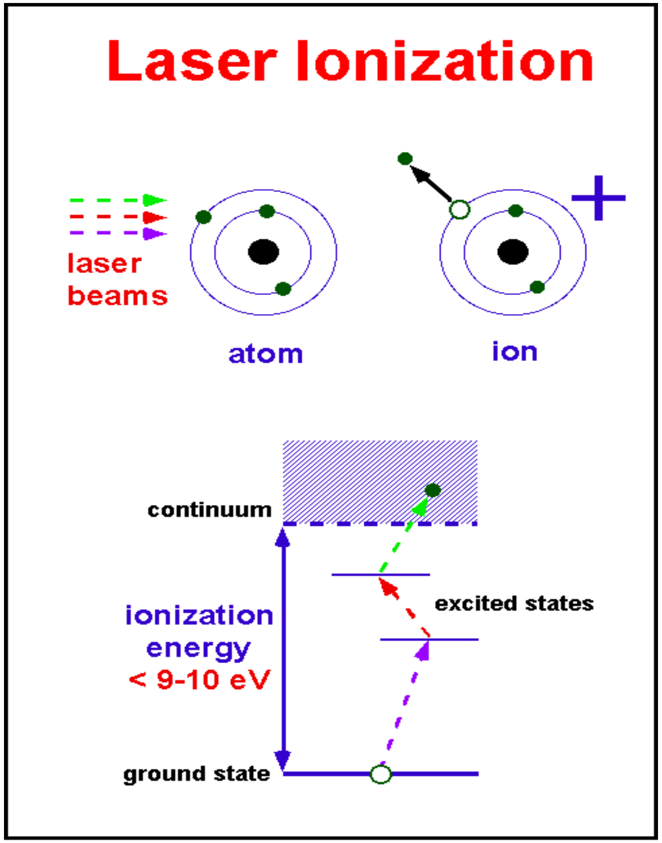




Laser Ionization source

- **LASER – RILIS** (Resonance Ionization Laser Ion Source)
  - Used at ISOLDE since 1994
  - Based on the selective ionization of a single atomic species
  - It has allow for isomeric separation



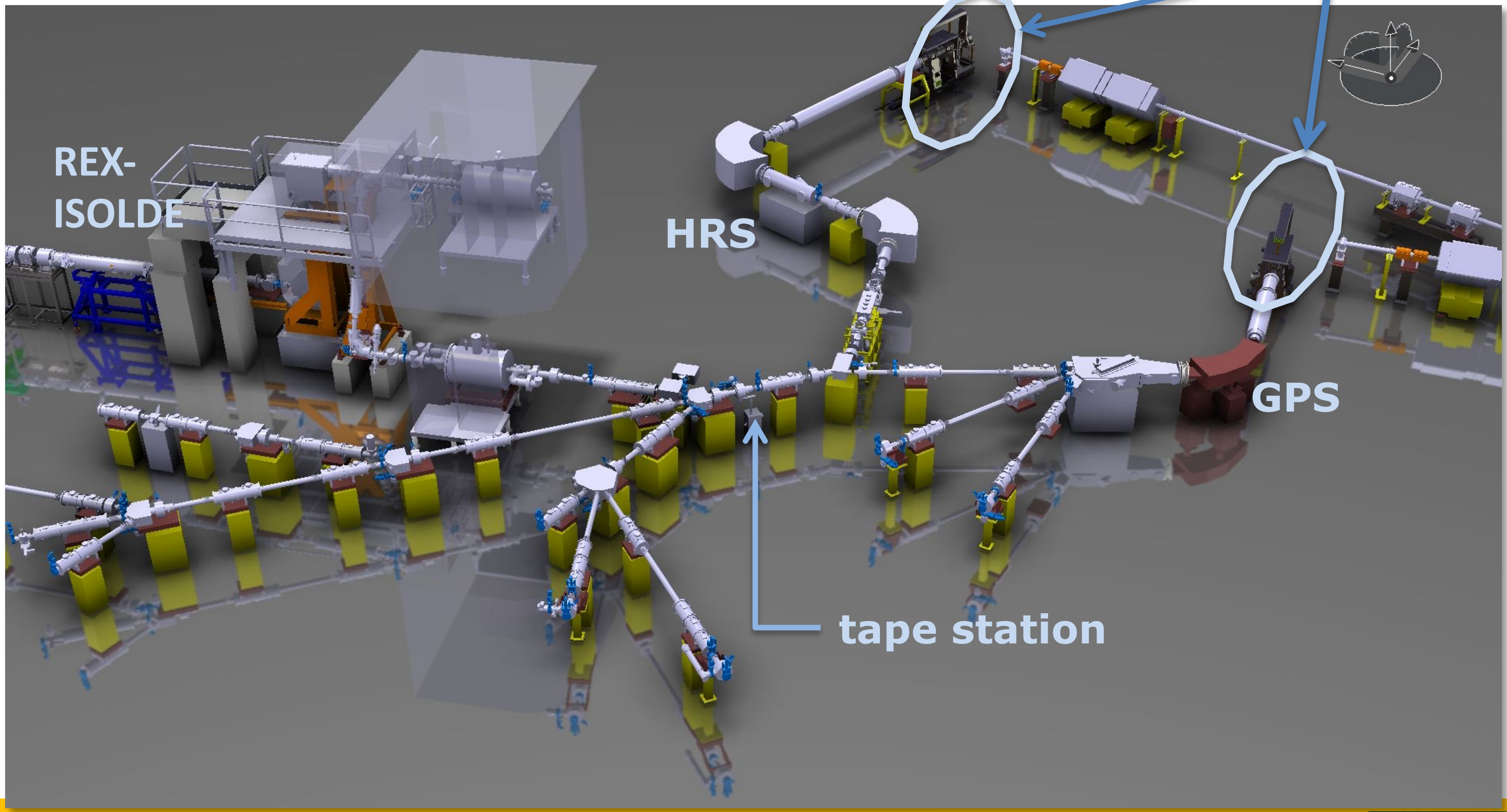


Separation @ ISOL

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

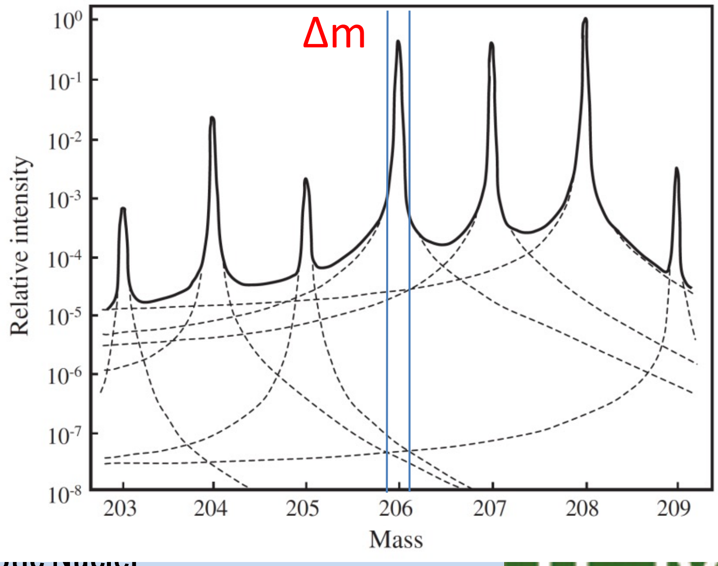
Target + Ion Unit

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

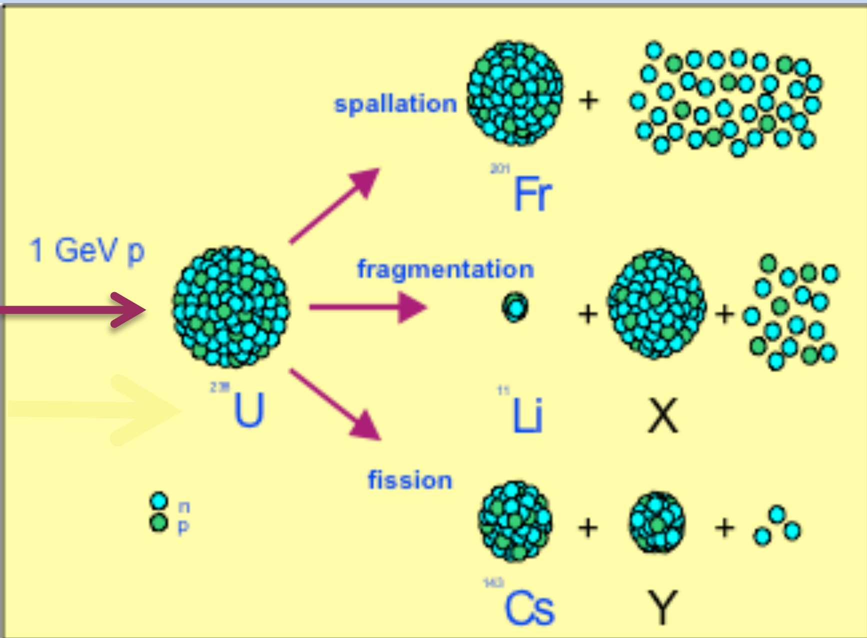


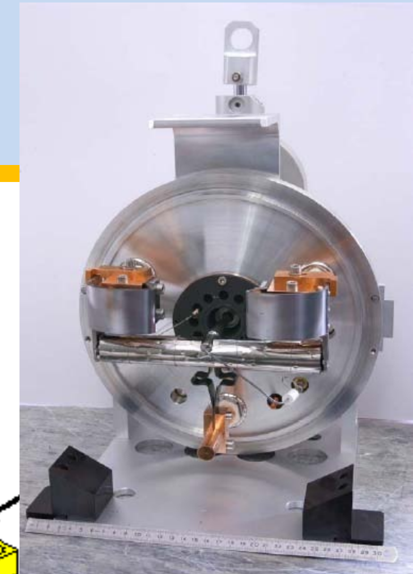
Mass separators @ ISOLDE

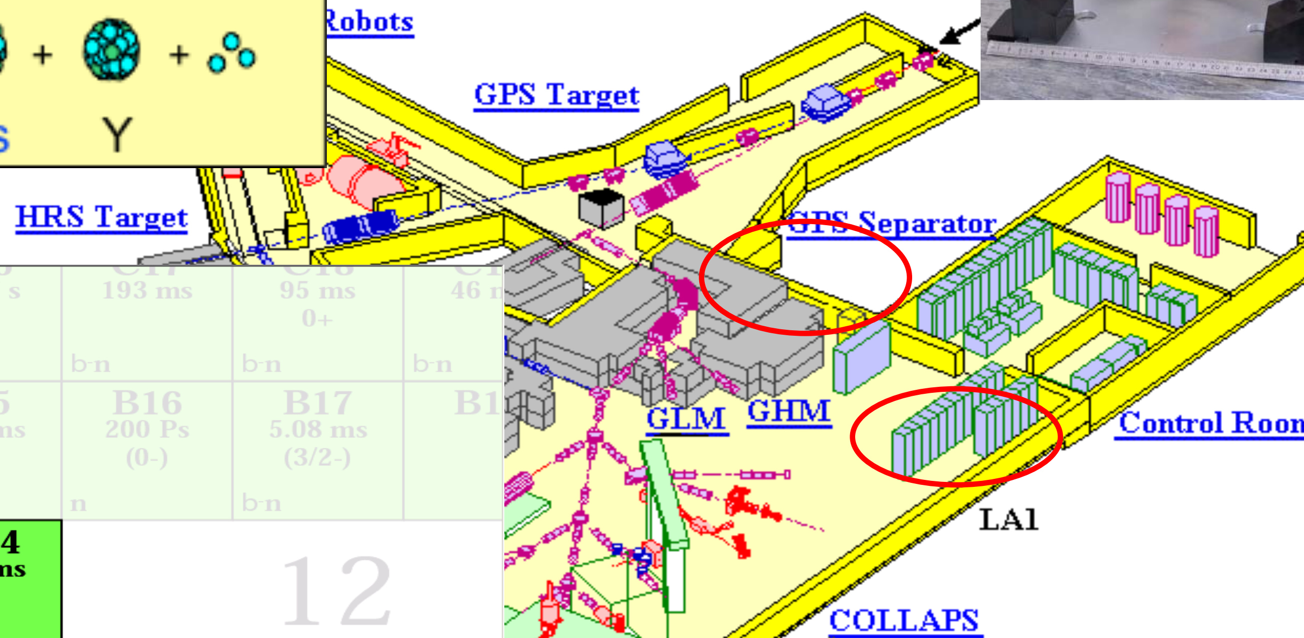
- The radioactive ions are accelerated at 20 – 60 kV and sent to the separating magnets.
- GPS (General Purpose)
  - Magnetic dipole + electrostatic switchyard
  - Can separate simultaneously 3 masses
  - m/Δm = 1000
- HRS (High Resolution)
  - 2 Magnetic dipoles
  - Separation power
  - m/Δm = 5000

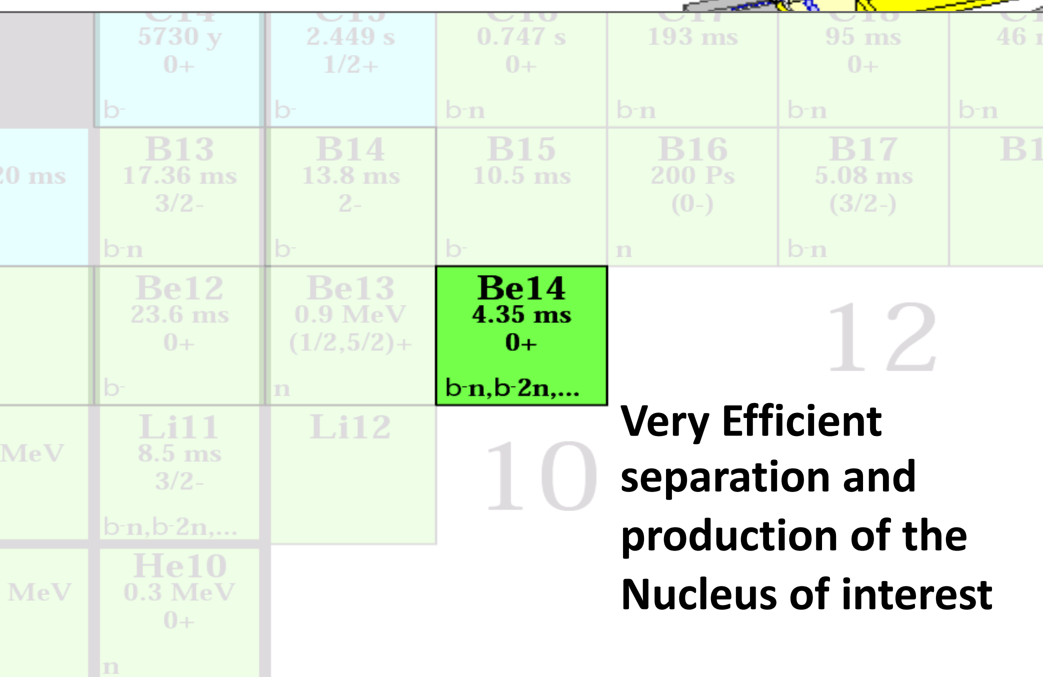


election @ ISOLDE



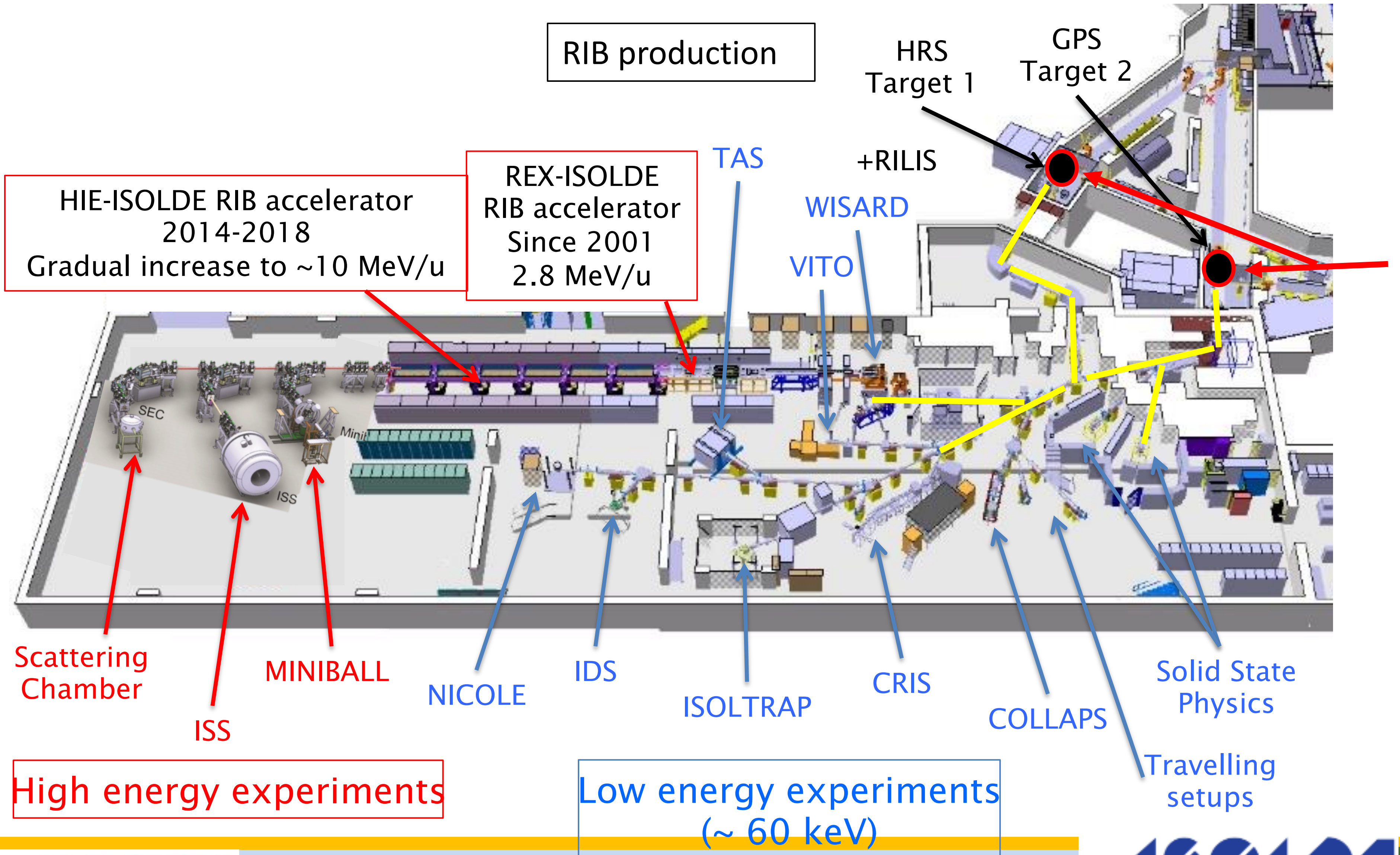






Very Efficient separation and production of the Nucleus of interest

The ISOLDE facility and set-ups



Summary: Two production Methods

Primary Target

extraction

ionisation

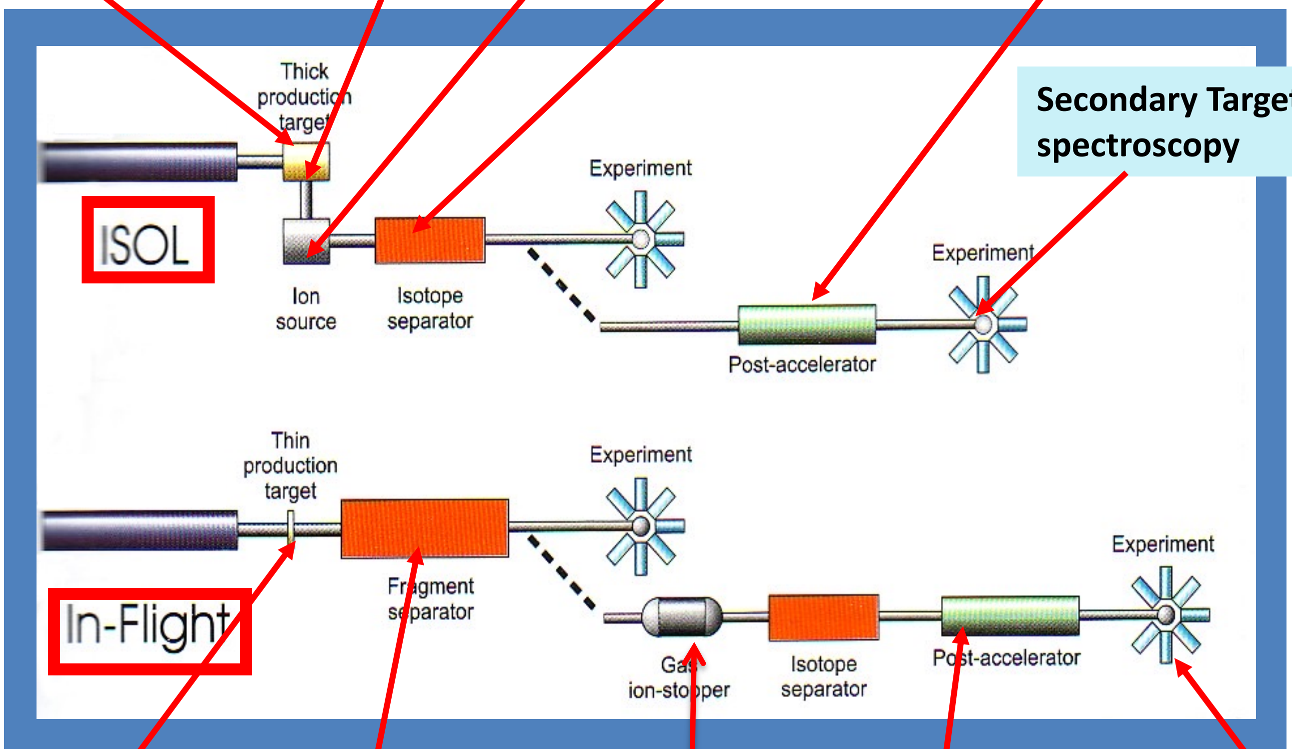
séparation

post-accelerator

Secondary Target spectroscopy

driver accelerator

driver accelerator
ions 100 MeV - 1 GeV/u



fragmentation / fission

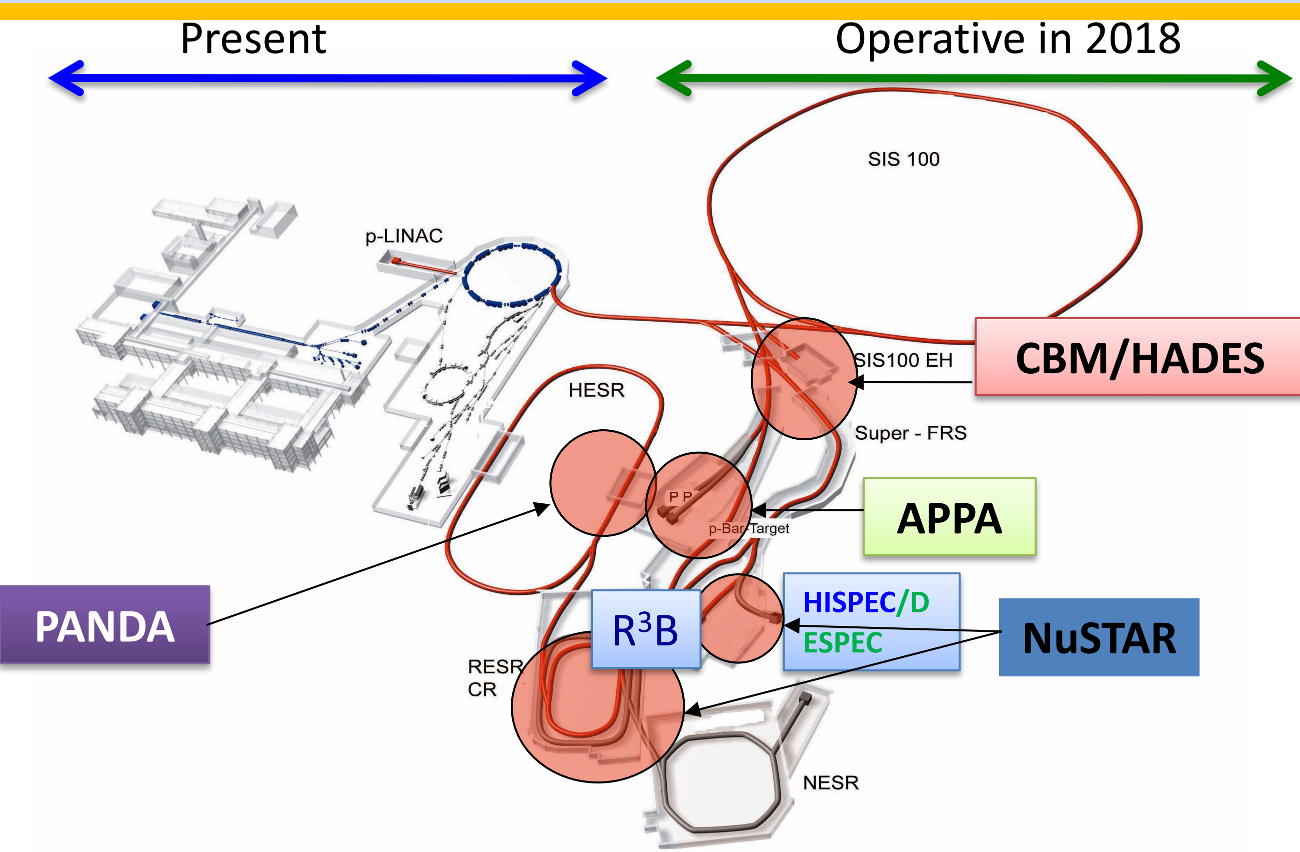
Fragment Separator

De-acceleration

Post-accelerator

Secondary Target Spectroscopie

Fair : Facility of Antiprotons and Ion Research



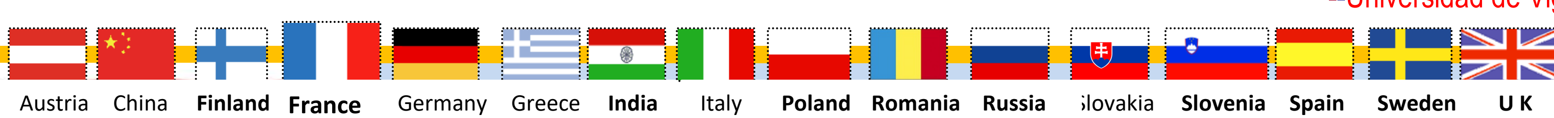
All the Spanish experimental groups participate in the project

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**

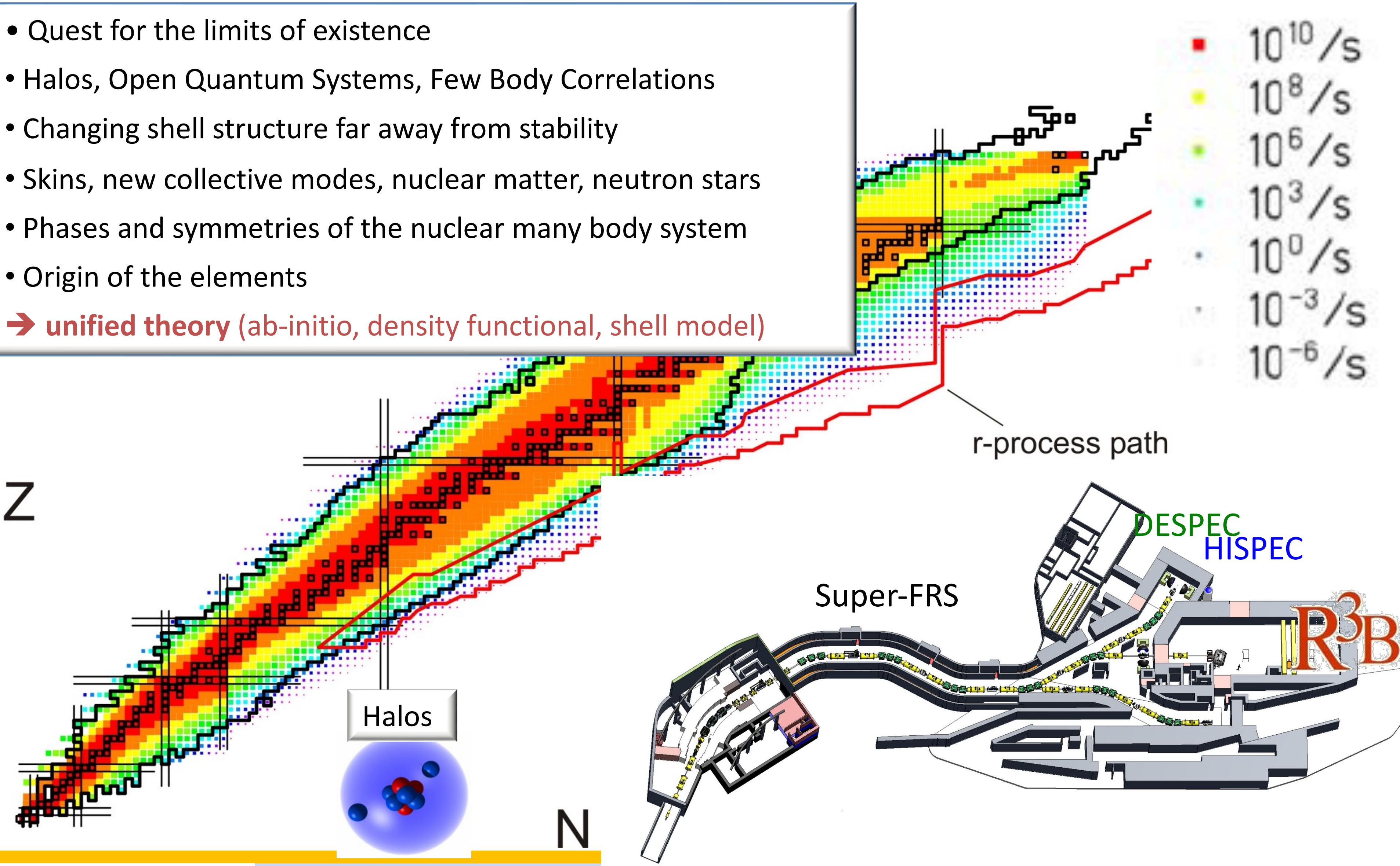
- R3B, HISPEC/DESPEC, EXL/ELISe, MATS
- 11 research groups



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

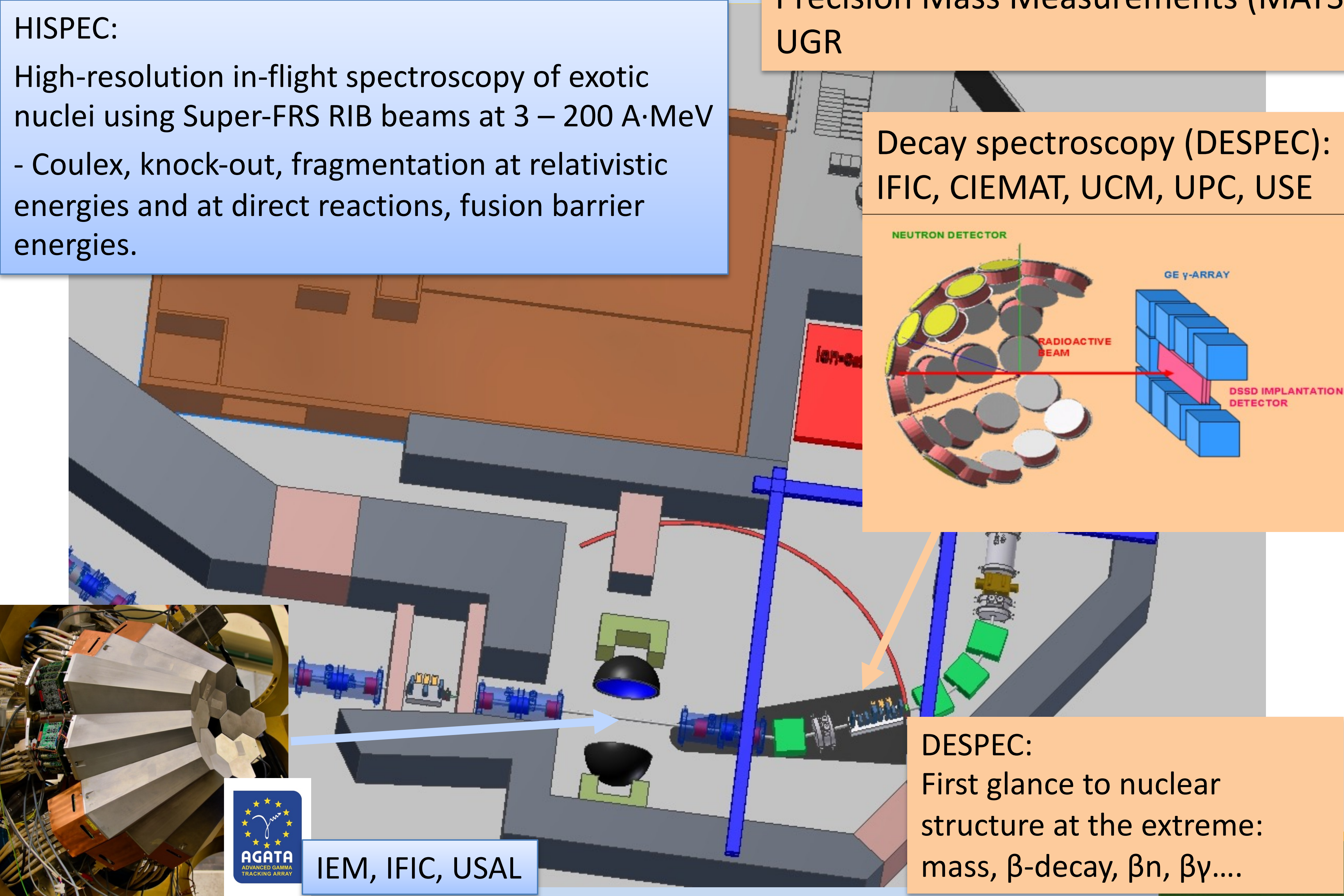
- Coulex, knock-out, fragmentation at relativistic energies and at direct reactions, fusion barrier energies.

Precision Mass Measurements (MATS

UGR

Decay spectroscopy (DESPEC):

IFIC, CIEMAT, UCM, UPC, USE



IEM, IFIC, USAL

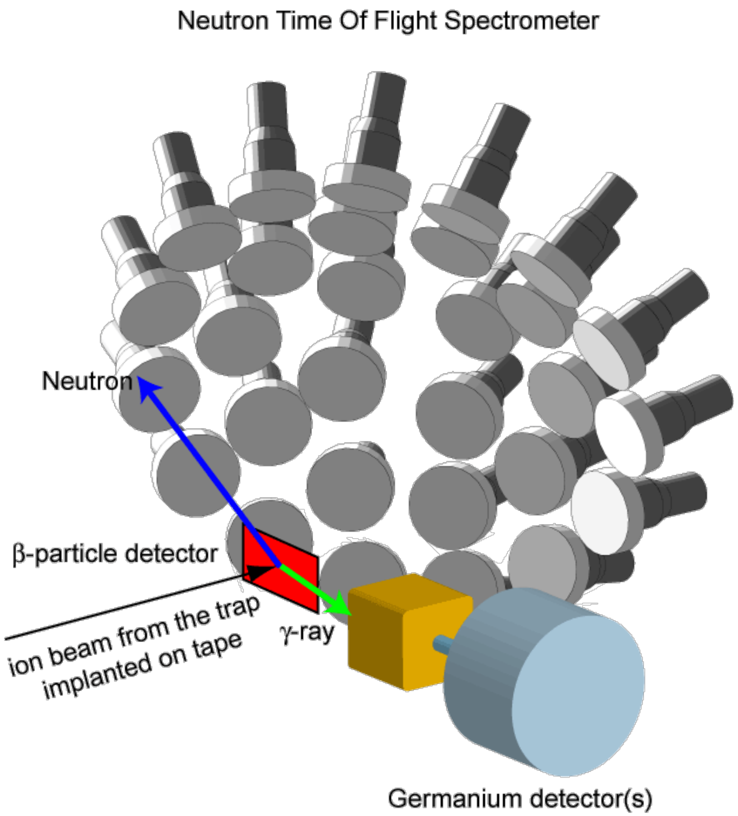
DESPEC:

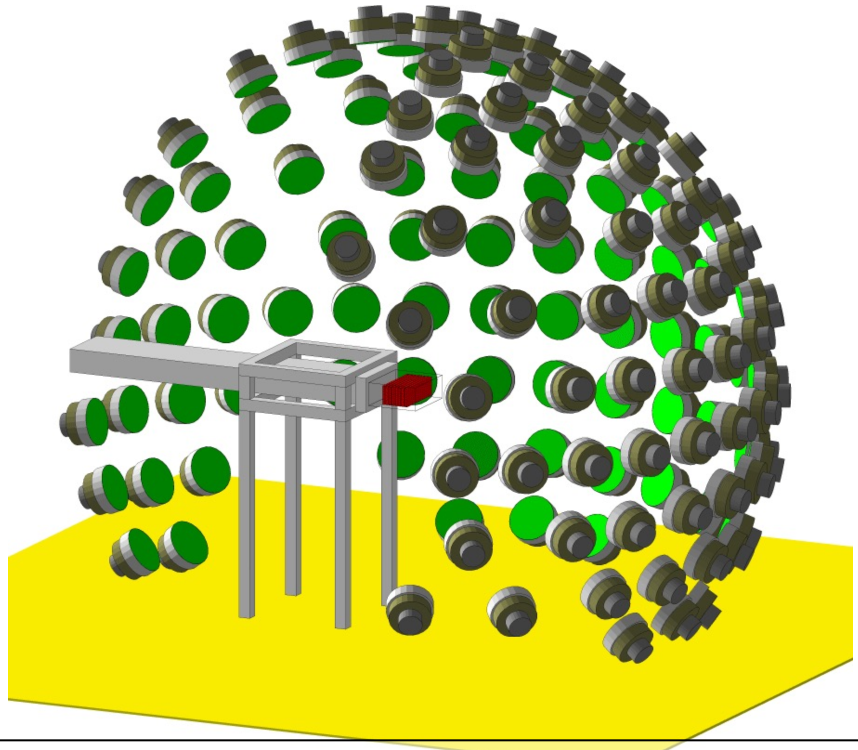
First glance to nuclear structure at the extreme: mass, β-decay, βn, βγ….

The neutron detectors for DESPEC

CIEMAT is the coordinator of the neutron detector working group of the DESPEC experiment and exploiting all possible international synergies (SPIRAL-2).

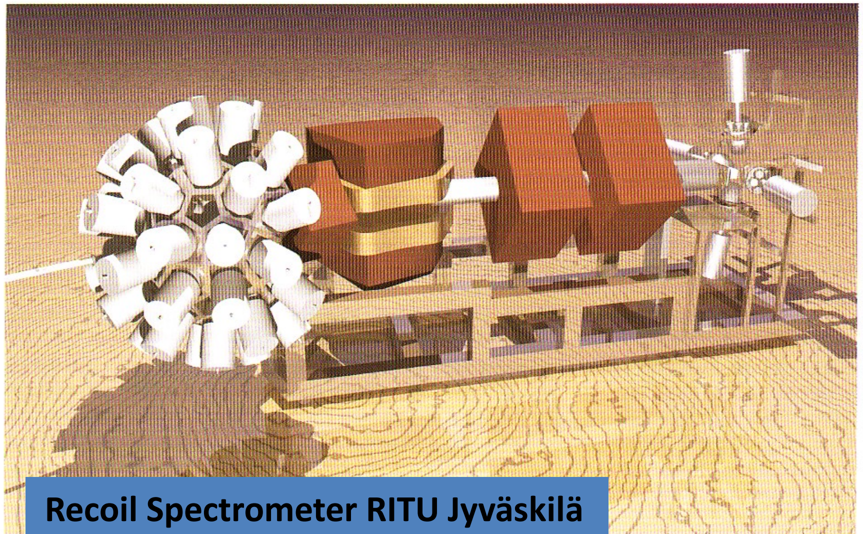
Design and construction of a demonstrator **CIEMAT: design and partial construction**



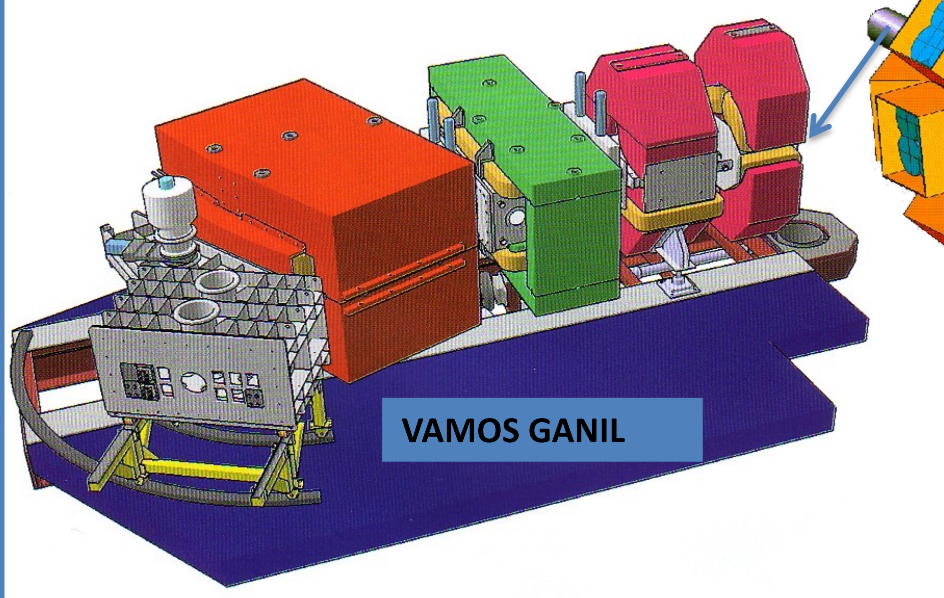


TOF spectrometer: array of liquid scintillators (BC501A)

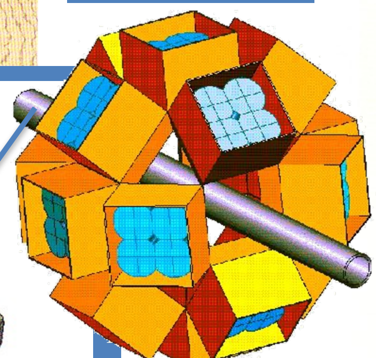
Identification and Measurement of fragments



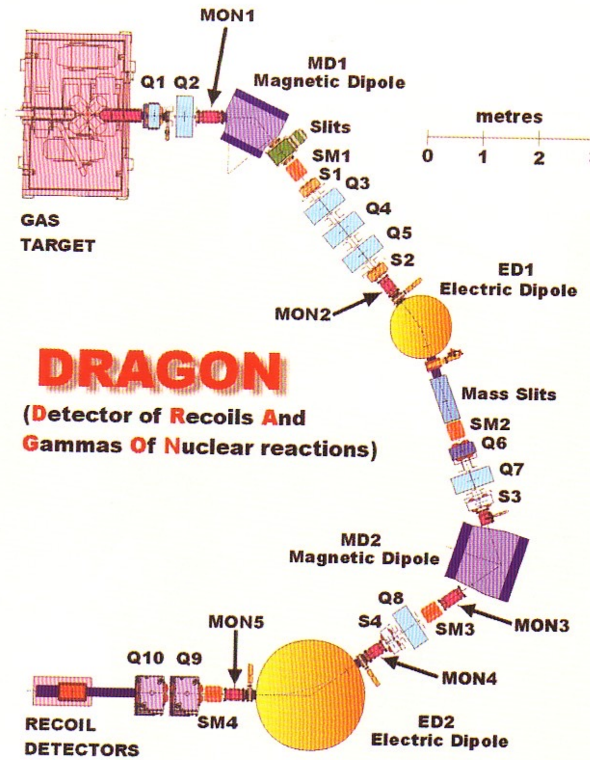
Recoil Spectrometer RITU Jyväskilä



VAMOS GANIL



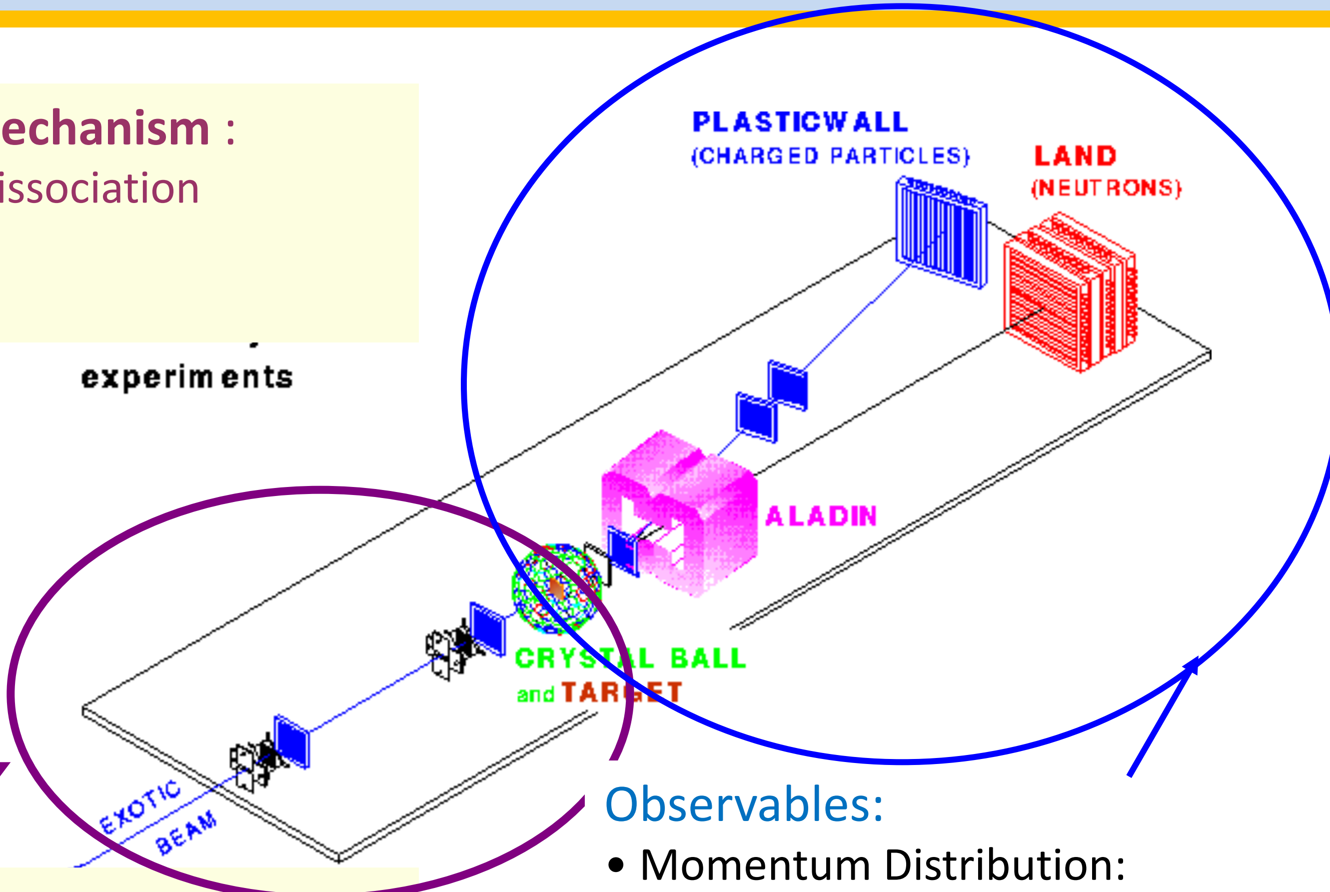
EXOGAM



Mass Spectrometer DRAGON
Vancouver CANADA

Reaction at High Energy @GSI → R3B @ FAIR

Reaction Mechanism :
- Coulomb dissociation
- Difraction
- Absorption



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

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