Production of Exotic Nuclei

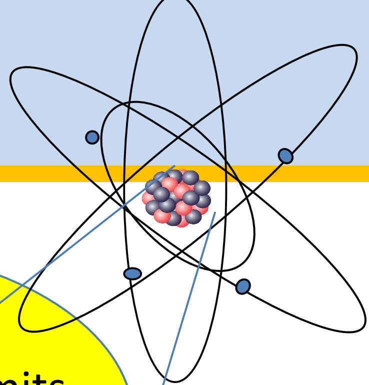
CSIC IEM

Exotic Nuclei and Radiactive Beams

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

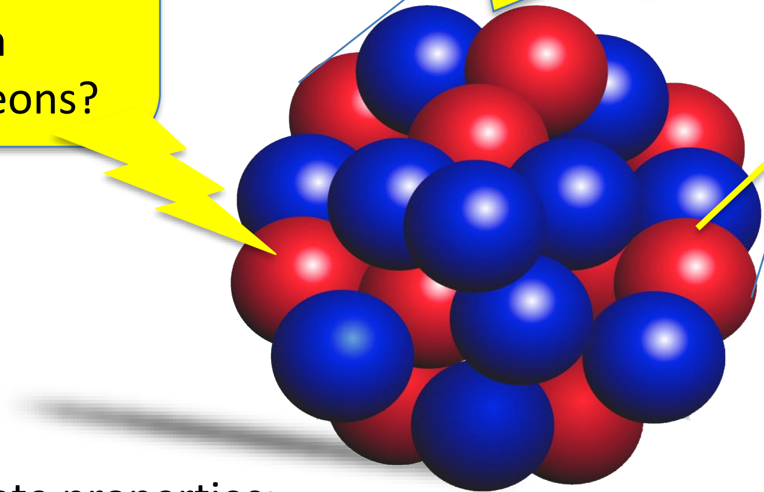
"The why and how of Radioactive beam Research", Mark Huyse,
"In-flight separation of projectile fragments", David Morrisey and Brad Sherril
"Isotope separation on line and post-acceleration", P. Van Duppen
http://www.euroschoolonexoticbeams.be/site/pages/lecture_notes

Open Questions in Nuclear Physics



What are the limits of nuclear stability?

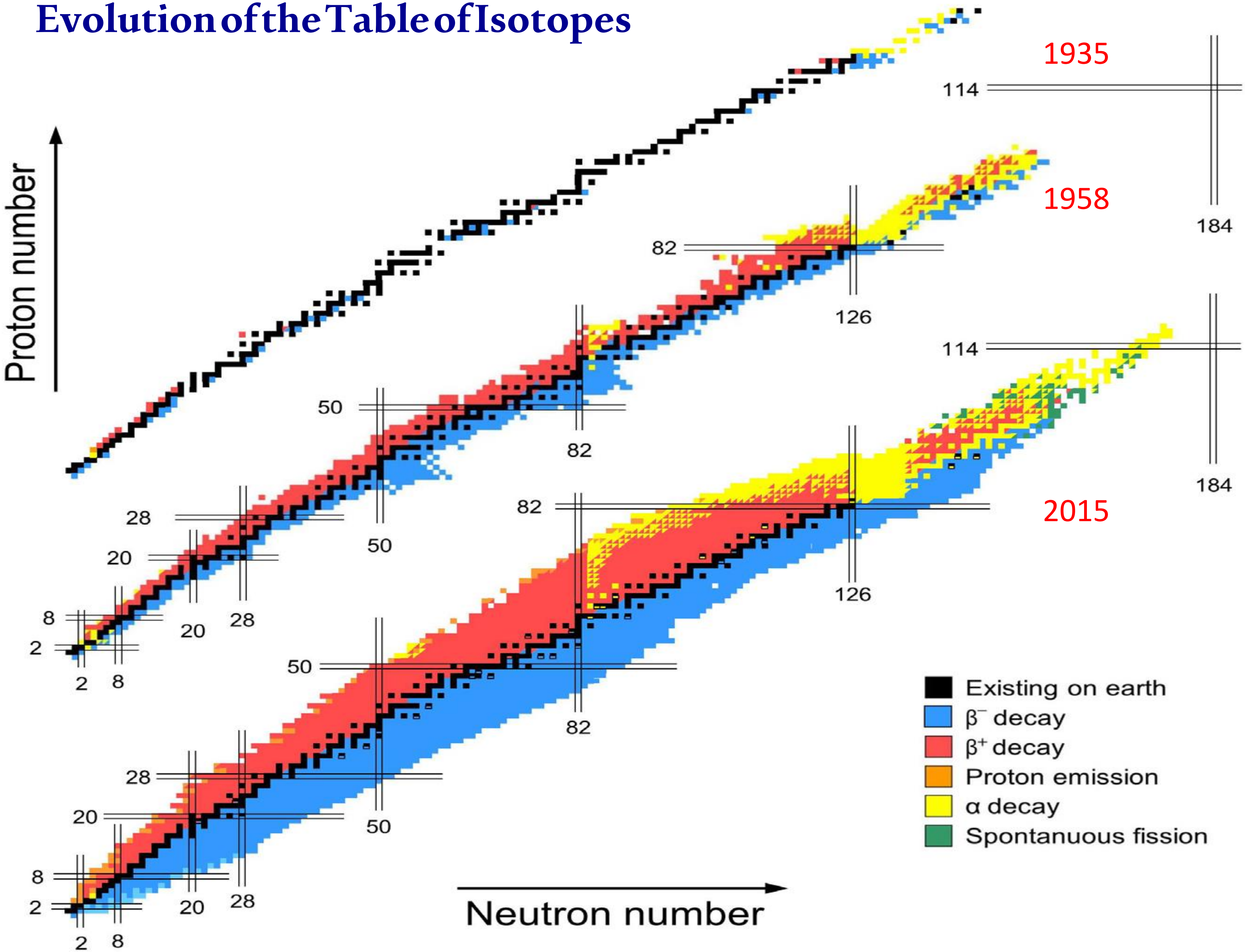
¿ How does the complexity of nuclear structure arise from the interaction between nucleons?



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

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

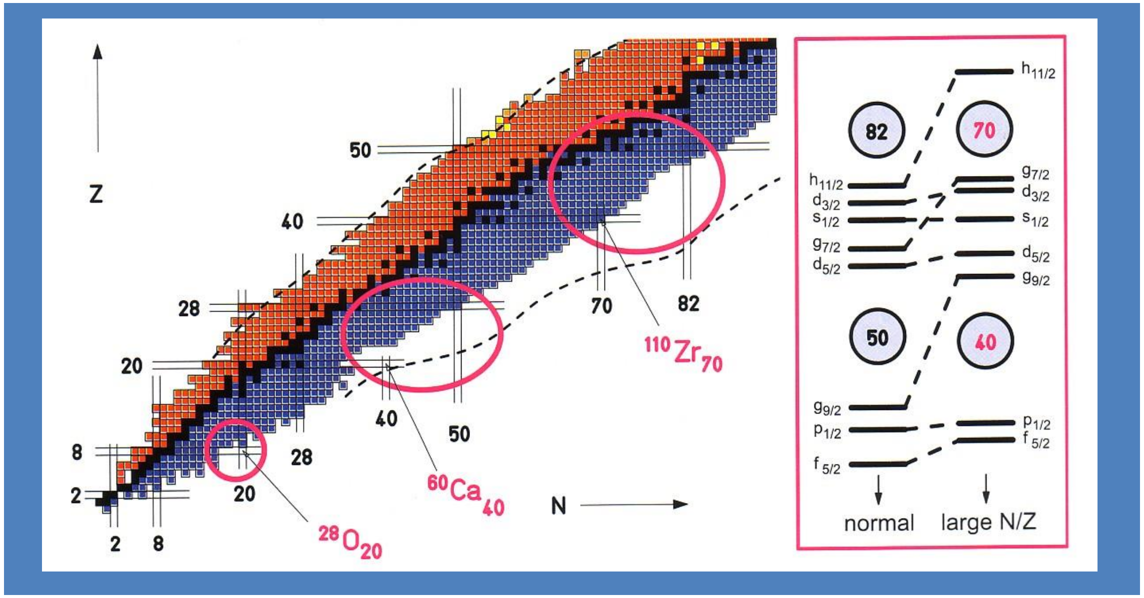
✓ β-decay gives first information of a new isotope.

✓ 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

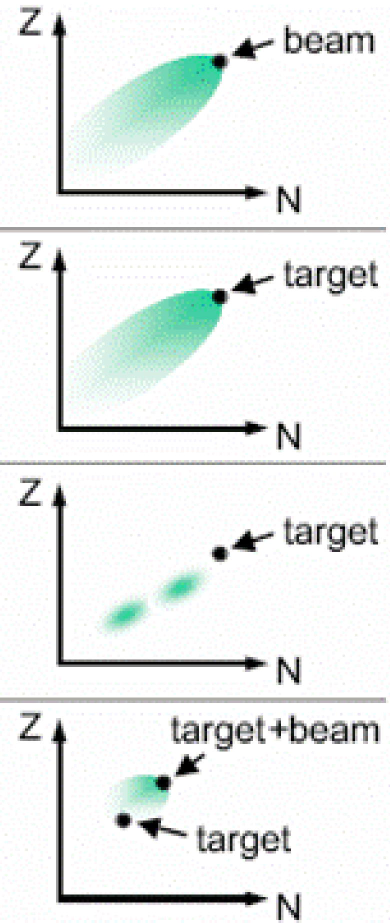
Extension of rare phenomena in the space of Z, N, J, Ex, superdeformation,

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

Production Methods

Beam → target → products		high energy >> *thermal energy*	many products
heavy ion + target	fragmentation	$v_{product} = v_{beam}$	up to 1000
p + target	spallation	few MeV/u	up to 1000
p/n + target	fission	~1 MeV/u	few 100
heavy ion + target	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

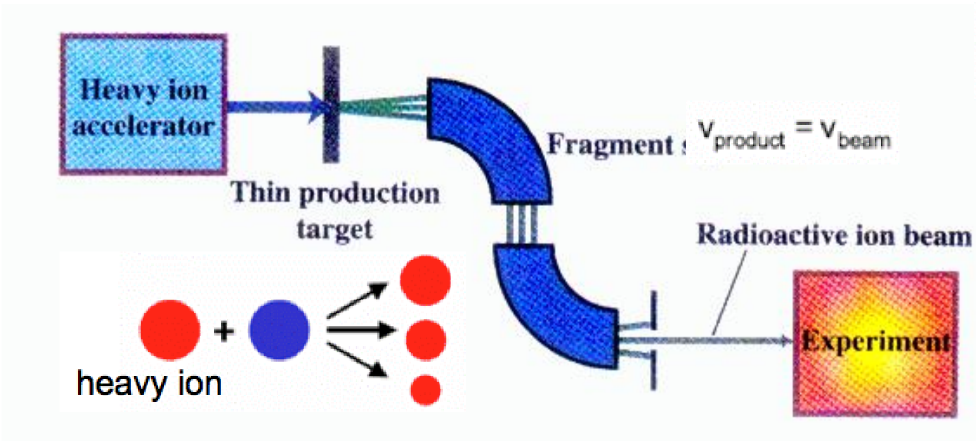
N-rich A~65 GSI , A~45 GANIL

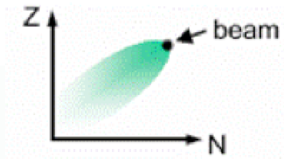
fission thermal ^{235}U, ^{239}Pu @ Grenoble ^{68}Fe, $^{71-74}$Ni, ^{79}Cu, $^{68-69}$Co

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

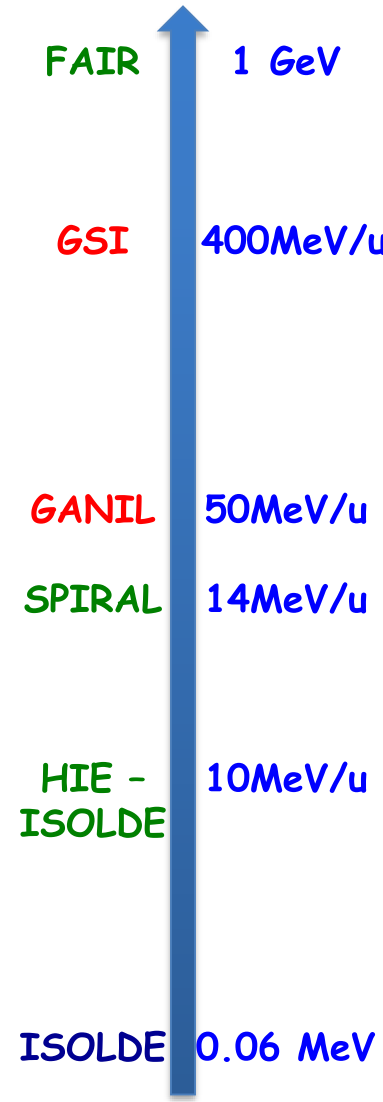
Production of Radioactive Beams

PROJECTILE FRAGMENTATION

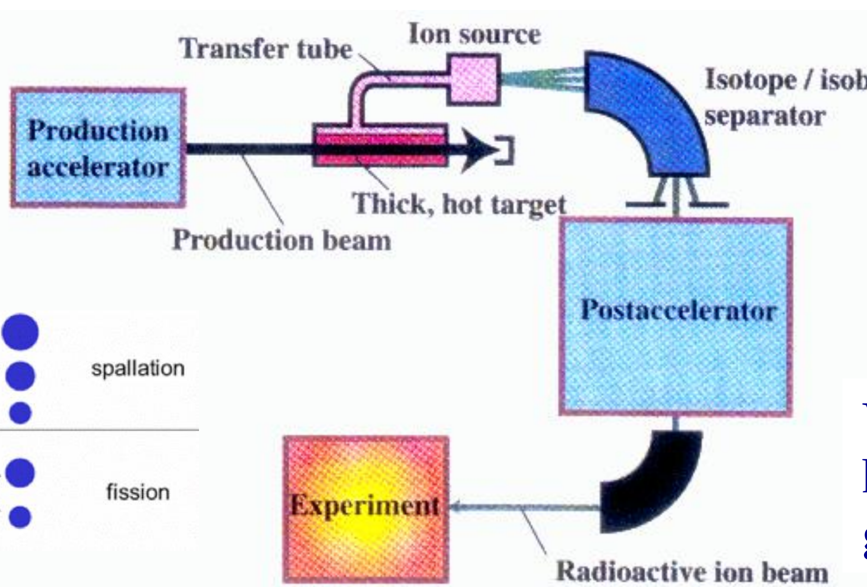


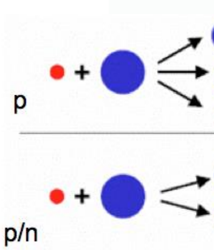


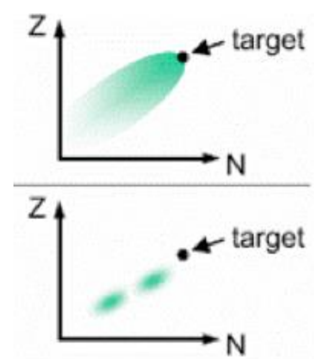
High energy,
large variety of species,
Short half-lives (μs),
cocktail beam



ISOL

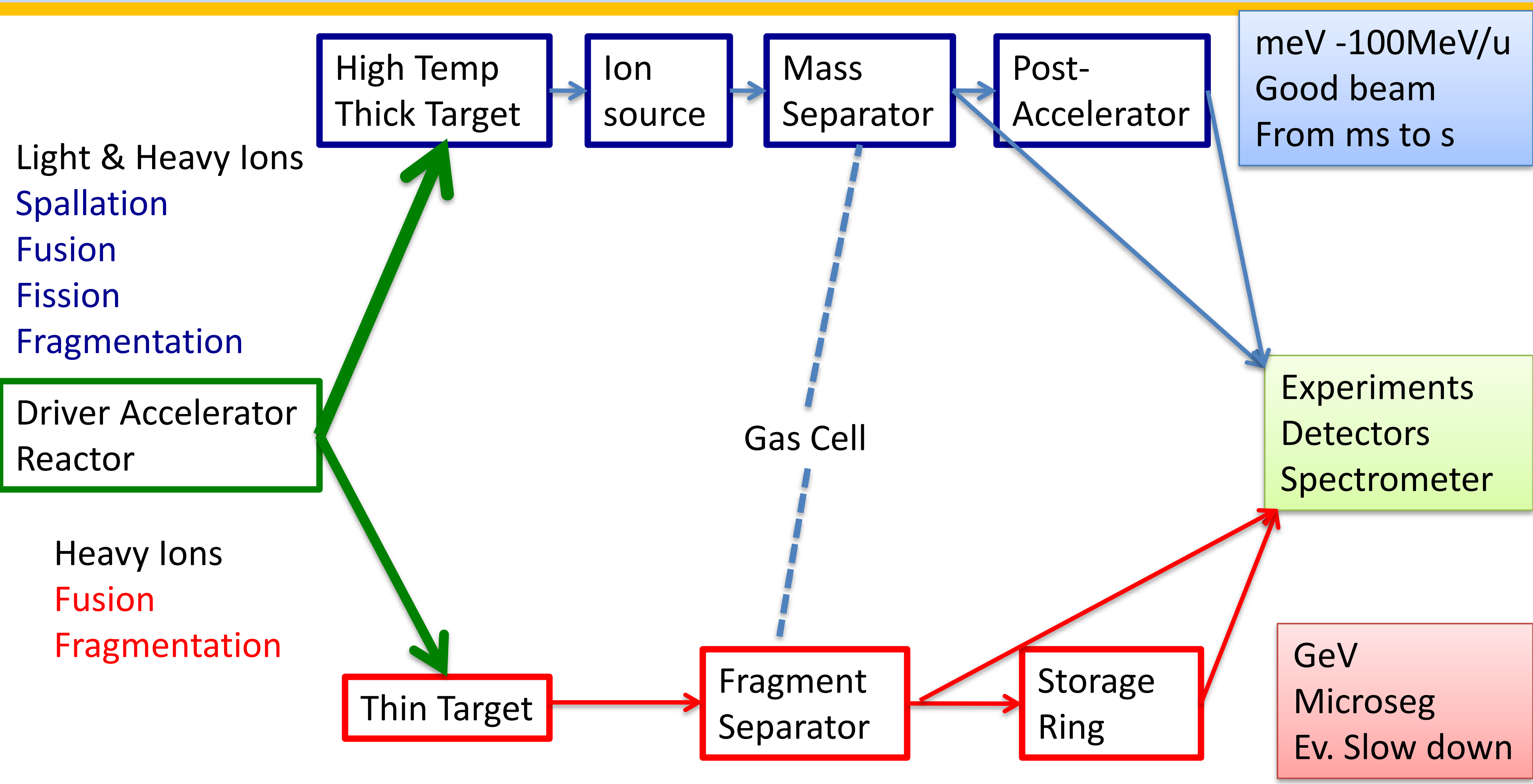






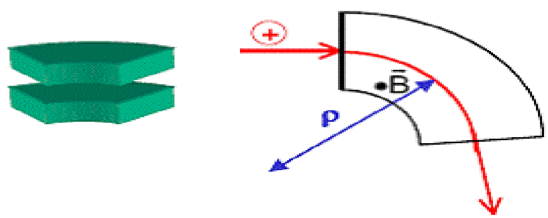
Variable energy,
high intensity,
good beam qualities

Production Methods



Separation at High Energy

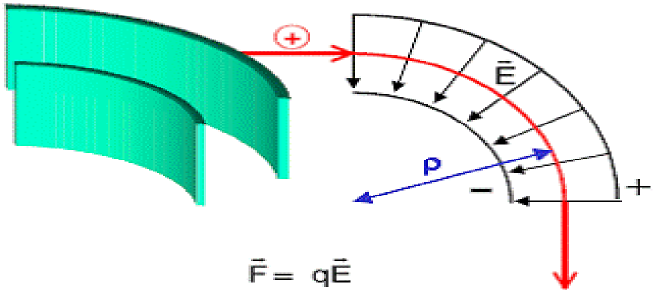
magnetic dipole



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

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

electric dipole



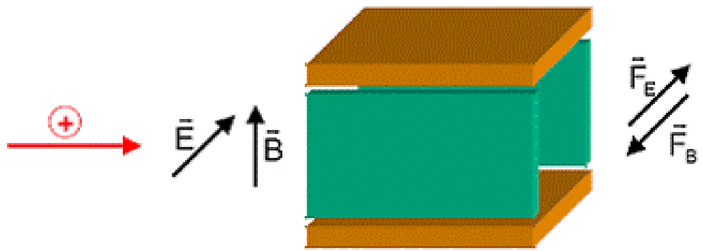
$\vec{F} = q\vec{E}$

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

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

velocity filter

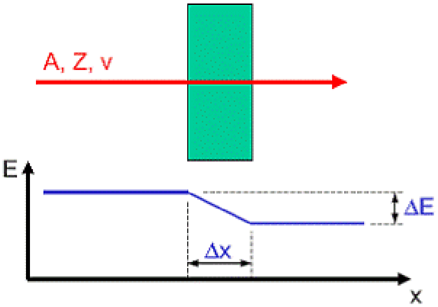
Wien filter, E-cross-B filter



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

Need Wien-vel-Filter to separate in velocity

Energy degrader



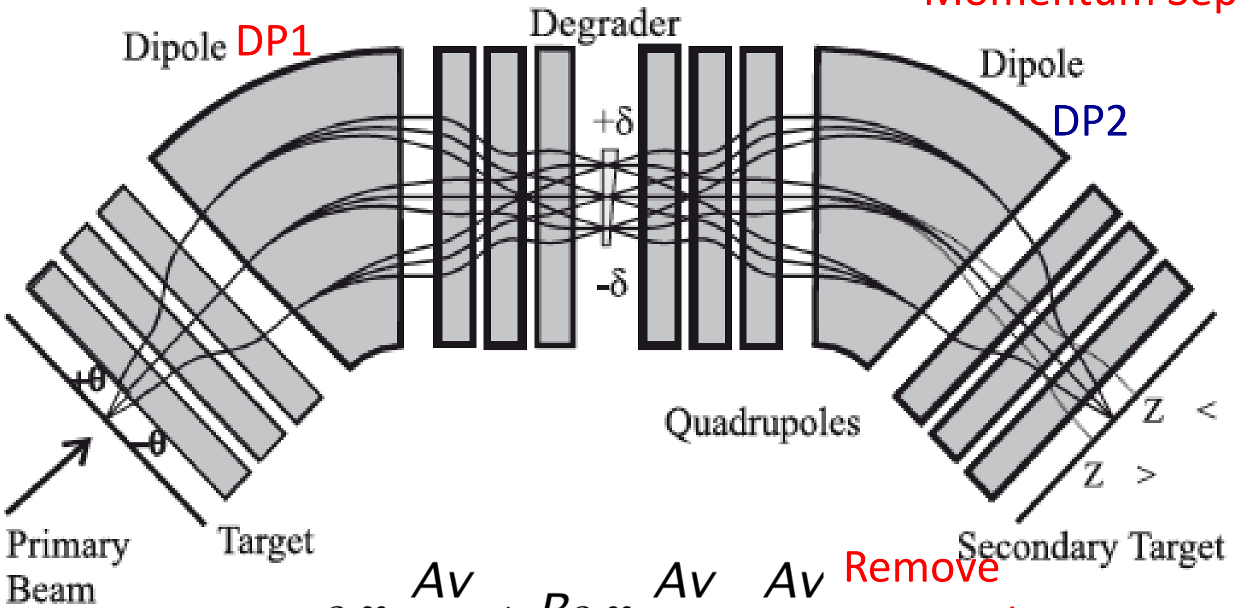
stopping power $S \equiv -\frac{dE}{dx} \propto \frac{Z^2}{v^2} \propto \frac{A Z^2}{E}$

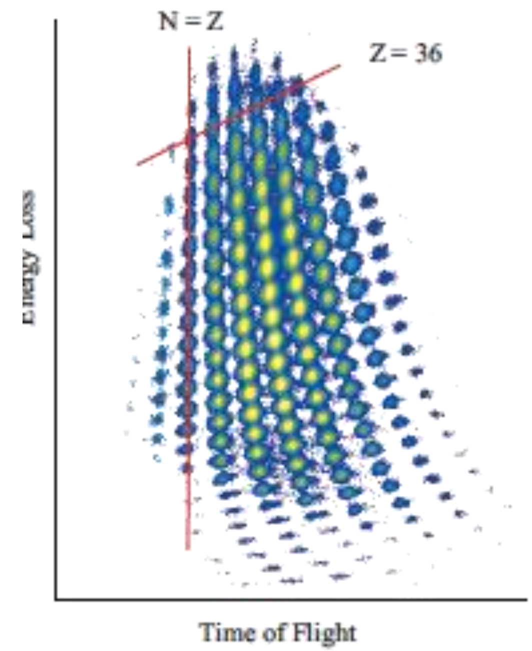
→ straggling (spread) in energy and angle

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 $10^{12} \rightarrow 10^{8}$

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 $\mu\ Z^2$

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

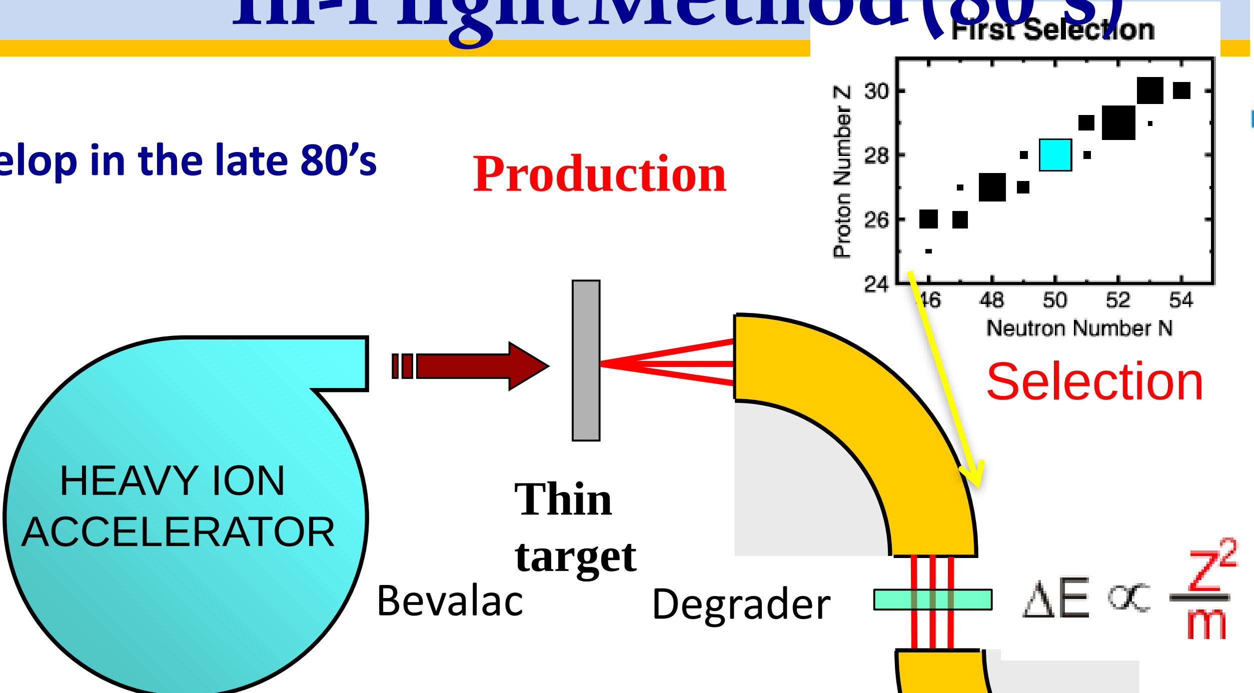
extended detection scheme
& better resolution

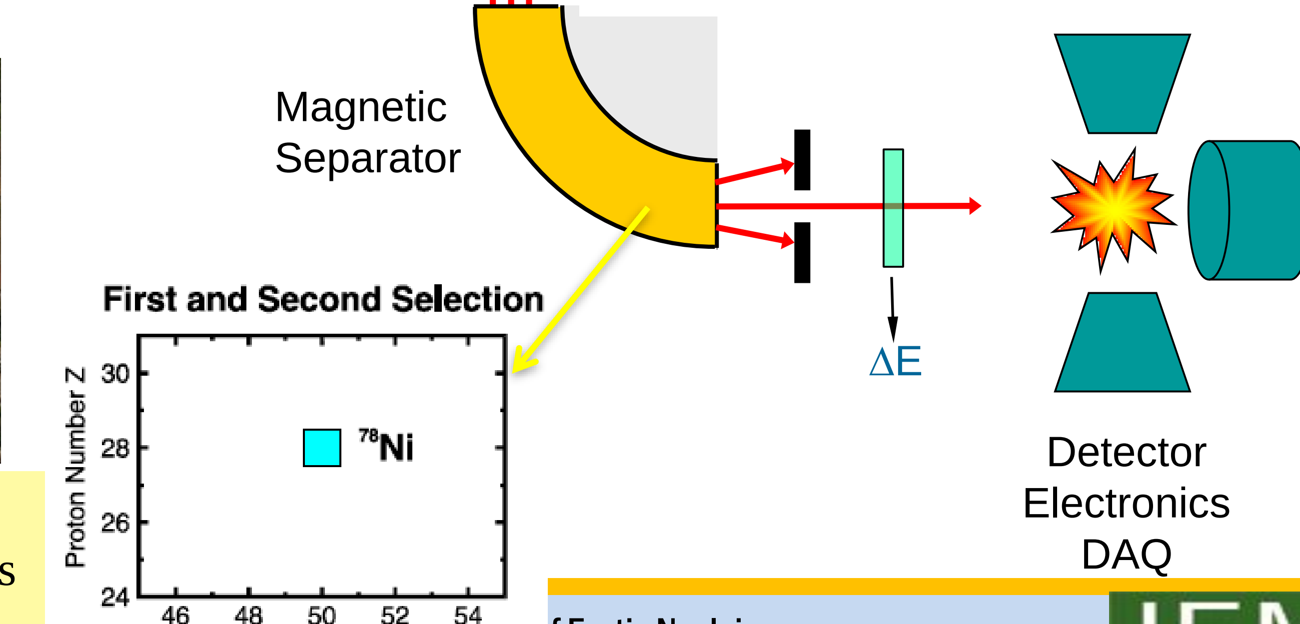
Full-acceptance measurements
with moderate sized detectors

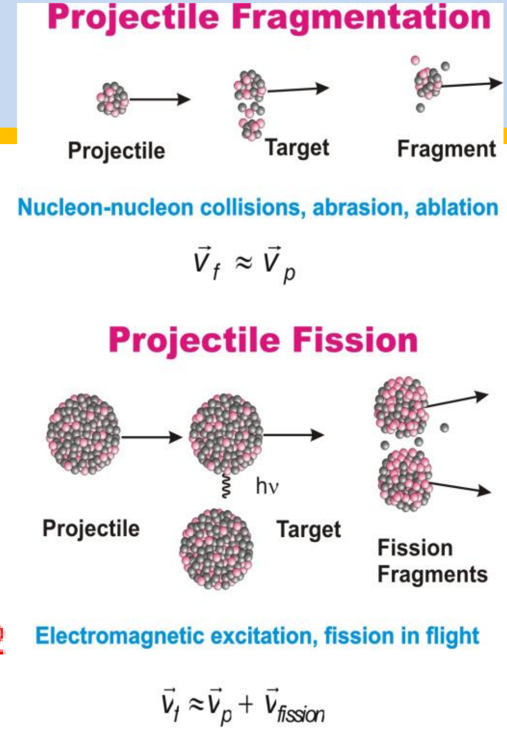
Possible study more exotic nuclei
efficient down to 1 ion/s, short lived

In-Flight Method (80's)

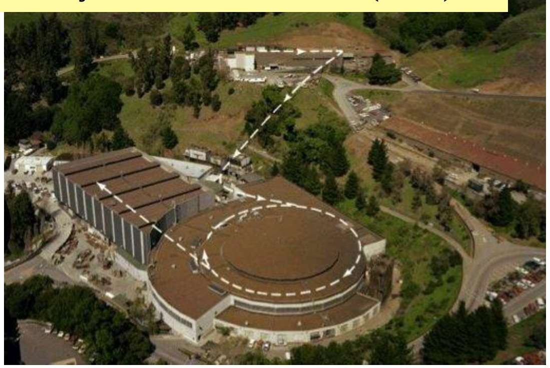
Develop in the late 80's







Phys.Rev. Lett. **43**, 1859 (1979).



Particle stability of 15 earlier unobserved nuclides from ^{22}N to $^{44,45}Cl$

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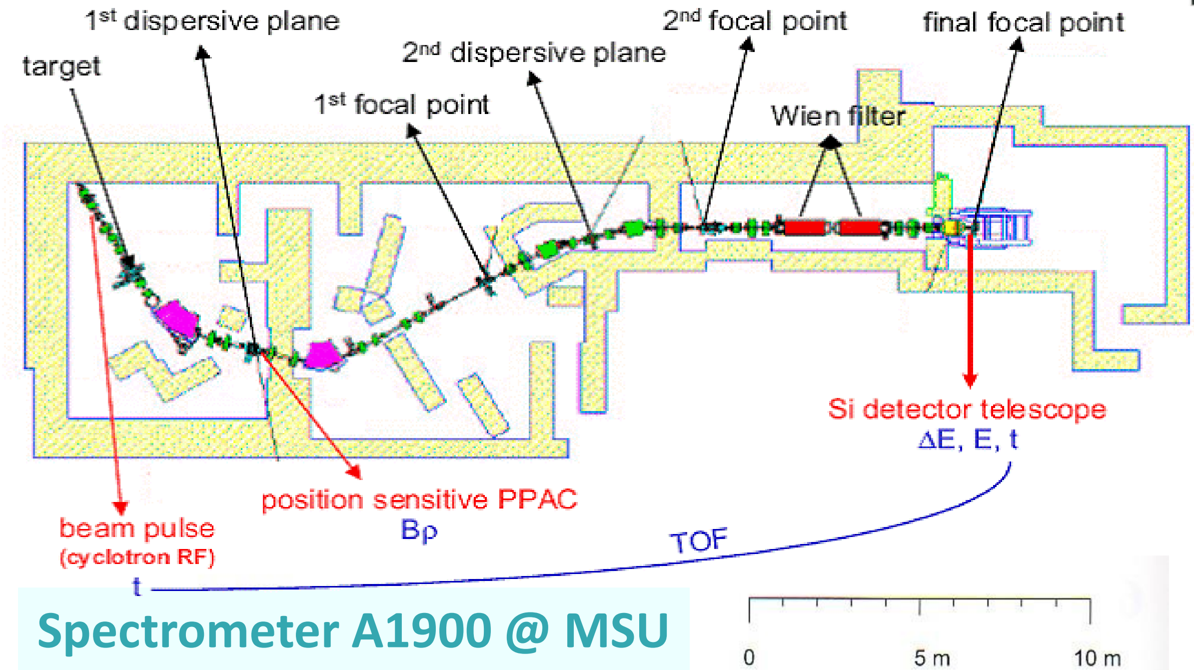
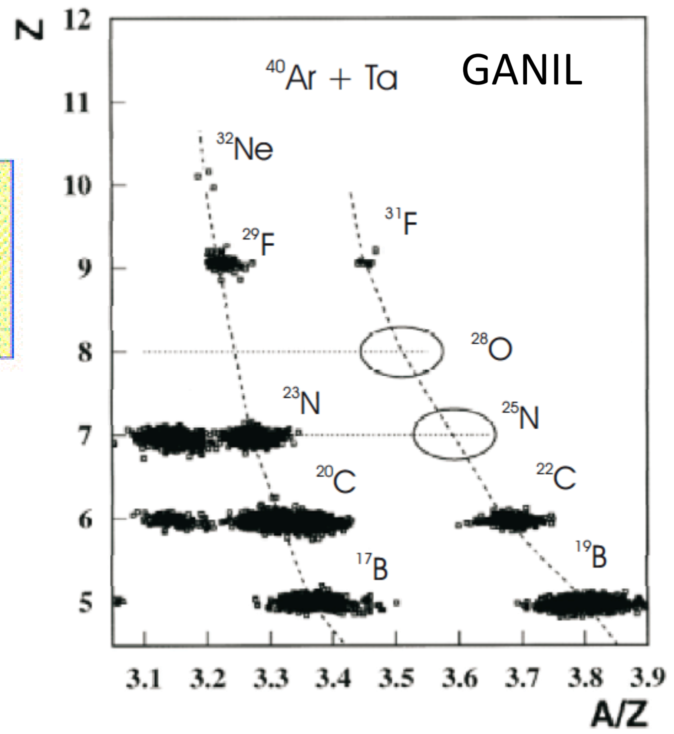
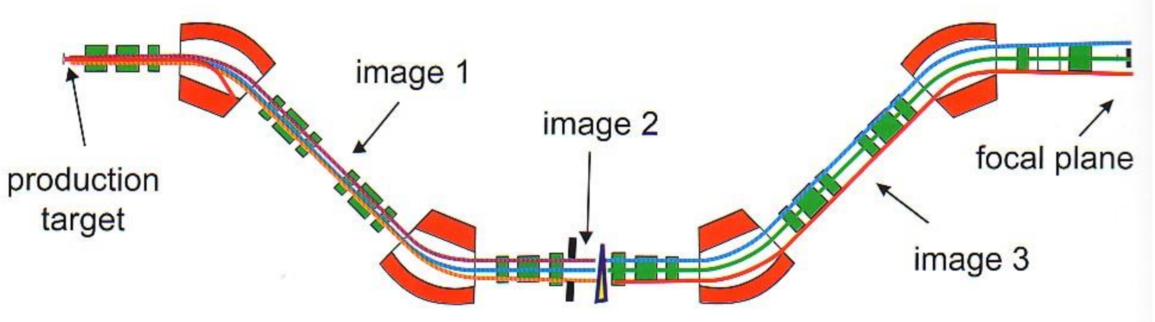
Different Spectrometer

Spectrometer LISE @ GANIL

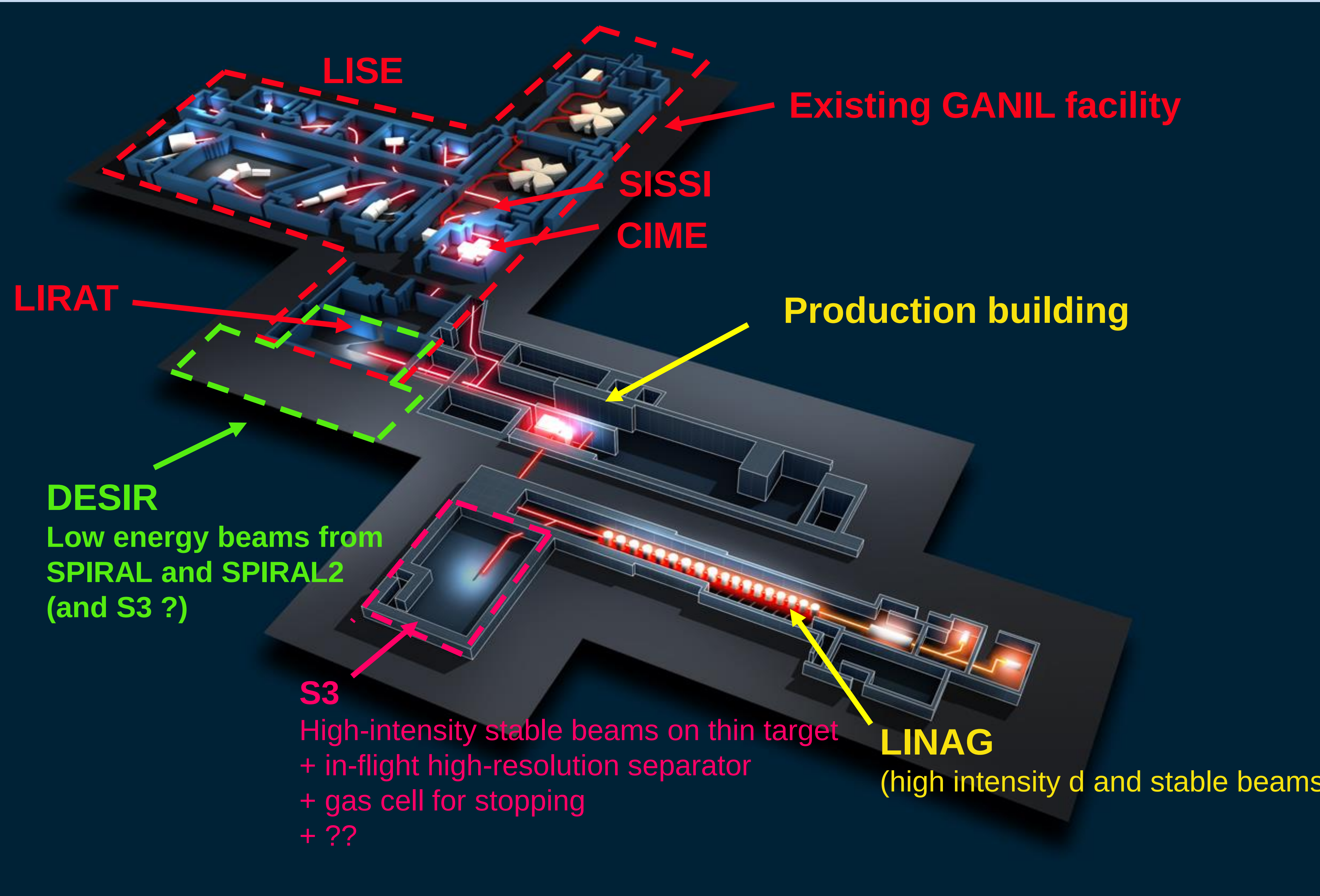




Spectrometer A1900 @ MSU

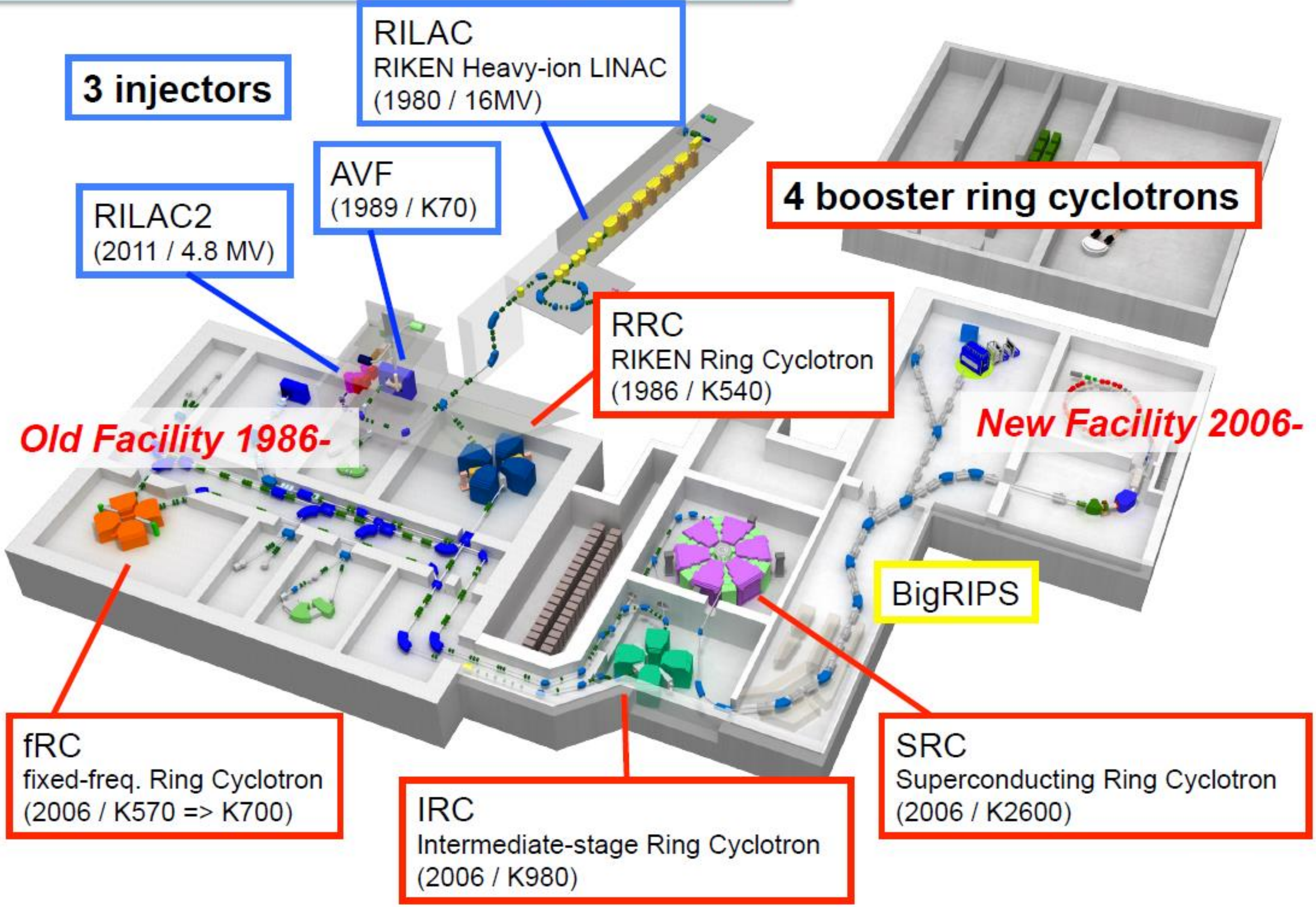


GANIL / SPIRAL 2



RIKEN RI Beam Factory (RIBF)

Y. Yano, NIM B261 (2007) 1009.

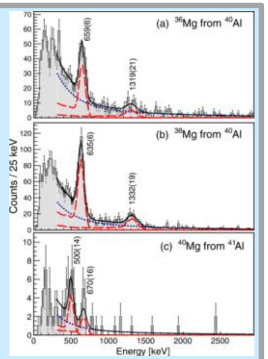


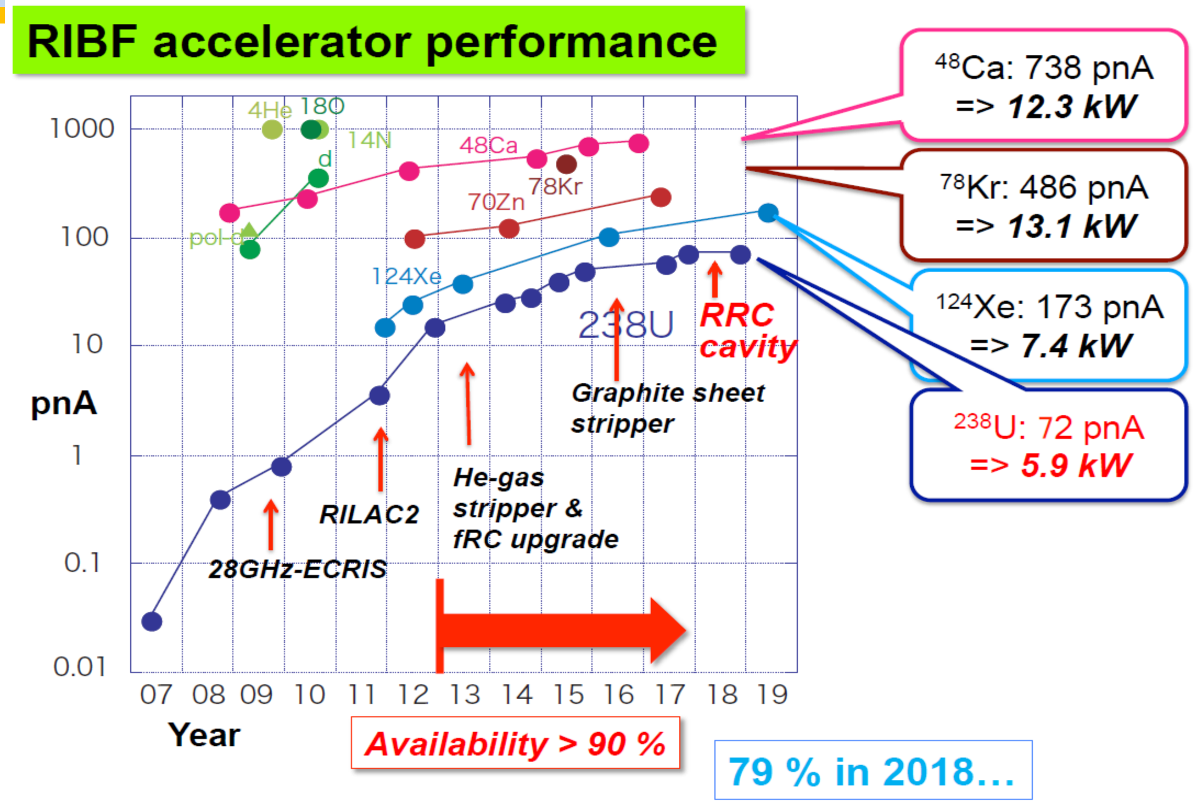
Steady increase of Beam Current @ RIKEN (i...)

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

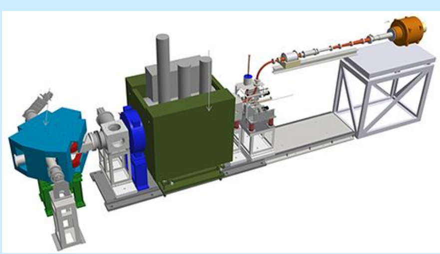
The origin is a mystery.

No theory can reproduces the data.

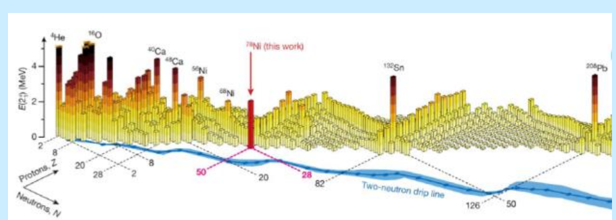




Quest for heavier super-heavies (Z=113)
Success in producing and accelerating high intensity vanadium beam
- Cleared the way for producing element 119 – (2017)

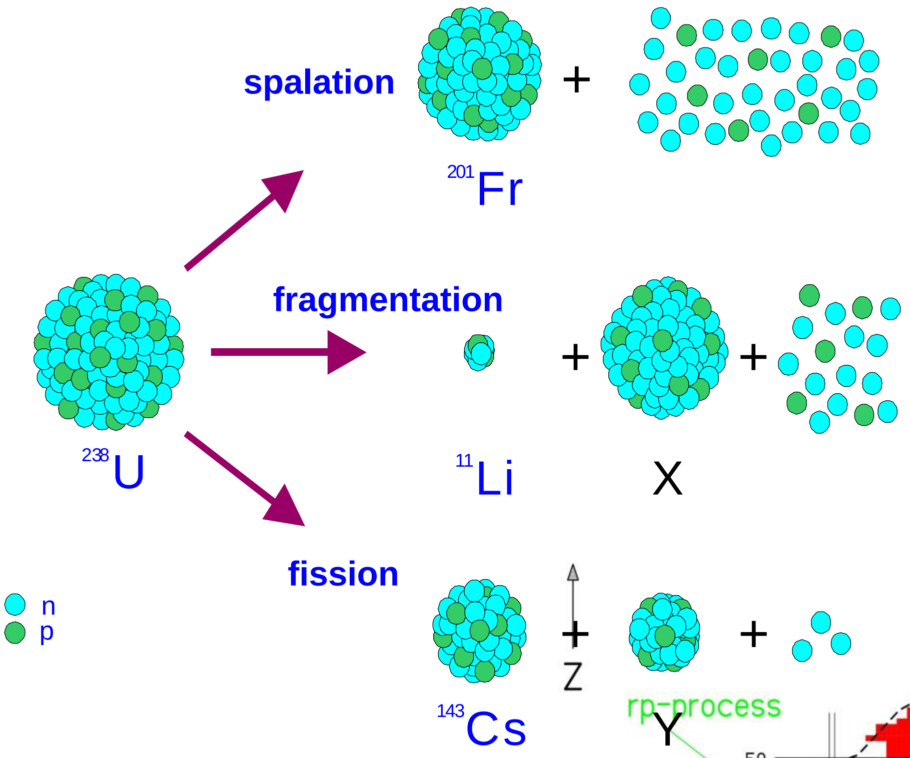


^{78}Ni (N=50) revealed as a doubly magic stronghold against nuclear deformation.
Taniuchi et al., Nature 569, 53 (2019)

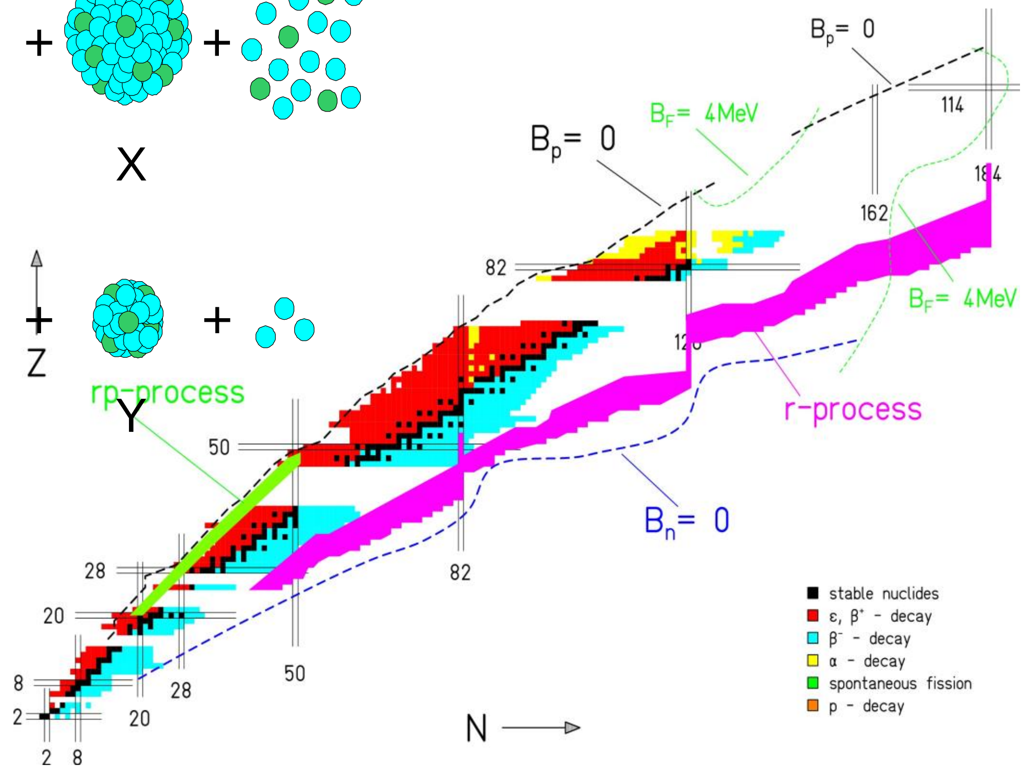


73 new isotopes discovered at RIKEN's RI Beam Factory (2017)

Isotope production



Nuclei chart @ ISOLDE

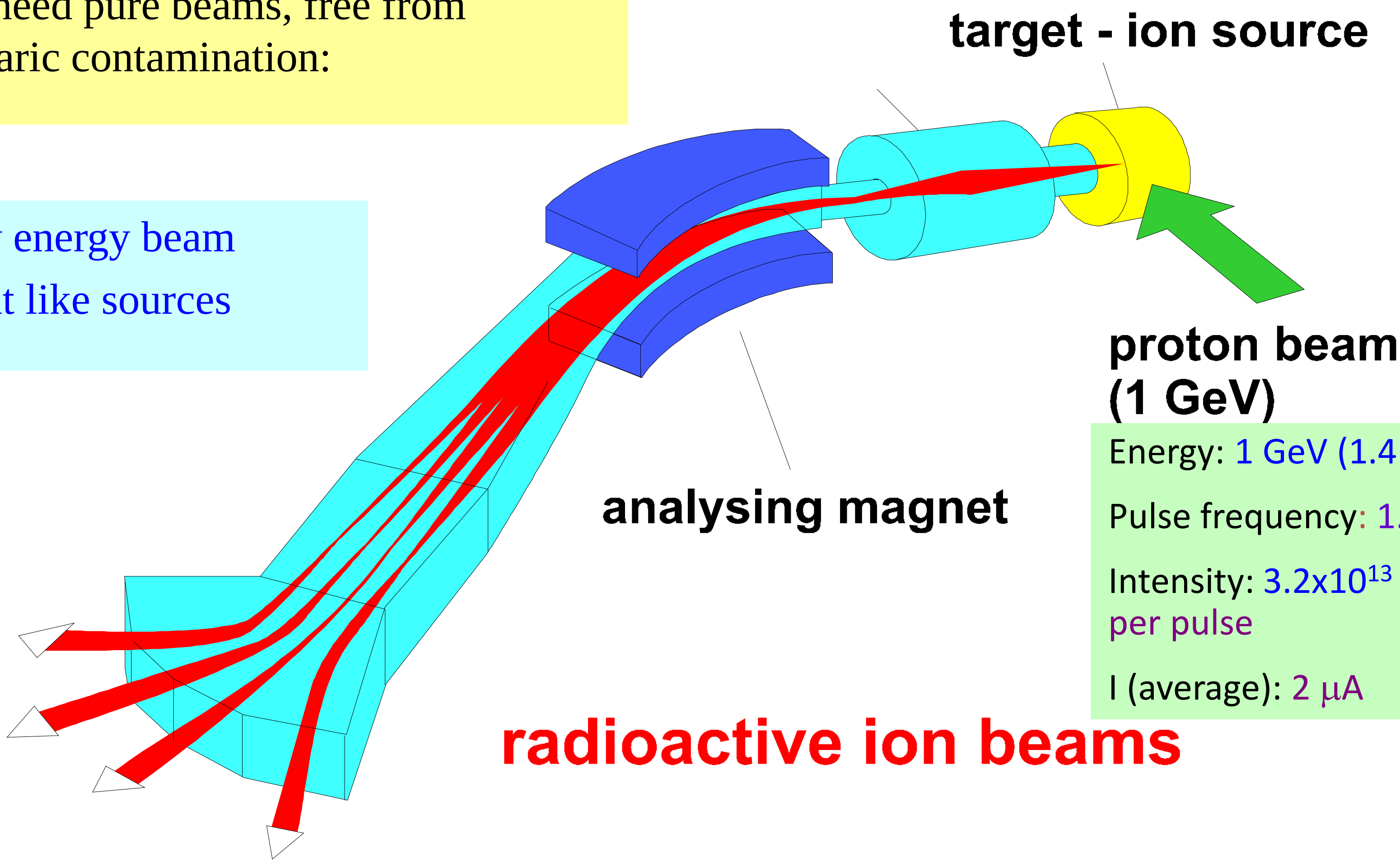


Exotic ion production

We need pure beams, free from isobaric contamination:

Low energy beam

Point like sources



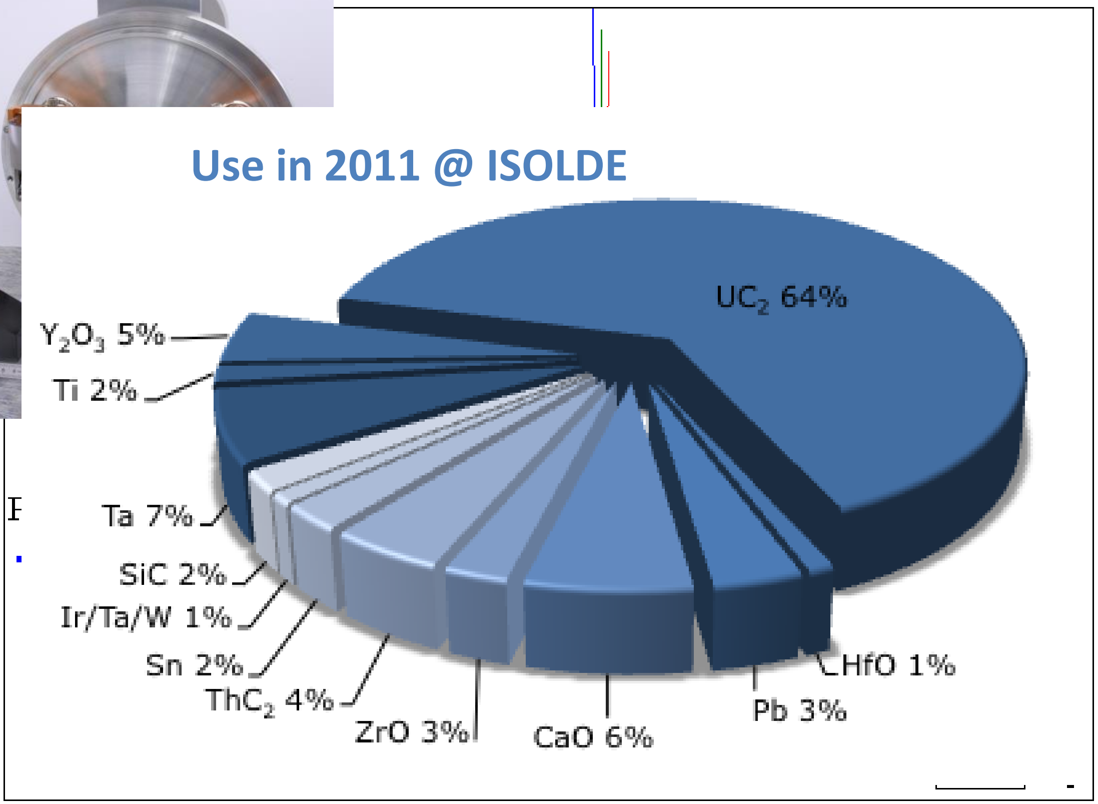
Energy: 1 GeV (1.4 GeV)

Pulse frequency: 1.2 s

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

I (average): 2 μA

Target – Ion-source matrix: a chemical laboratory

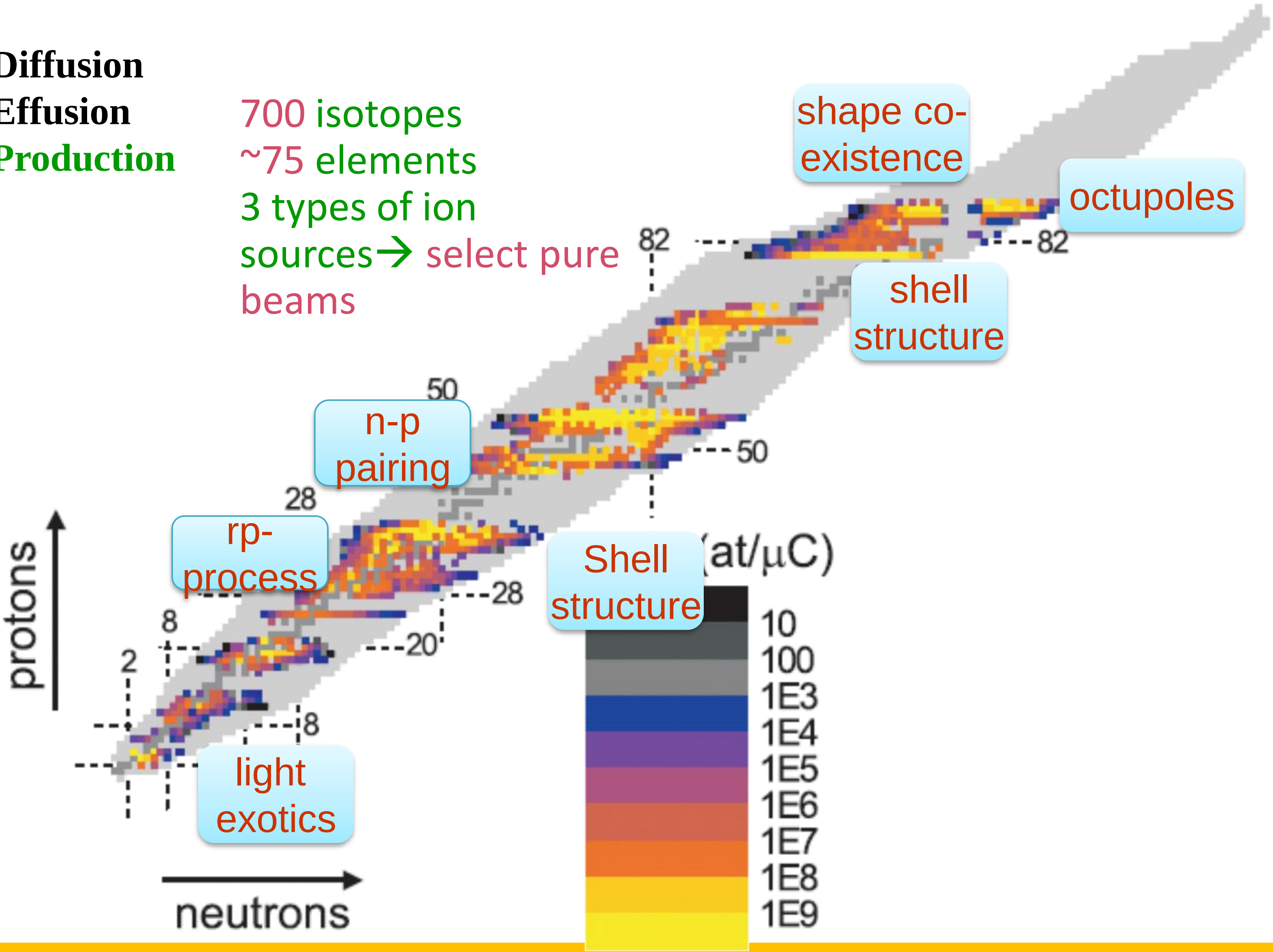


- **Container: 20 x 2 cm cylinder of Ta**
- **Material:**
  - **Liquid** **La, Pb, Sn**
  - **Metal foil/powder** **Nb, Ti,**
  - **Oxides** **CaO, MgO**
  - **Carbides** **SiC, UC, ThC**
- **Ion-source**
  - **Surface**
  - **Plasma**
  - **Laser**
- **Fluorination** **CF4 or SF6**

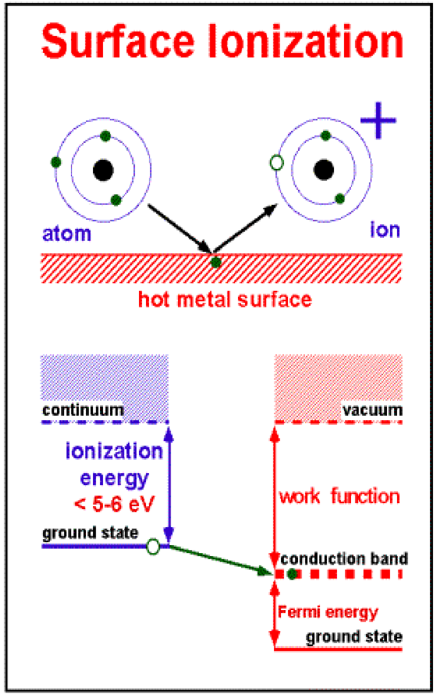
ISOLDE Main potential

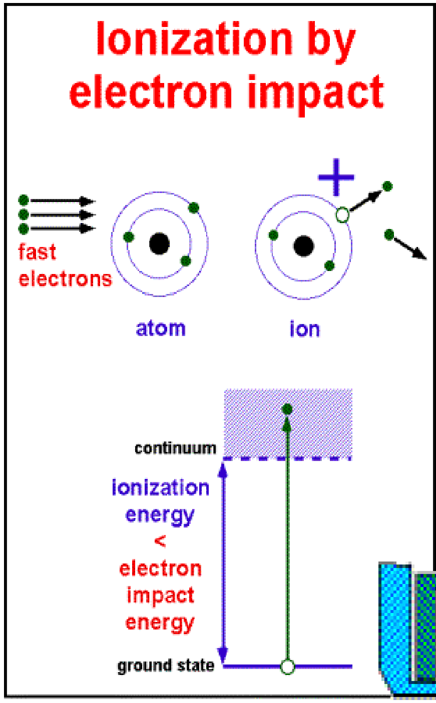
- **Diffusion**
- **Effusion**
- **Production**

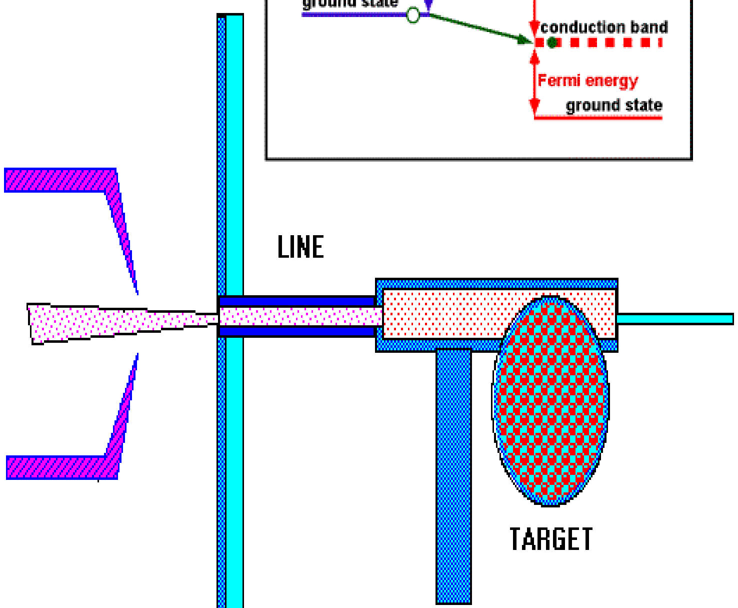
700 isotopes
~75 elements
3 types of ion sources→ select pure beams

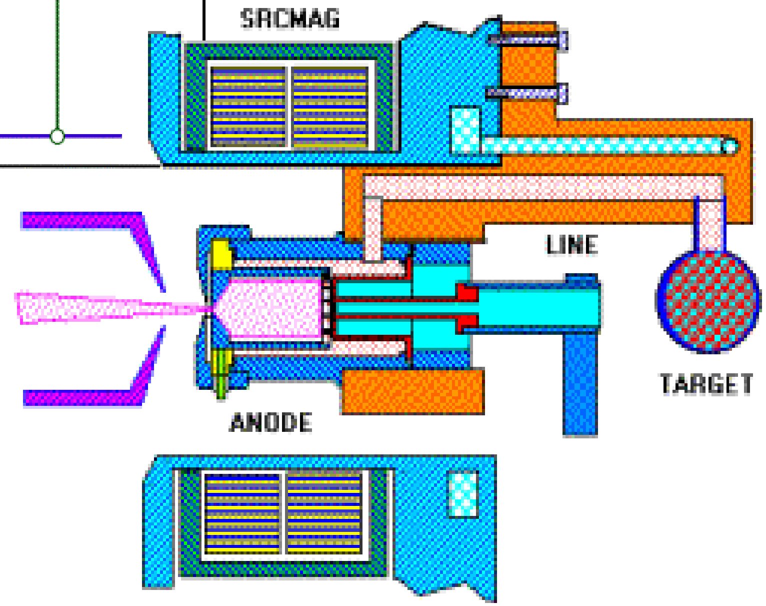


Surface & plasma ionization

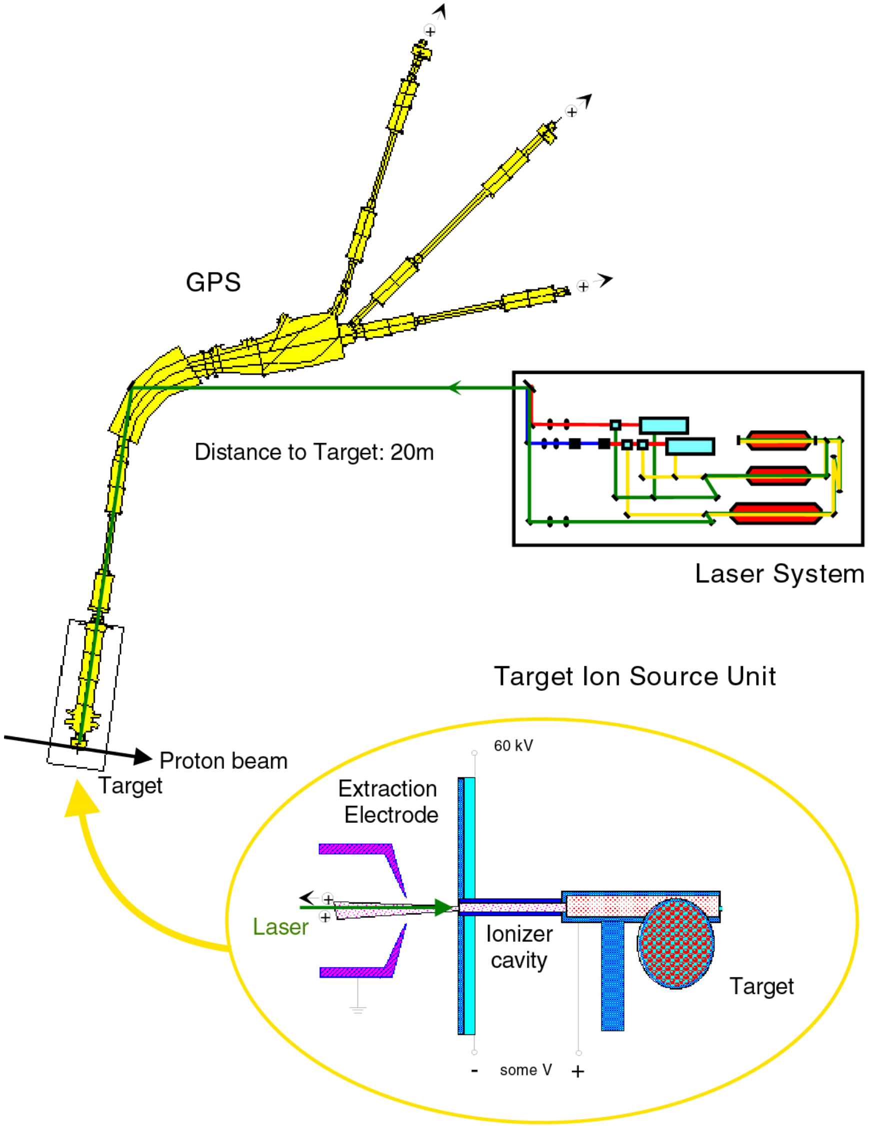


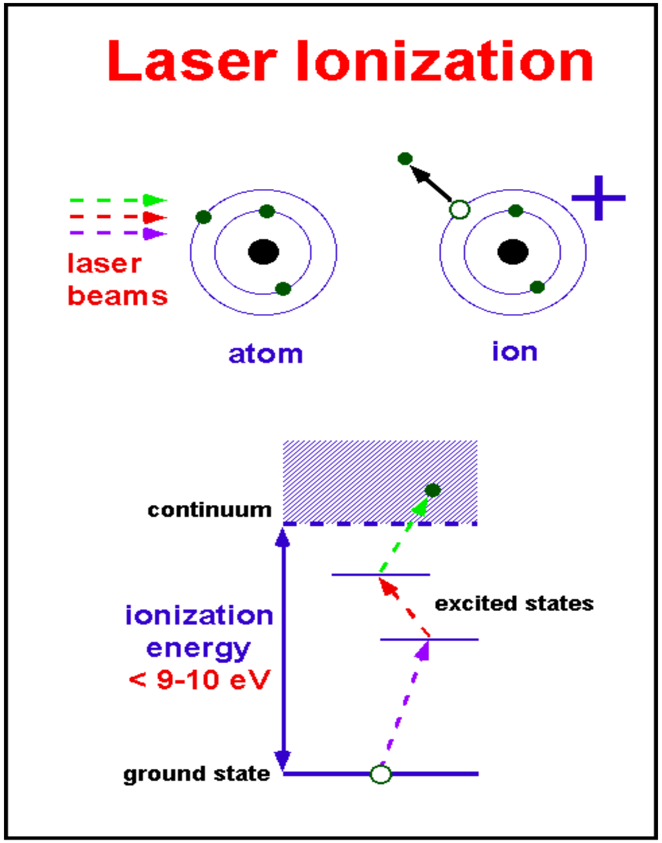






Laser Ionization source



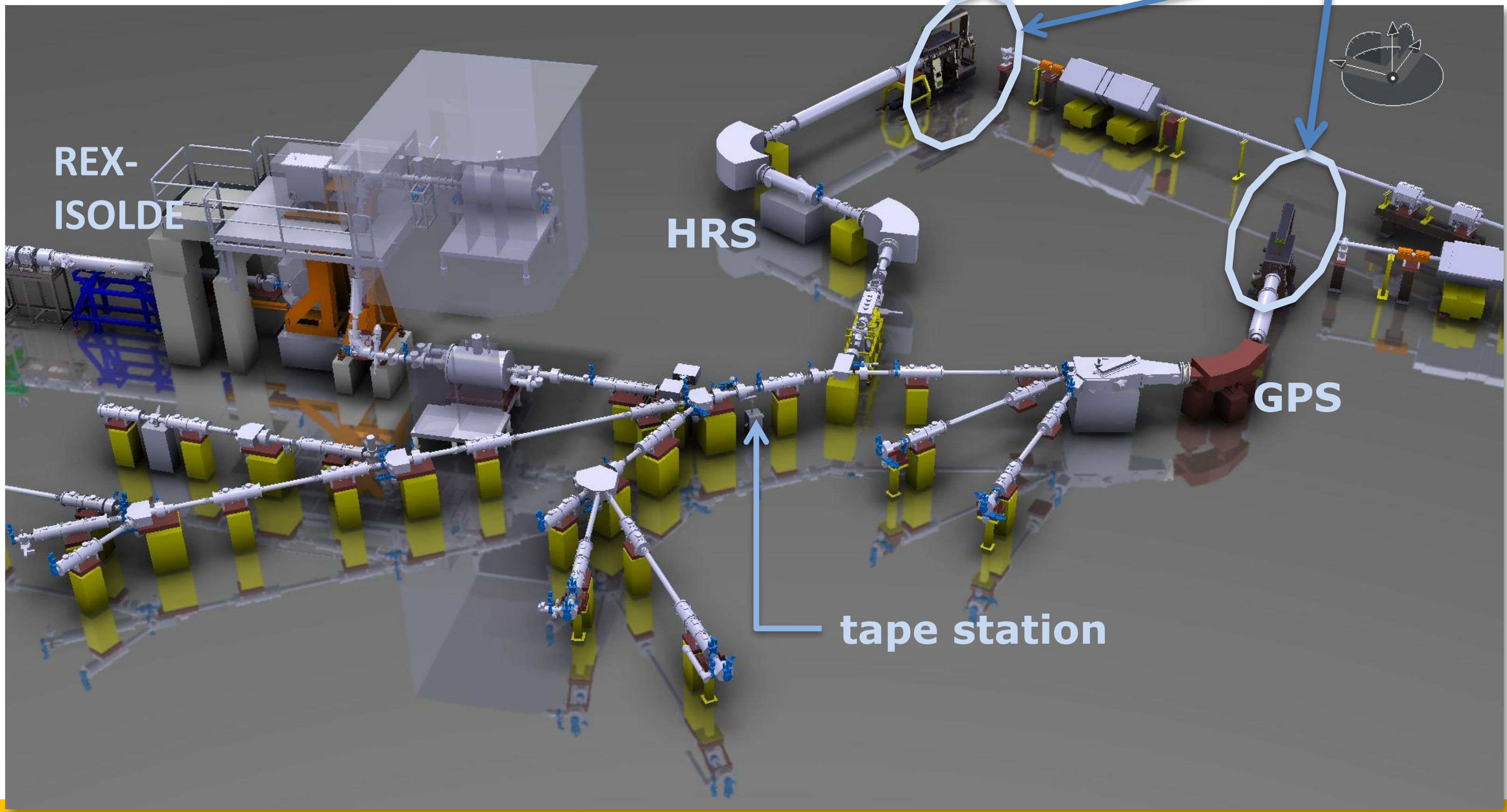


Separation @ ISOL

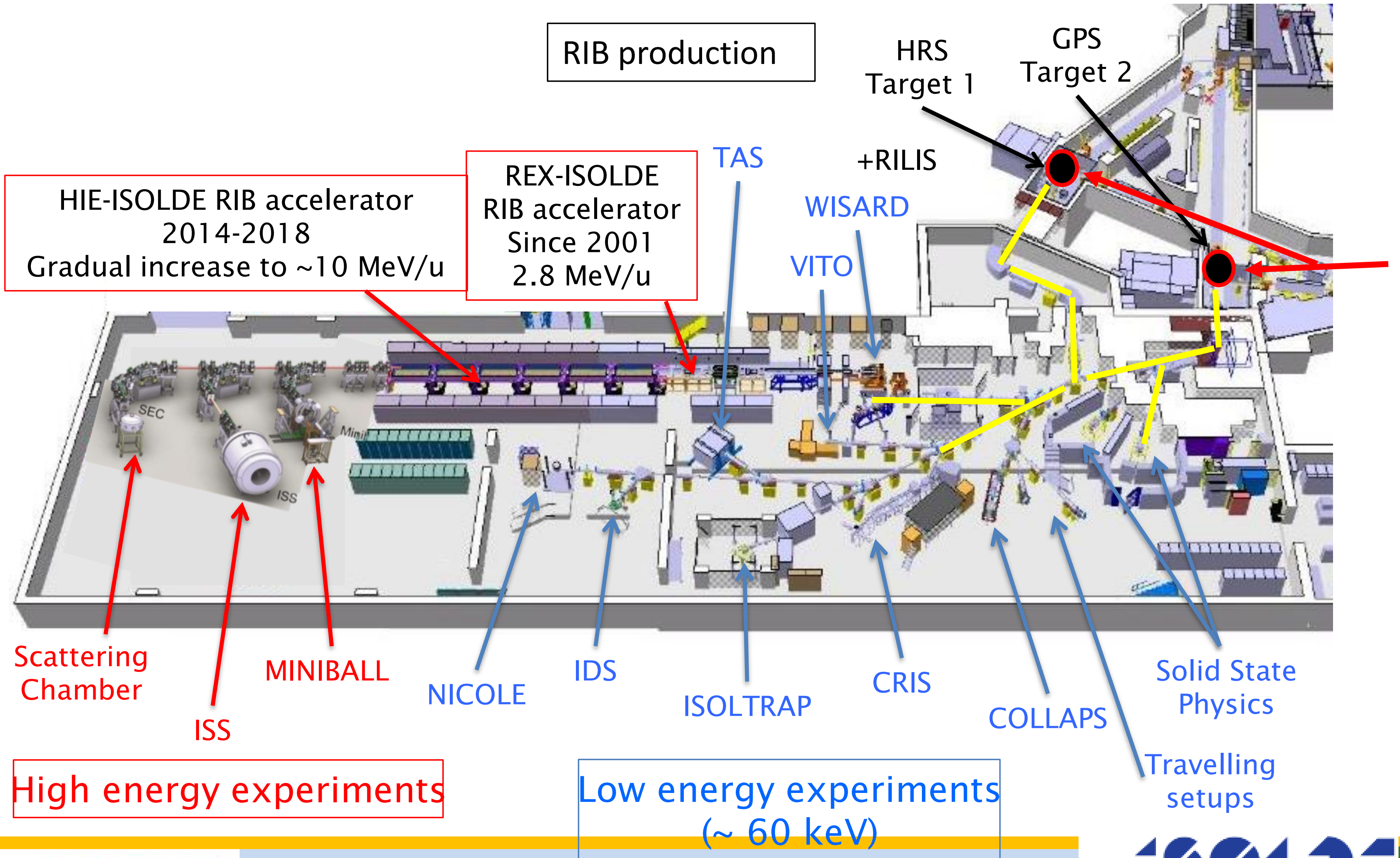
The produced ions must leave the target:
- Recoil Energy (fast)
- Diffusion (slow)

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

Target + Ion Unit



The ISOLDE facility and set-ups



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 & Seper-heavy nuclei

E < 100 MeV/u → Nuclear Matter

Some reactions :

fusion – evaporation, $^{14}O + ^{40}Ca$, $^{30}S + ^{40}Ca$, $^{64}Ge + ^{40}Ca$...

Super heavy $^{248}Cm(^{20}O,4n)^{264}Rf$ ...

Coulomb Excitation, **Neutron rich Nuclei**

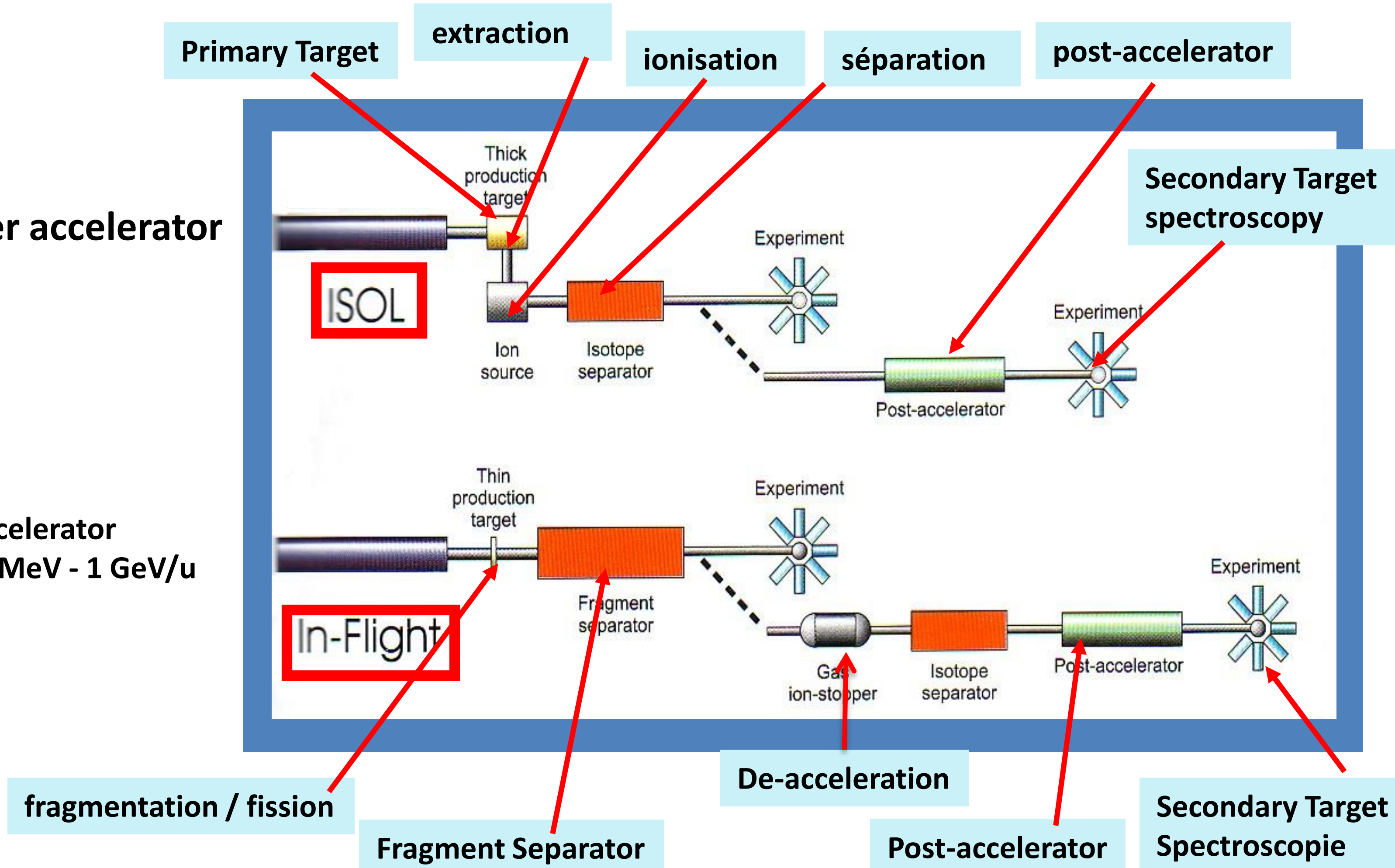
transfert, **of 1 or several nucleons for neutron rich nuclei**

Astrophysics $H(^{19}Ne, ^{20}Ne)\gamma$ $^{4}He(^{15}O, ^{19}Ne)\gamma$ ...

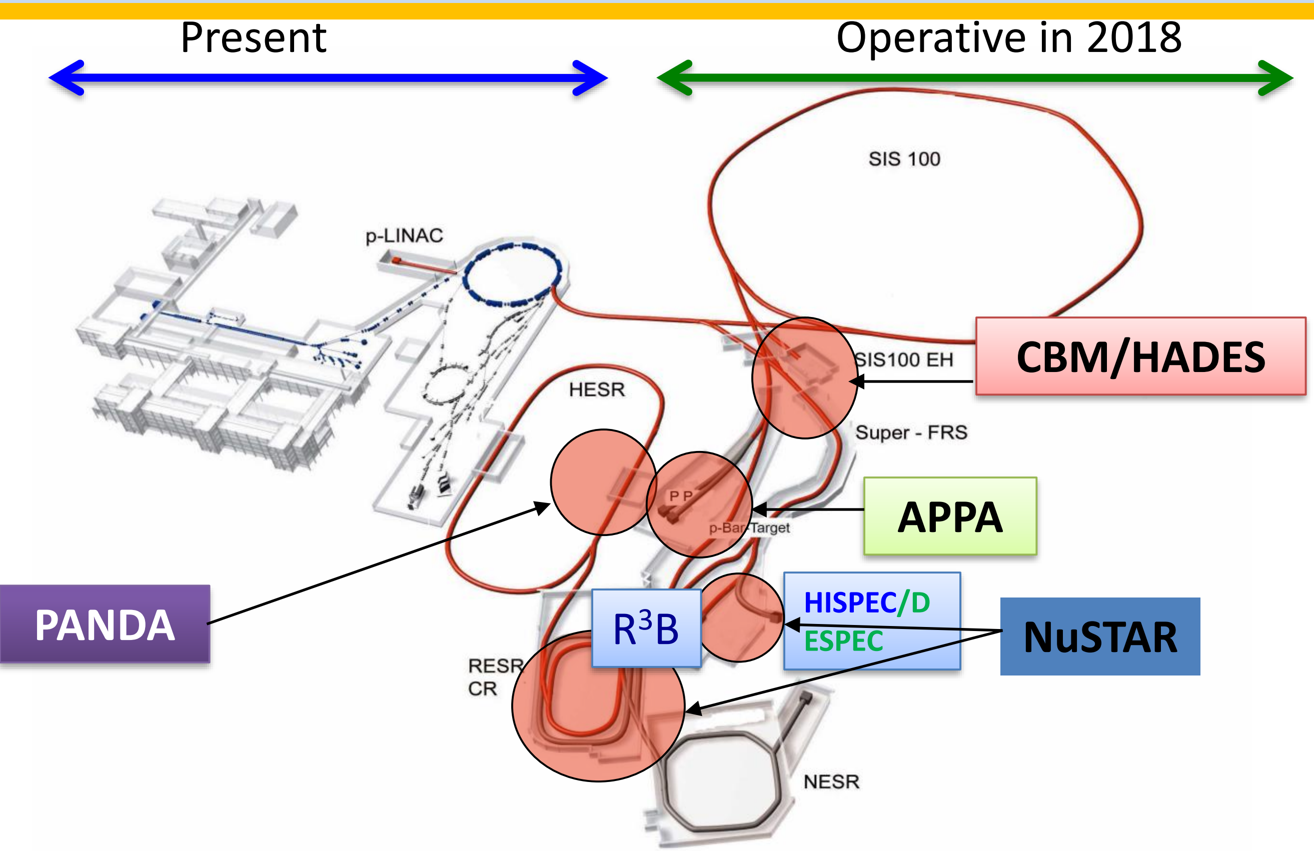
Summary: Two production Methods

driver accelerator

driver accelerator
ions 100 MeV - 1 GeV/u



Fair : Facility of Antiprotons and Ion Research



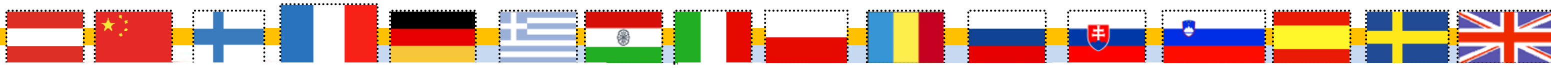
All the Spanish experimental groups participate in the project

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



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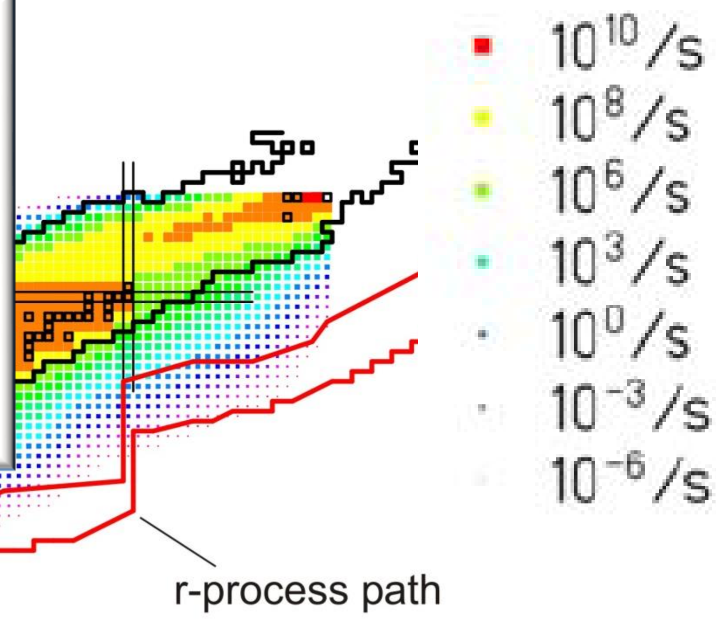
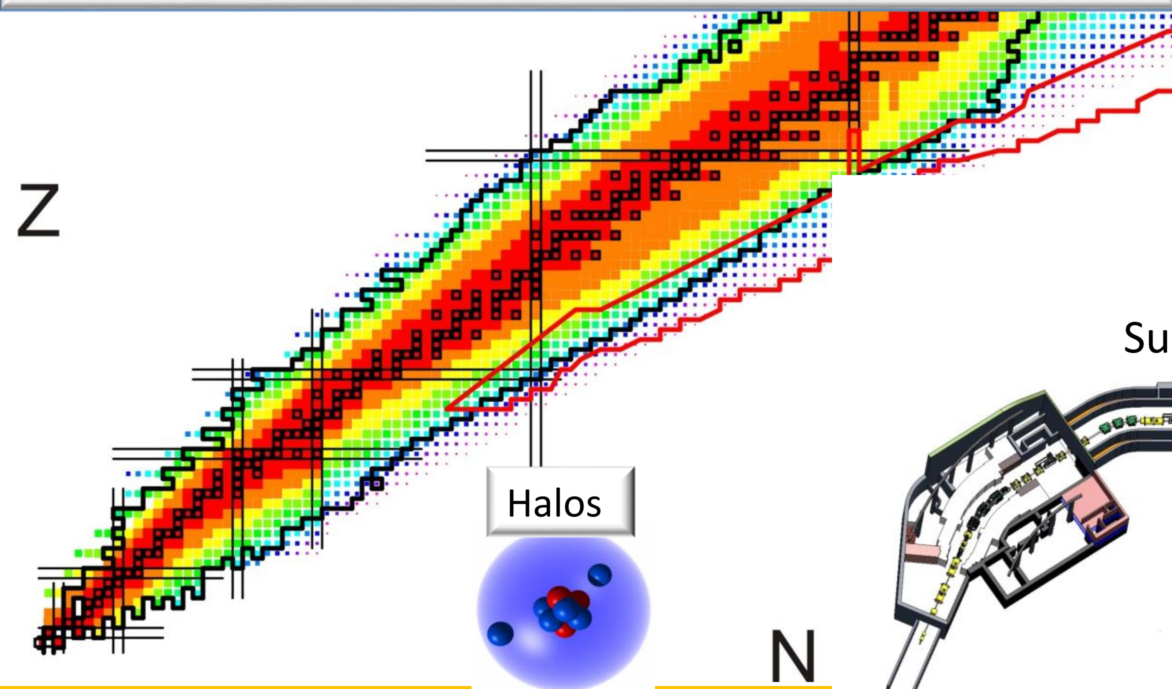
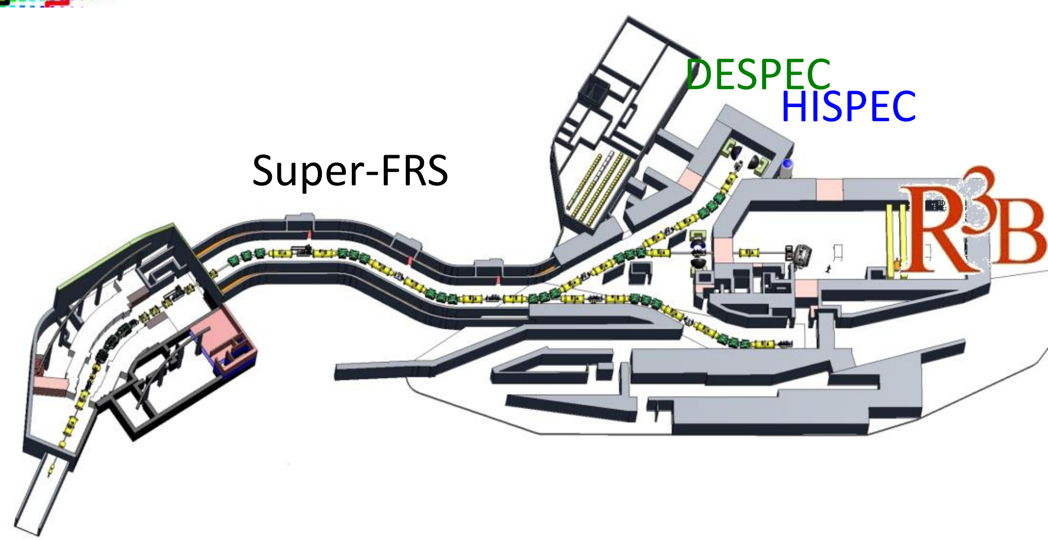
Central Topics for NuSTAR at FAIR

- 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

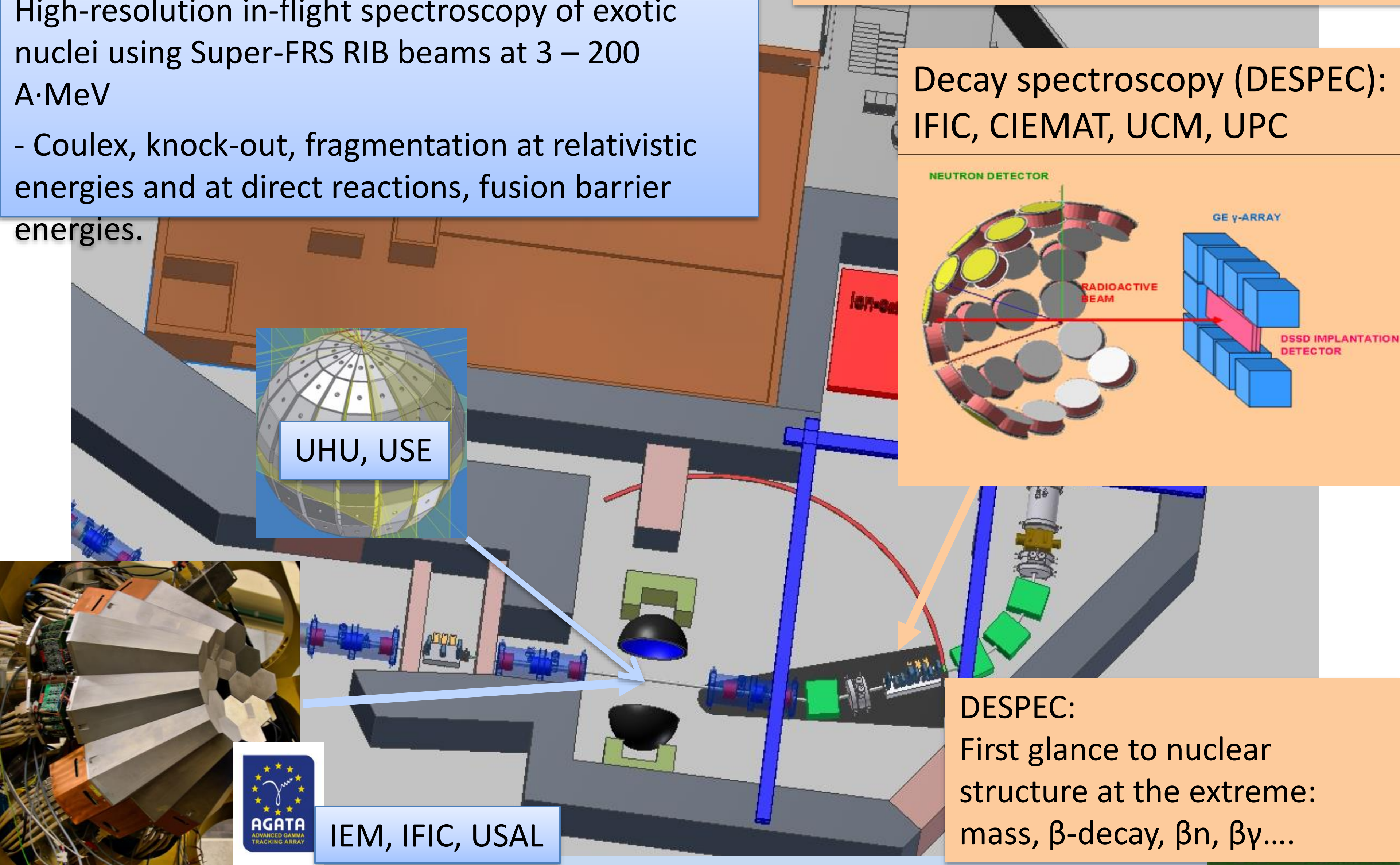
HISPEC:

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

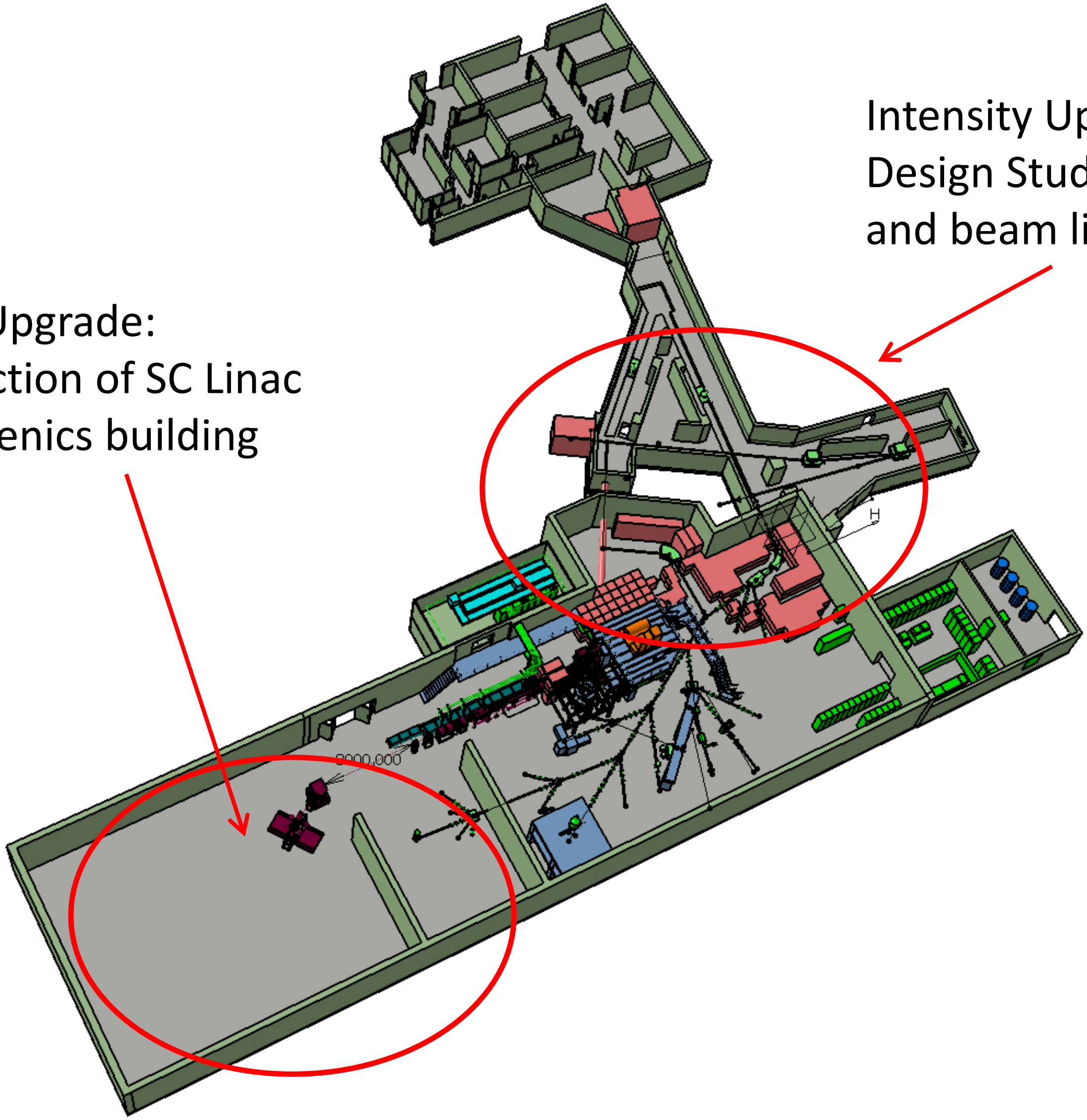
IEM, IFIC, USAL

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

The HIE-ISOLDE Project

Intensity Upgrade:
Design Study of target Area
and beam lines

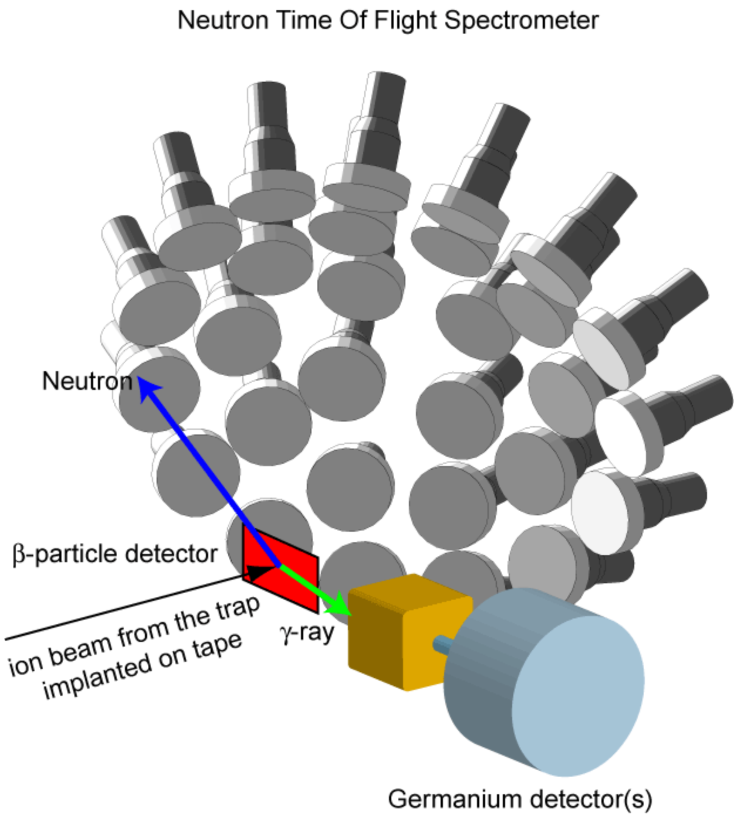
Energy Upgrade:
Construction of SC Linac
& cryogenics building

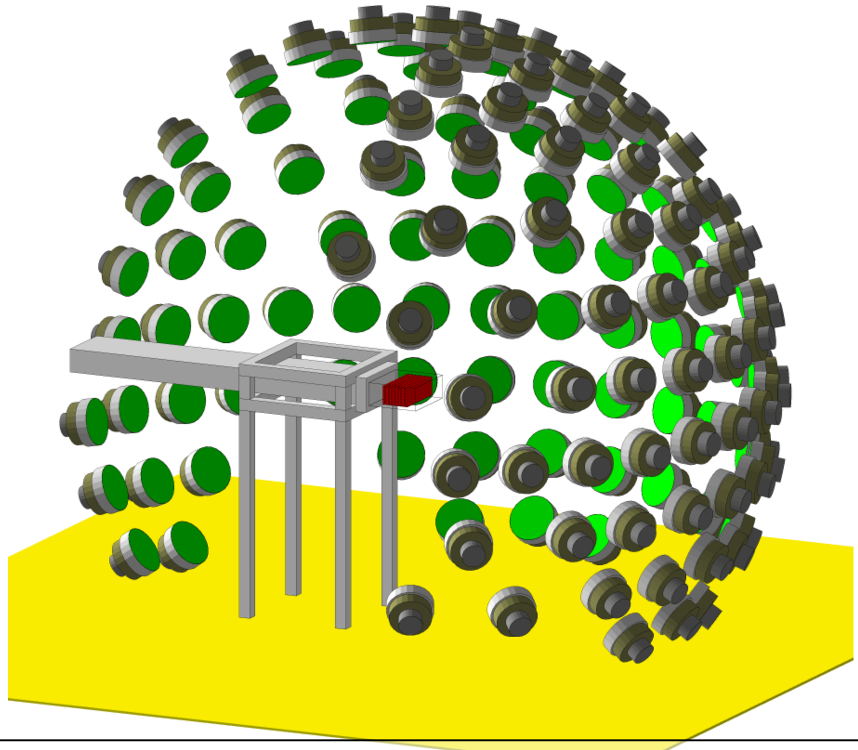


The neutron detectors for DESPEC

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

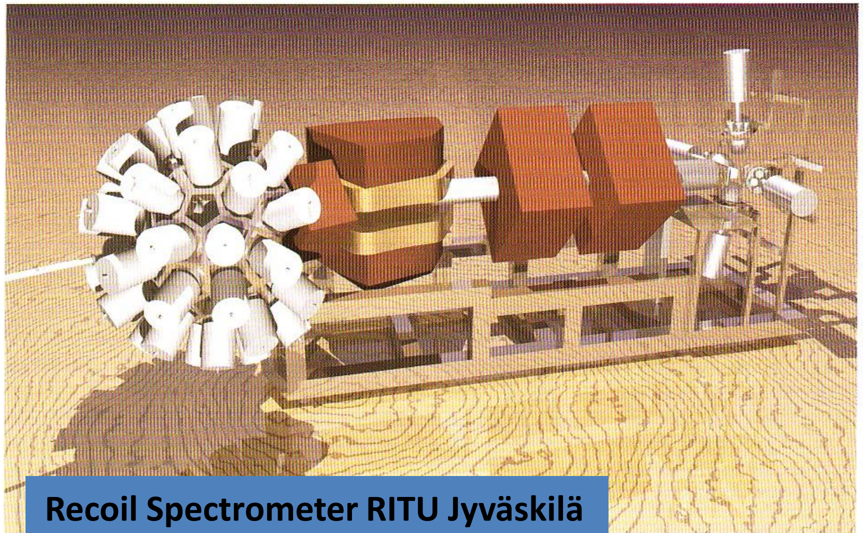
Design and construction of a demonstrator **CIEMAT: design and partial construction**



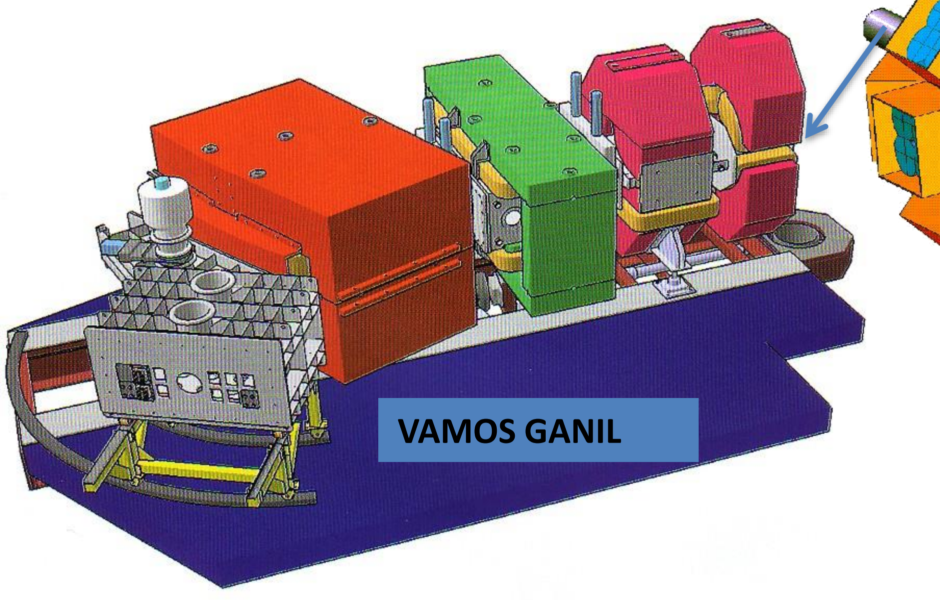


TOF spectrometer: array of liquid scintillators (BC501A)

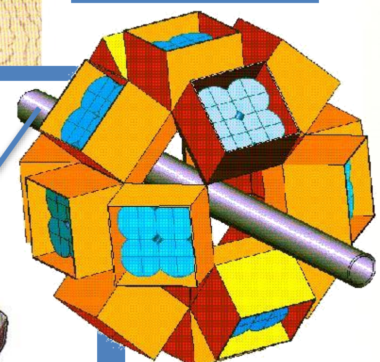
Identification and Measurement of fragments



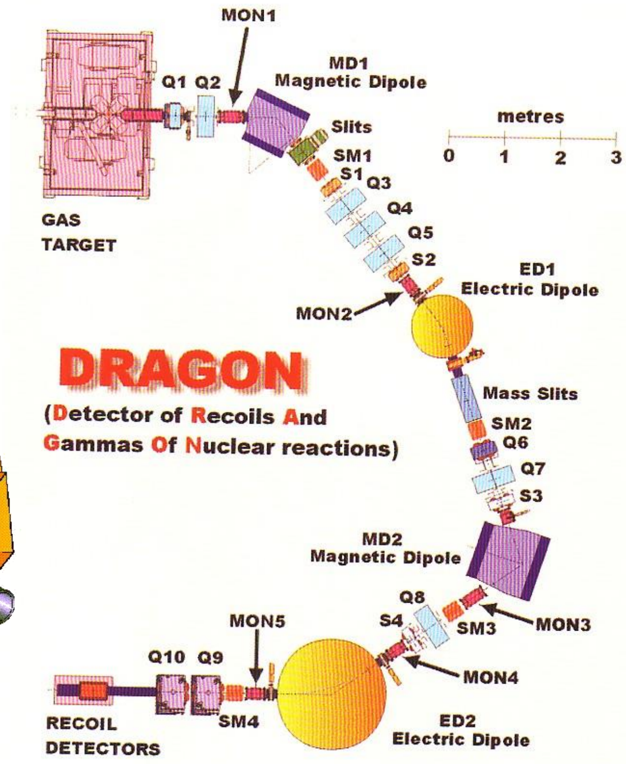
Recoil Spectrometer RITU Jyväskilä



VAMOS GANIL



EXOGAM

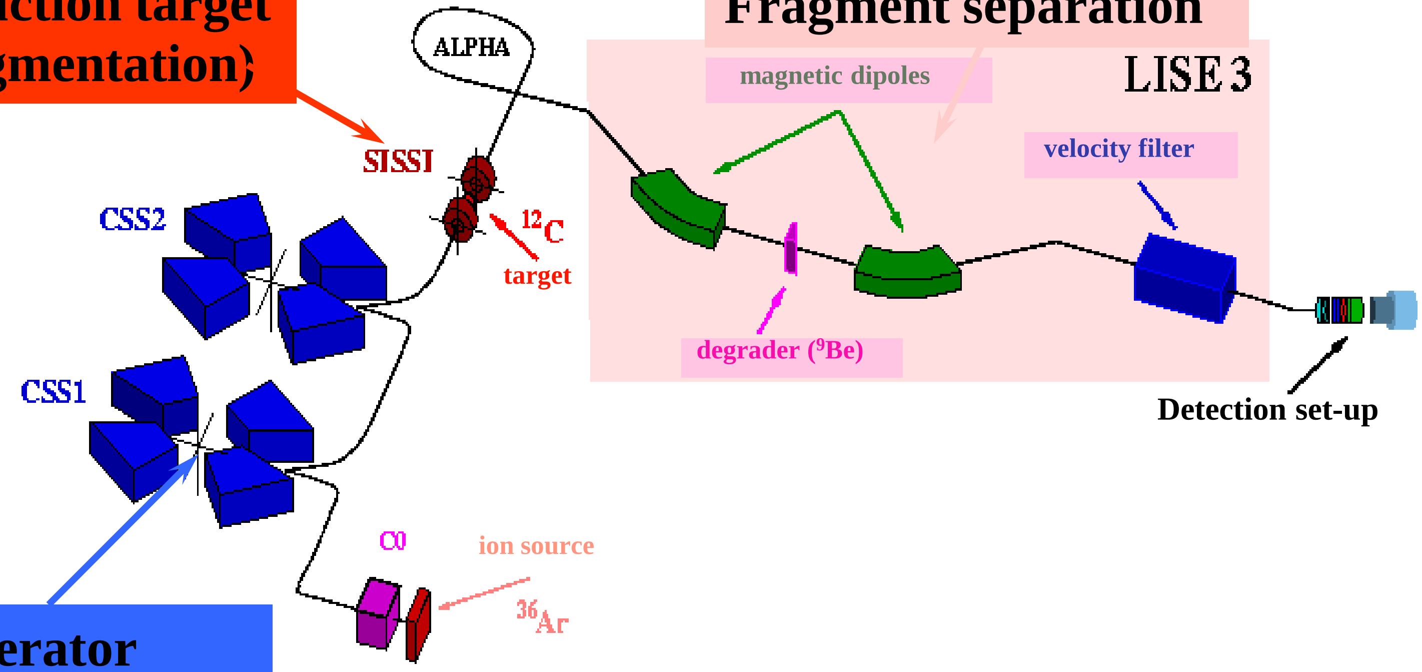


Mass Spectrometer DRAGON
Vancouver CANADA

Production of nuclei @ GANIL

Production target (fragmentation)

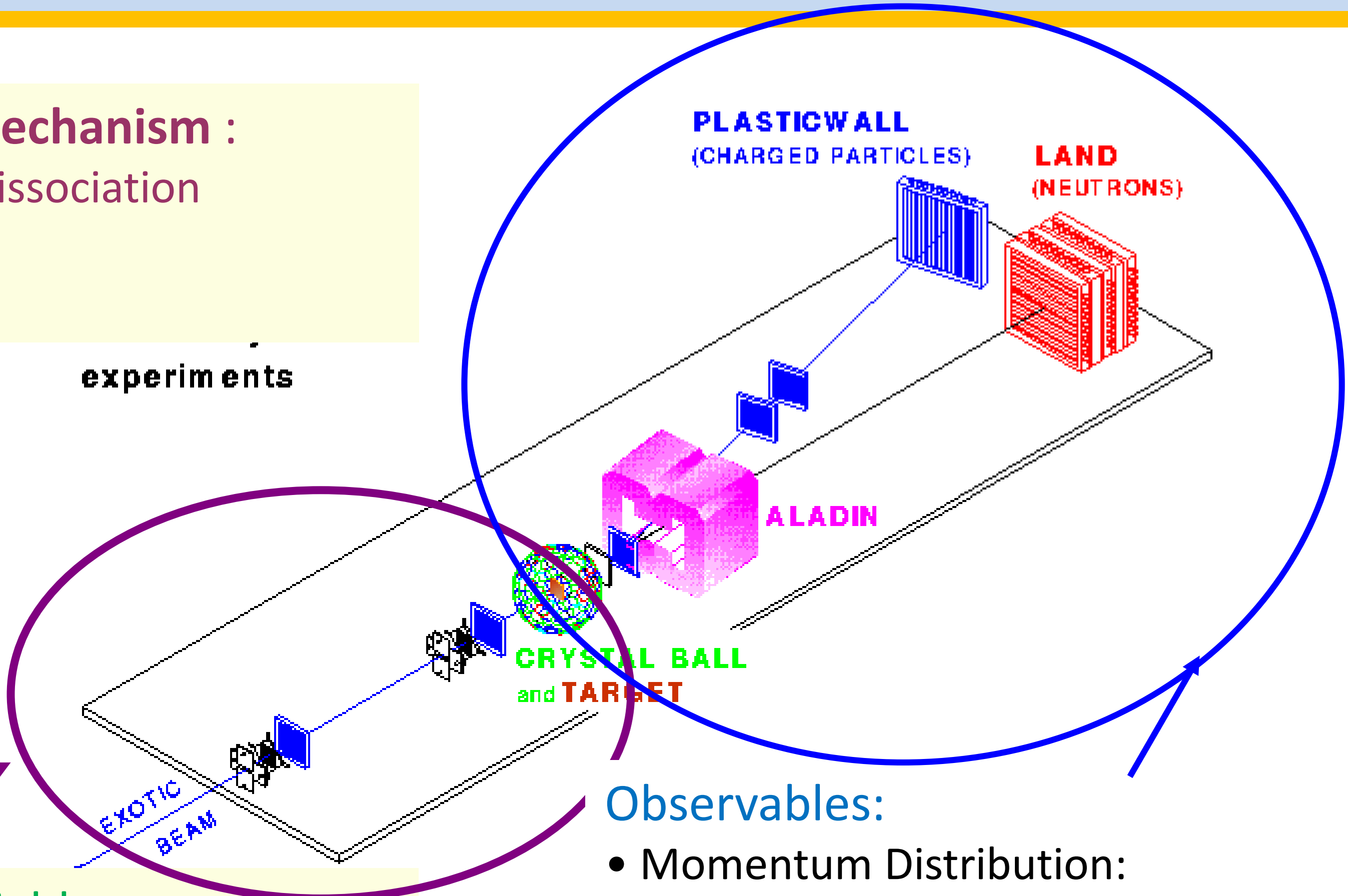
Fragment separation



Accelerator
$^{36}Ar^{18+}$ @ 95 MeV/u

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 → ^{22}Ne

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