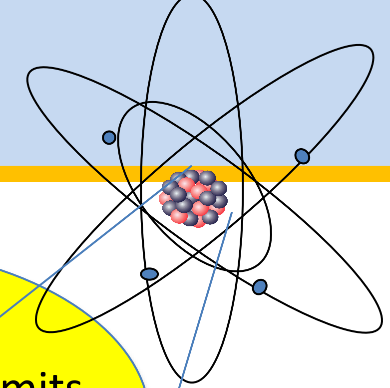
Production of Exotic Nuclei

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

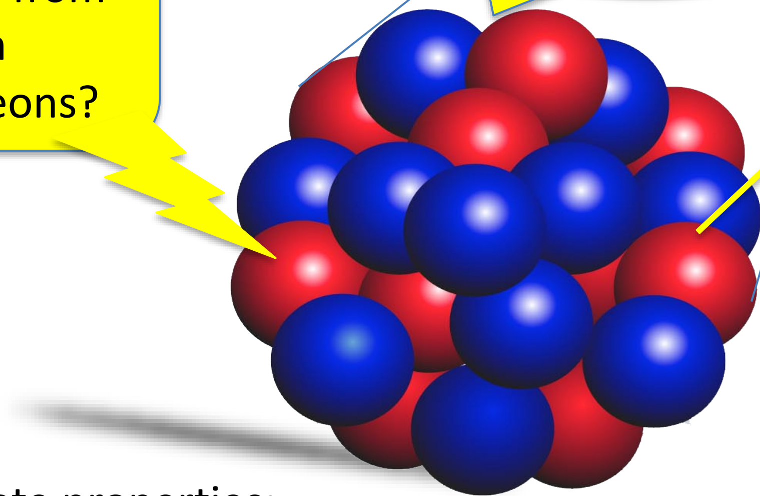
Open Questions in Nuclear Physics



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

What are the limits of nuclear stability?

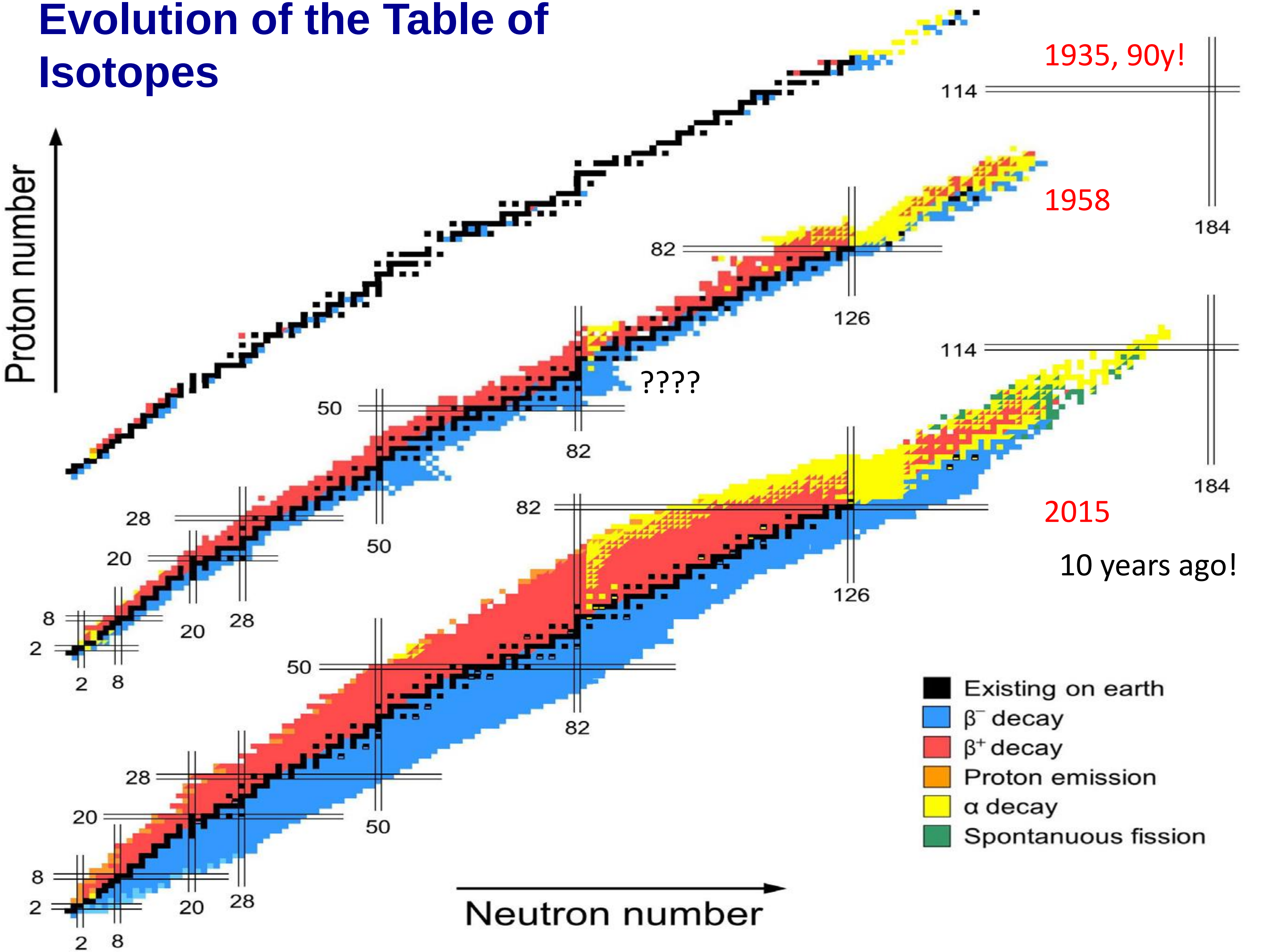
How and where in the Universe are the chemical elements produced?



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
New LRP released Nov 2024
https://www.nupecc.org/lrp2024/Documents/nupecc_lrp2024.pdf

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 = Z+N
~1/min	β ($T_{1/2}$, P_{xn})
1/sec	β-γ, β-n, β-p
100/sec	
	β-γ-γ, β-n-γ, β-p-γ
10^4/sec	

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

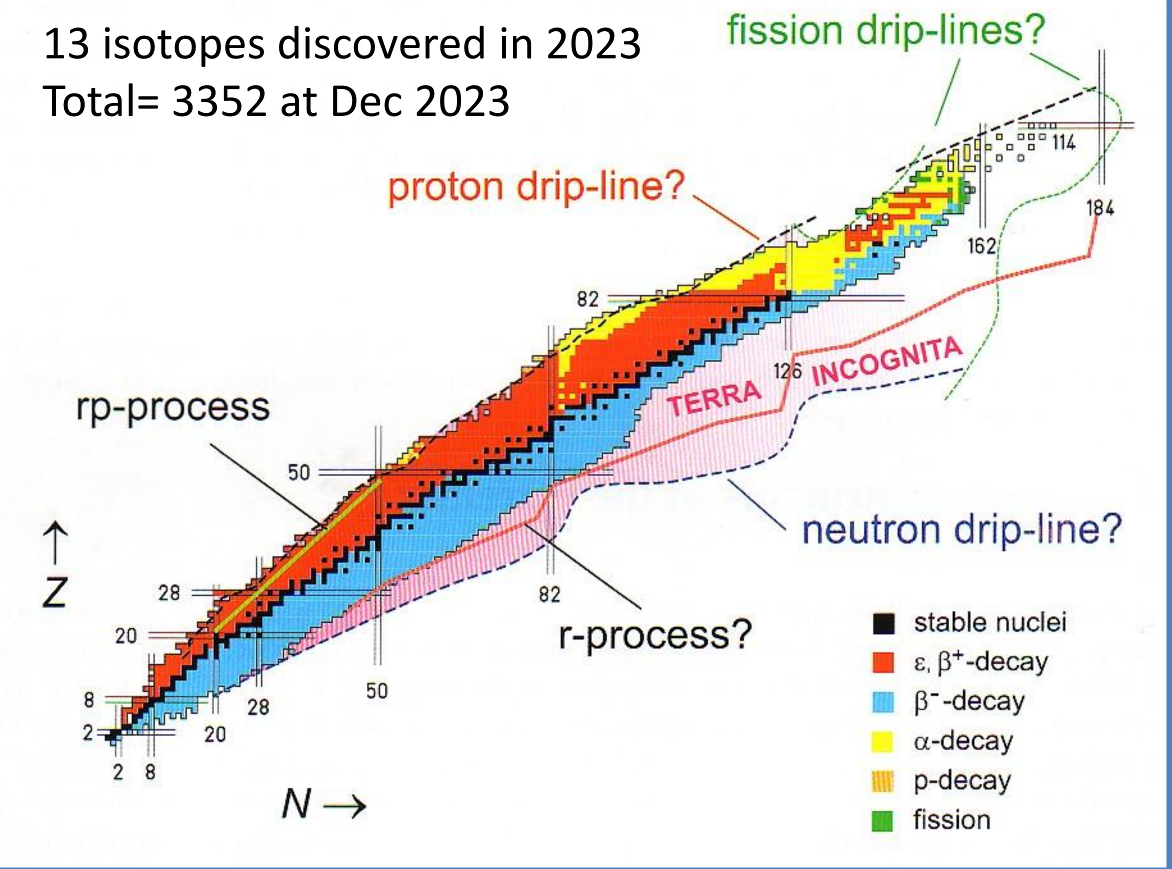
✓ β-decay gives first information of a new isotope.

✓ When the production is high $\Rightarrow$ detailed structure information can be achieved.

Exotic Nuclei

Situated far from the valley of Stability
Very different N/Z compare to the stable one
Close to the drip lines : $B_n = 0$, $B_p = 0$
at the frontier of discovery

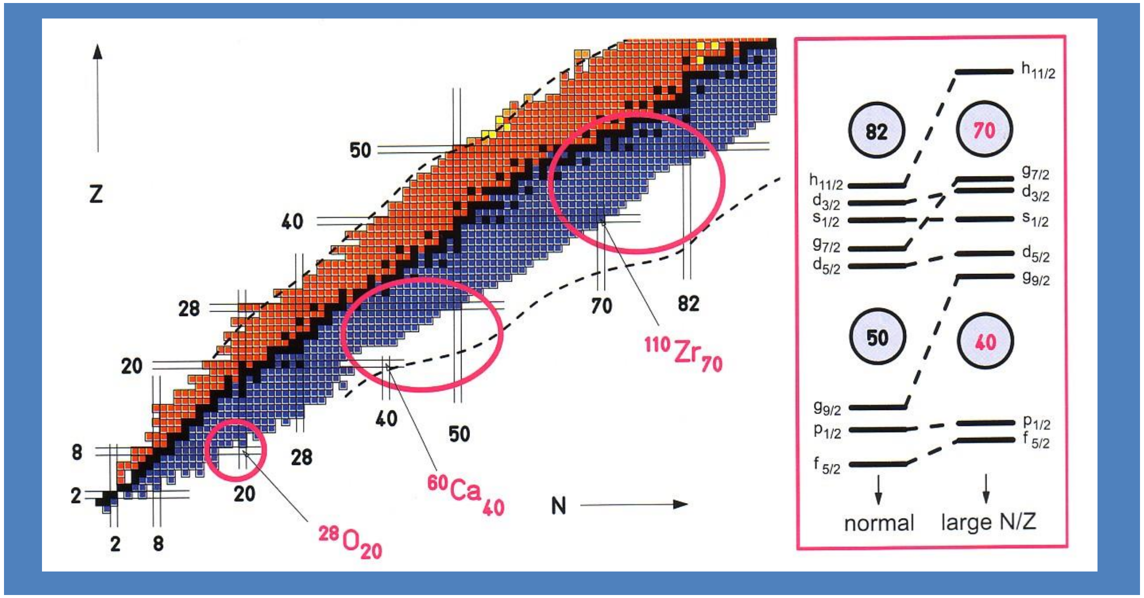
13 isotopes discovered in 2023
Total= 3352 at Dec 2023



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

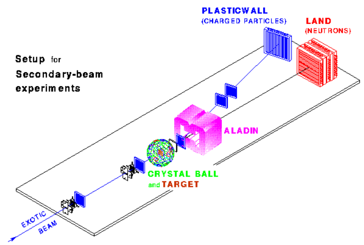
Extension of rare phenomena in the space of Z, N, J, Ex, superdeformation,

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

To explore a new phenomenon many different approaches are needed

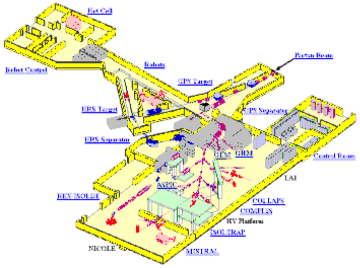
GSI
Reacciones a E_r=700 MeV/u



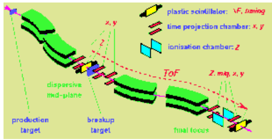
Elastic Scattering

Spins Moments

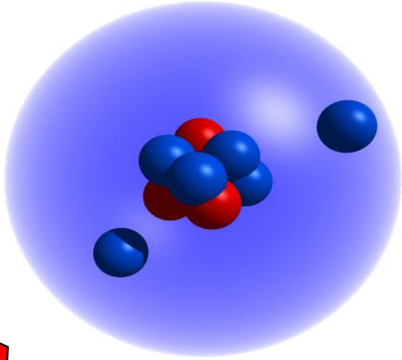
ISOLDE
Desintegración beta E_r=0



Reaction Cross Sections



Masses

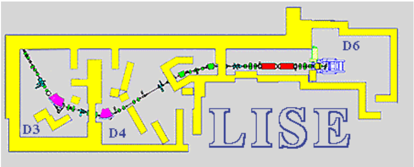


Beta Decay

Momentum Distributions

Unbound Nuclei

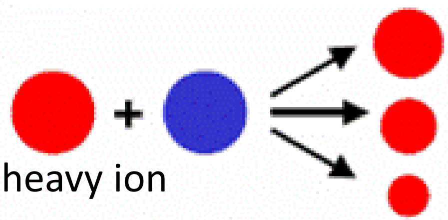
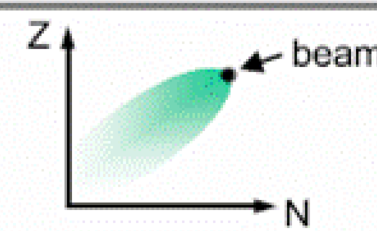
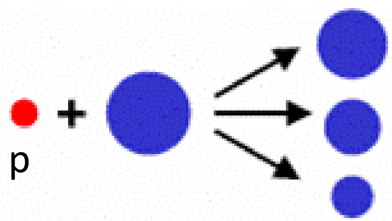
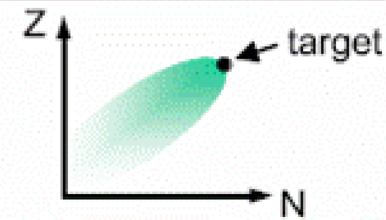
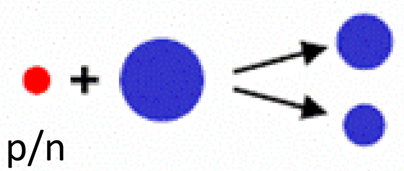
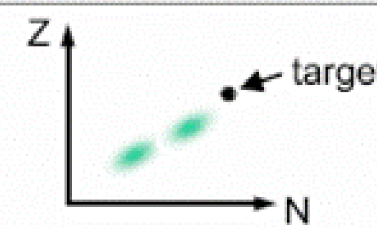
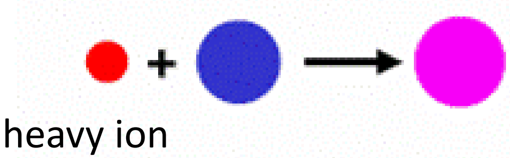
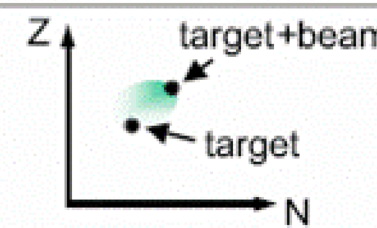
GANIL
Reacciones a E_r=30-60 MeV/u



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 Transfer and spectroscopic factors Heavy & Super-heavy nuclei
E < 100 MeV/u	→	Nuclear Matter

Production Methods

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

Cross Section

Incoming particules/s

~ 10^8 - 10^{12} /s

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, rates of 1 à 10^{11} at/s

transfer, 1 or several nucleons pick up, stripping…

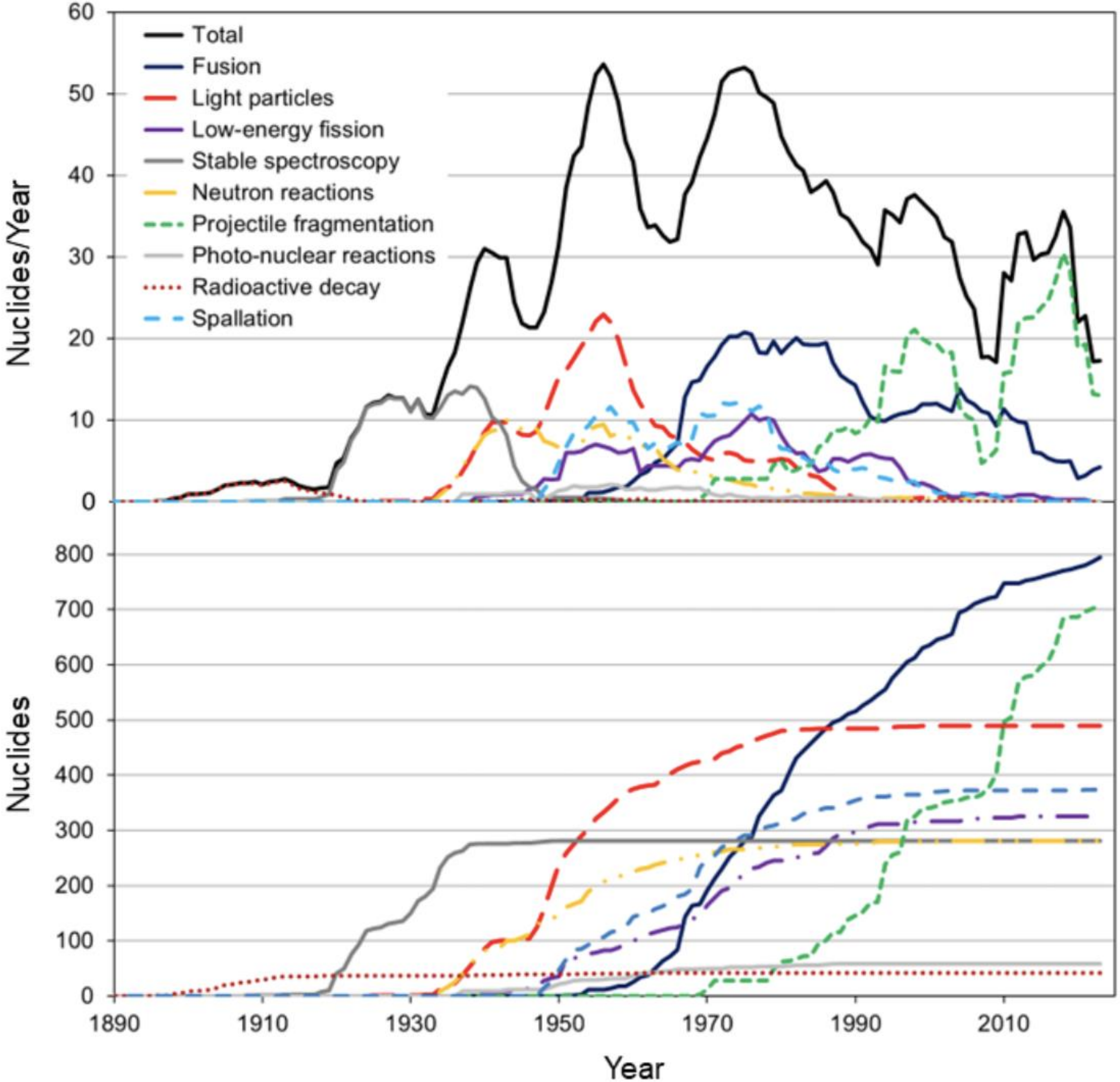
inélastic ^{76}Ge (9 MeV/u) + Ta ou W → ^{62}Mn, $^{71-73}$Cu

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

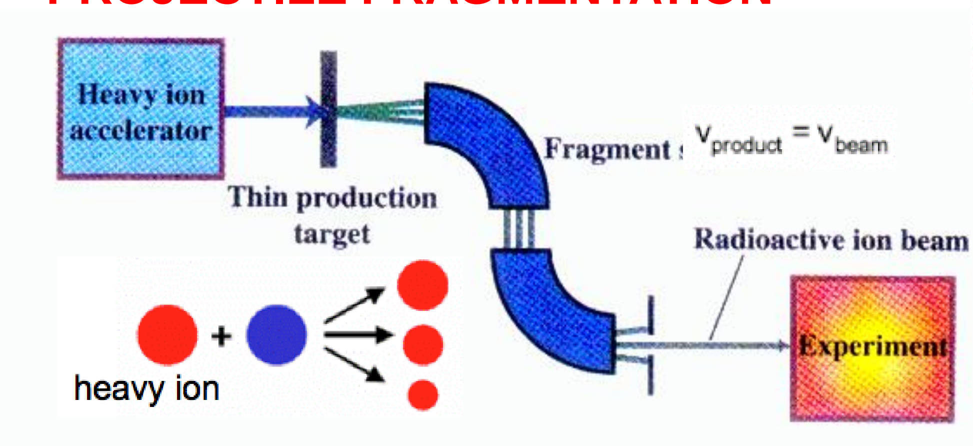
relativistic ^{235}U (750 MeV/u) + Pb → 50 products

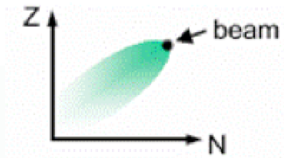

Total
Fusion
Light particles
Low-energy fission
Stable spectroscopy
Neutron reactions
Projectile fragmentation
Photo-nuclear reactions
Radioactive decay
Spallation
Nuclides/Year
Nuclides
Year
60
50
40
30
20
10
0
800
700
600
500
400
300
200
100
0
1890
1910
1930
1950
1970
1990
2010

Production of Radioactive Beams

Energies of Outcoming beam

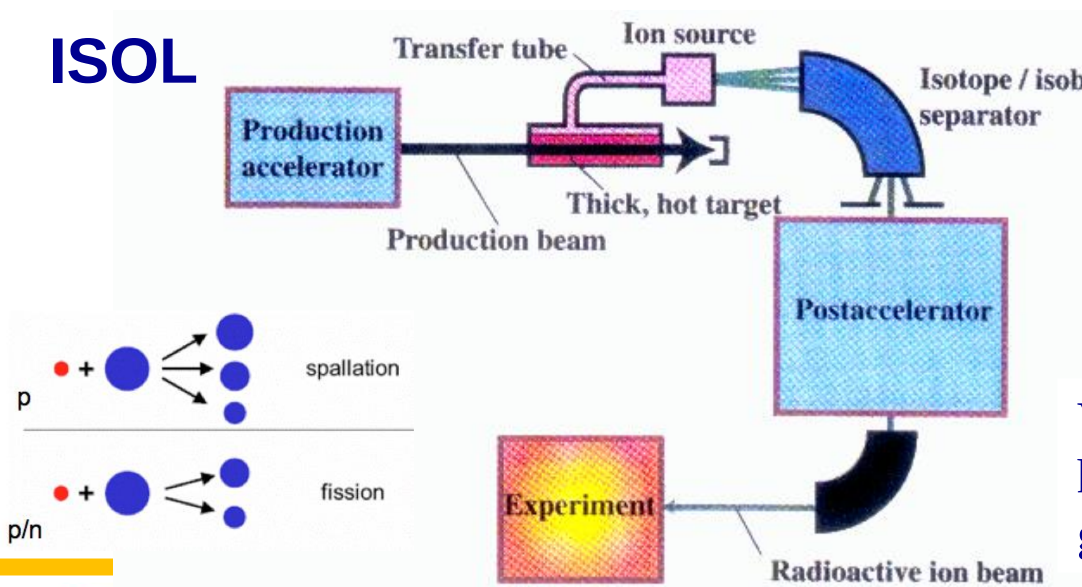
PROJECTILE FRAGMENTATION

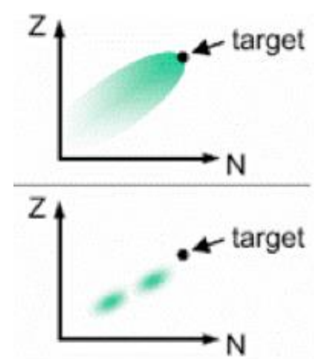




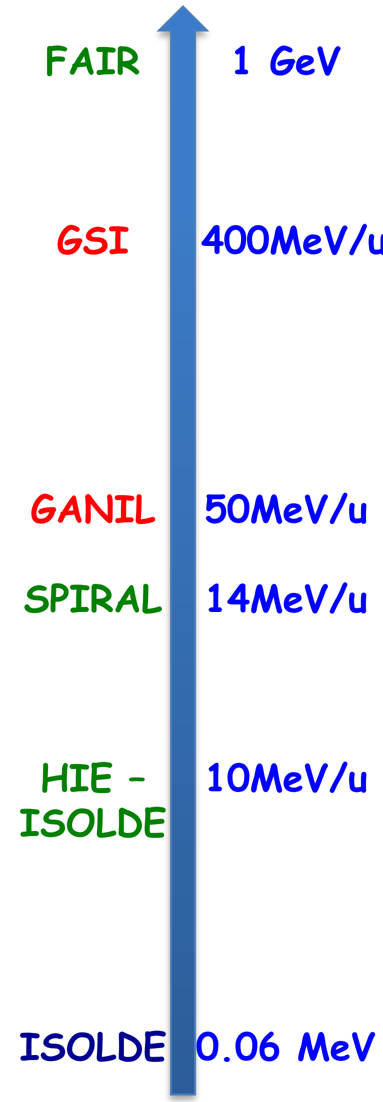
High energy,
large variety of species,
Short half-lives (μs),
cocktail beam

ISOL

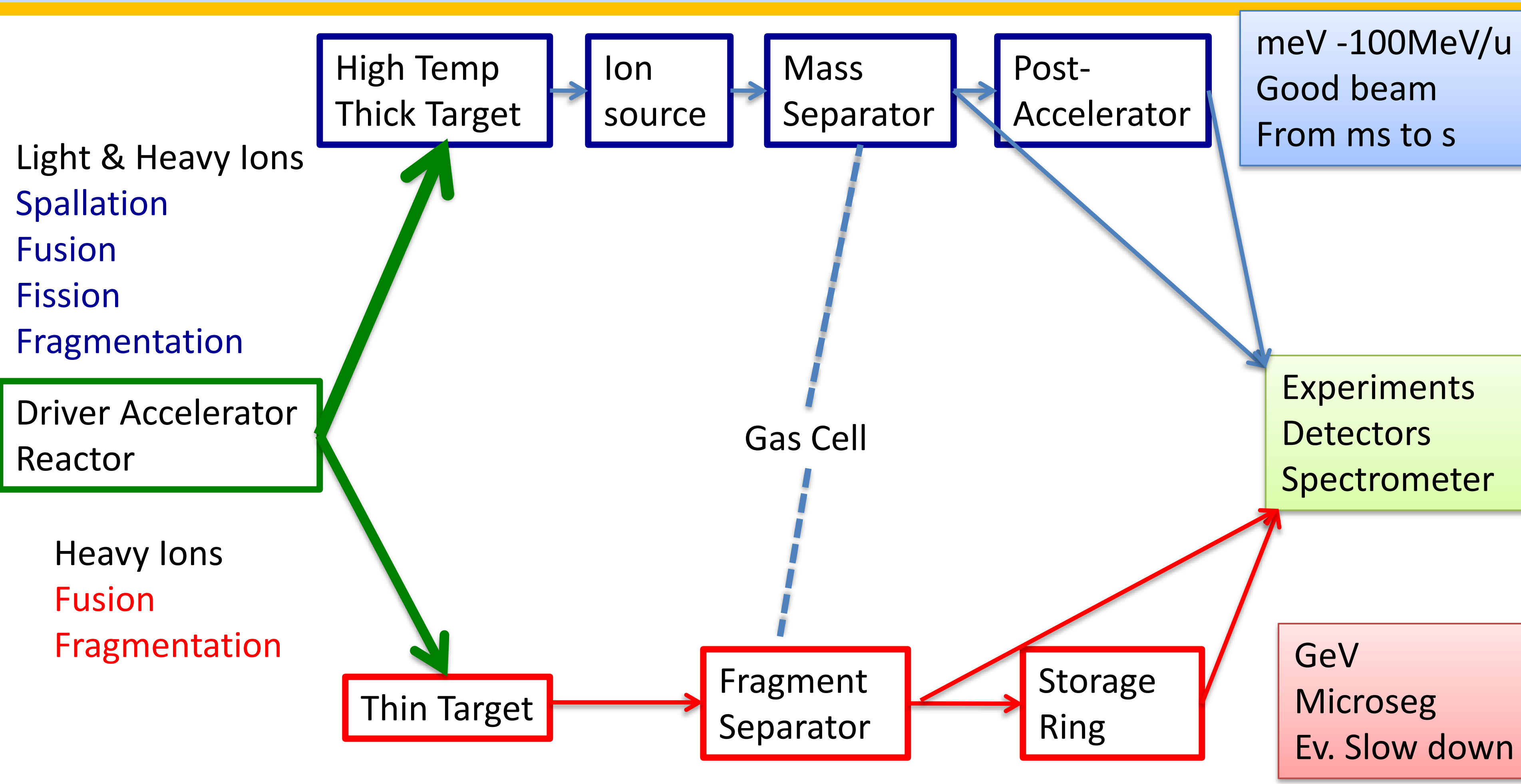




Variable energy,
high intensity,
good beam qualities

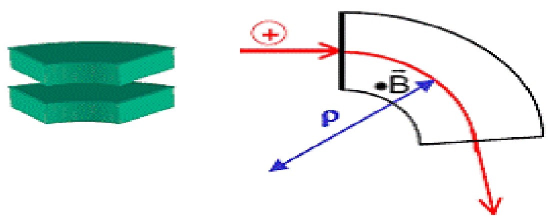


Production Methods



Separation at High Energy (See Talk by Teresa K)

magnetic dipole

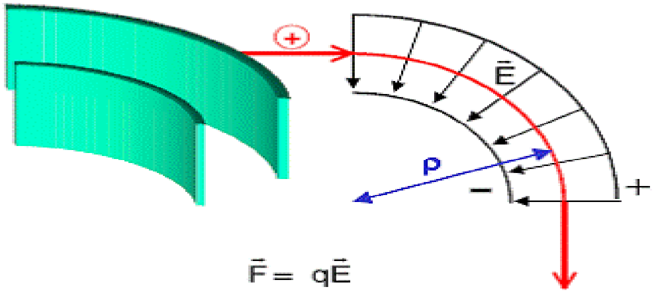


$\vec{F} = q\vec{v} \times \vec{B}$

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

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

electric dipole

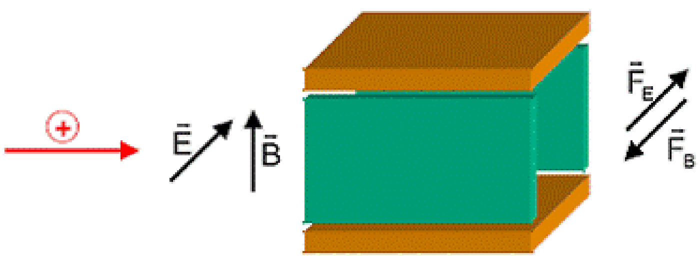


$\vec{F} = q\vec{E}$

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

velocity filter

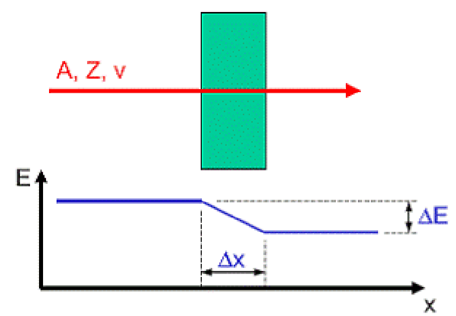
Wien filter, E-cross-B filter



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

Need Wien-vel-Filter to separate in velocity

Energy degrader



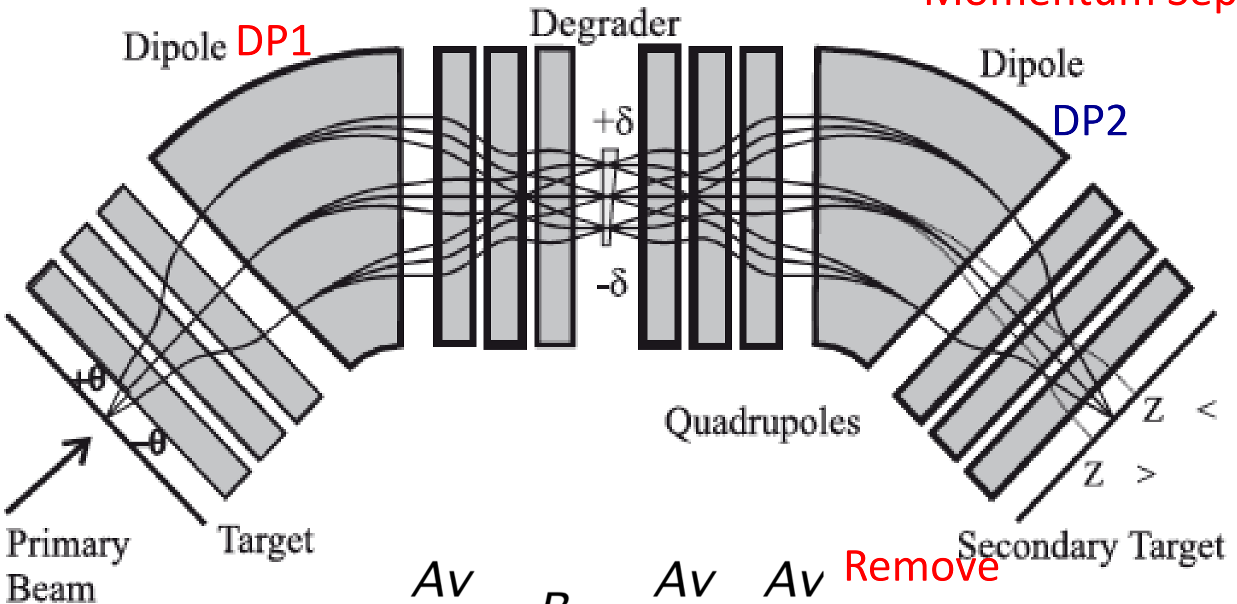
stopping power $S \equiv -\frac{dE}{dx} \propto \frac{Z^2}{v^2} \propto \frac{A\,Z^2}{E}$

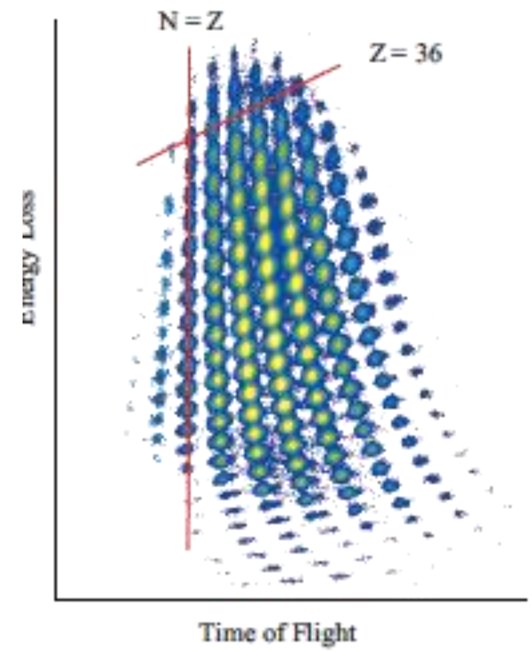
→ straggling (spread) in energy and angle

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 $\propto Z^2$

T_{vol} (Target - detector)= $\frac{d}{v} \propto \frac{A}{Z}$

In flight method

Higher energy

Targets
In the order of 1-4 g/cm^2

Reaction products
Kinematically forward focused

extended detection scheme
& better resolution

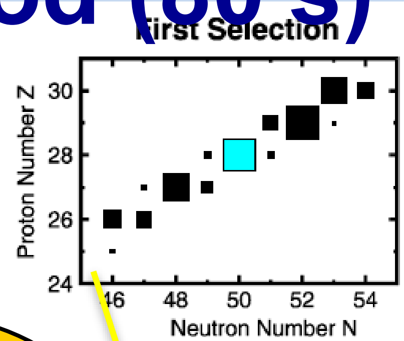
Full-acceptance measurements
with moderate sized detectors

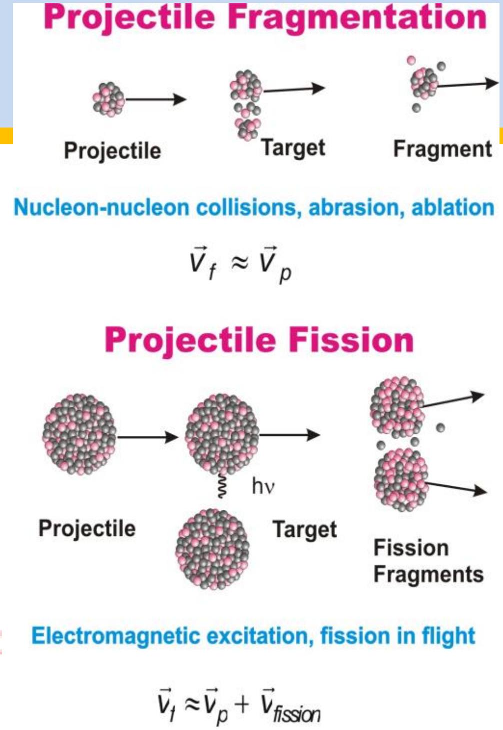
Possible study more exotic nuclei
efficient down to 1 ion/s, short lived

In-Flight Method (80's)

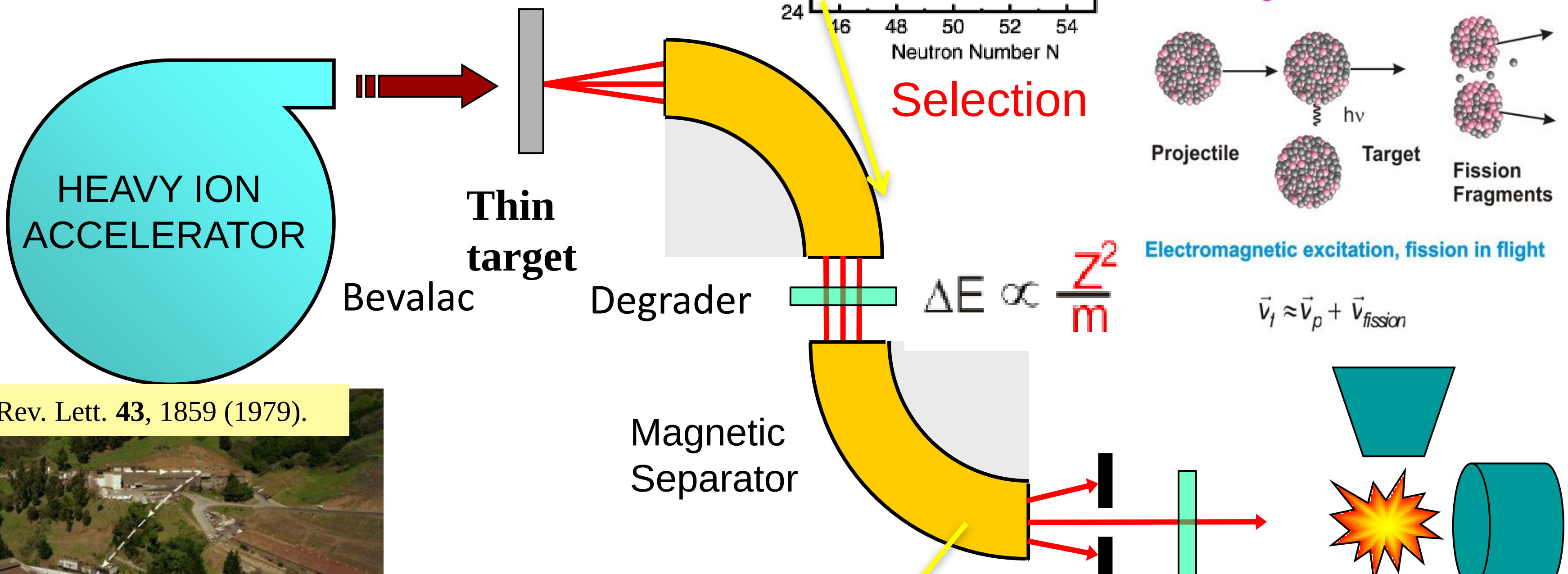
Develop in the late 80's

Production

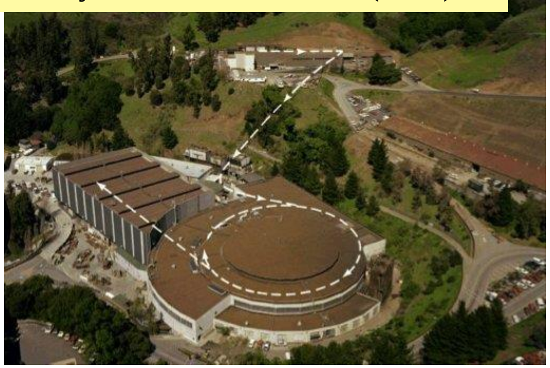


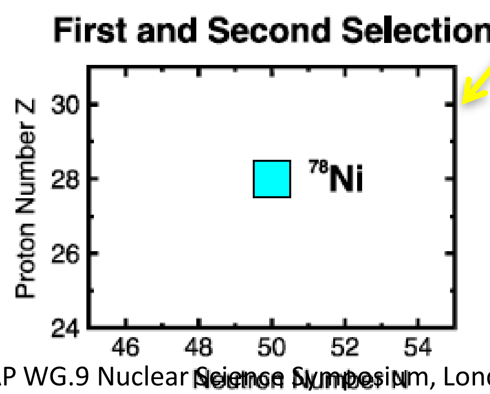


Selection



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

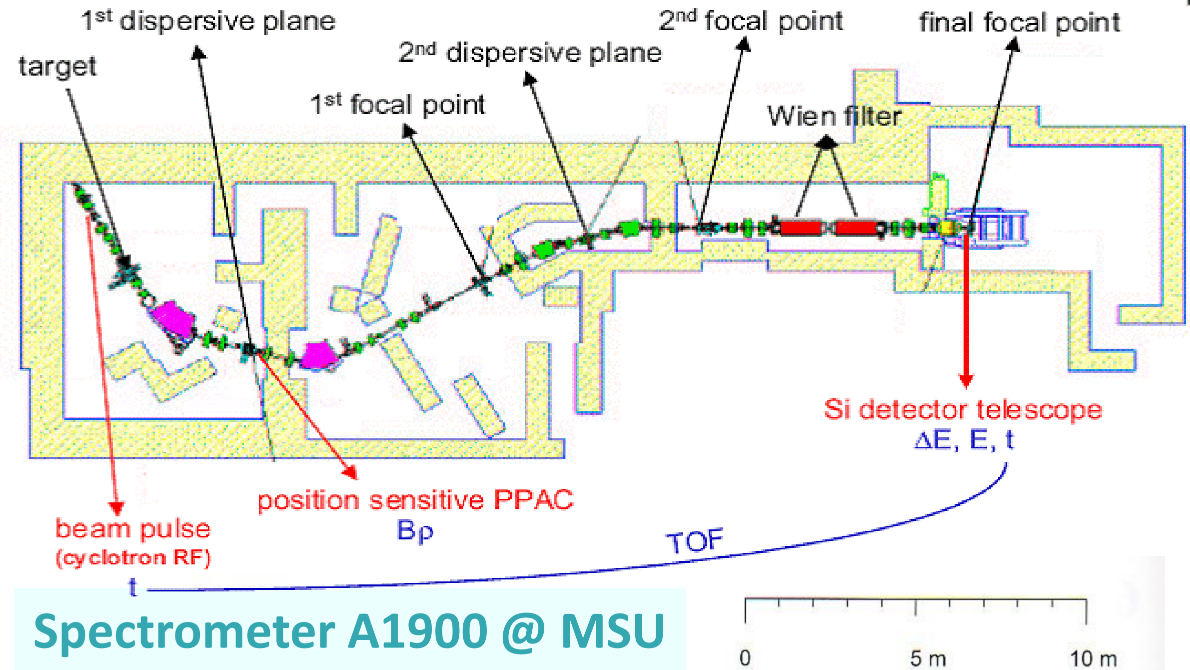


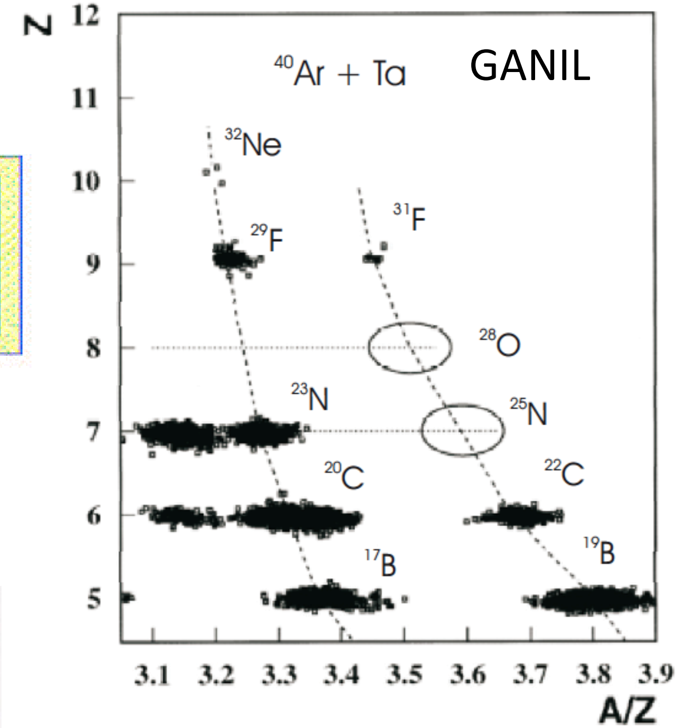


Particle stability of 15 earlier unobserved nuclides from ^{22}N to ^{44,45}Cl.

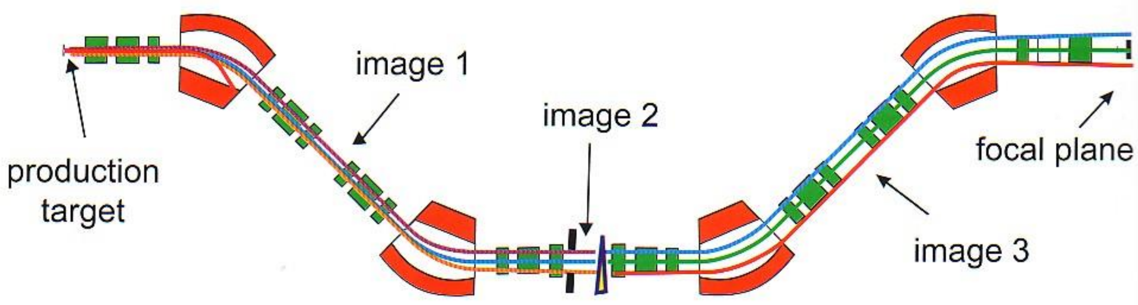
Different Spectrometer

Spectrometer LISE @ GANIL



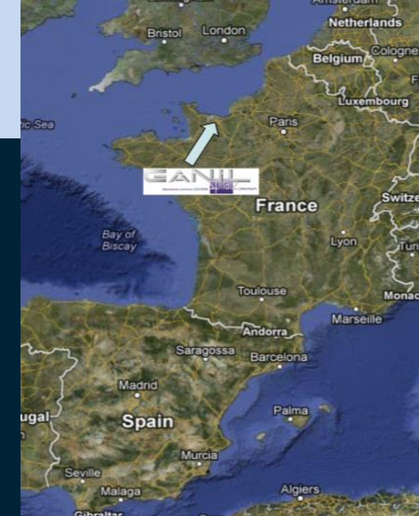


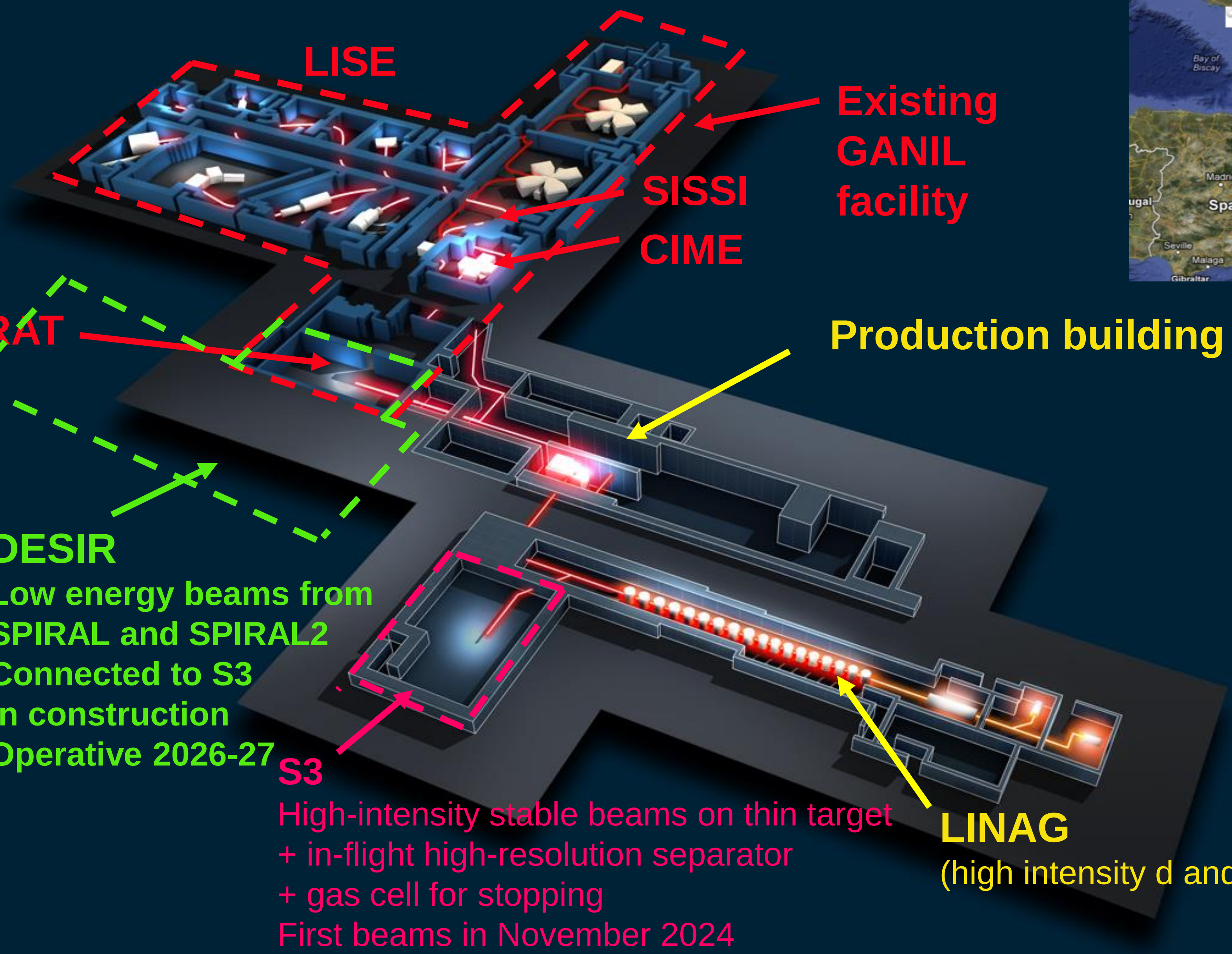
Spectrometer A1900 @ MSU



Talk of T. Kurtukian!

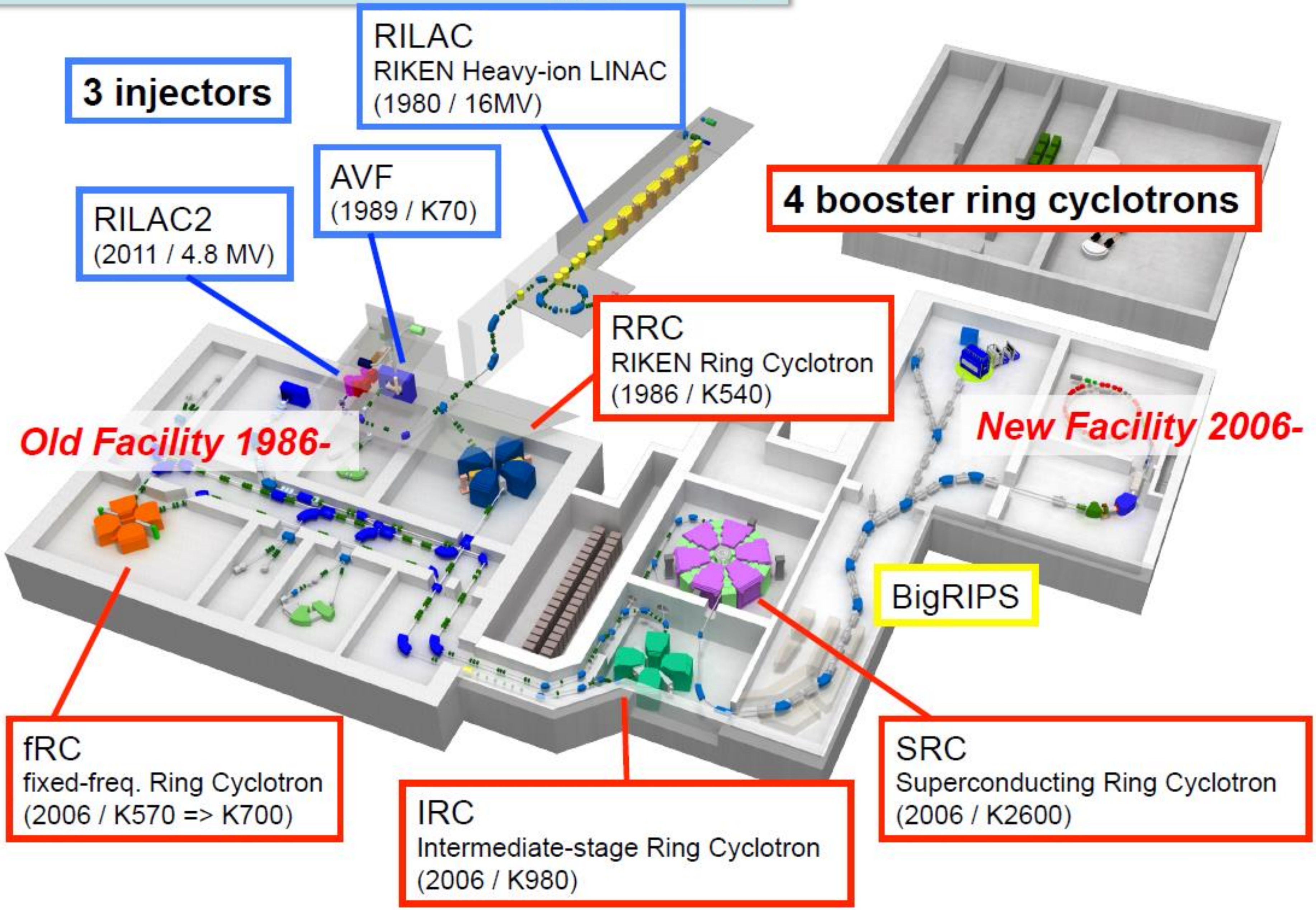
GANIL / SPIRAL 2





RIKEN RI Beam Factory (RIBF)

Y. Yano, NIM B261 (2007) 1009.

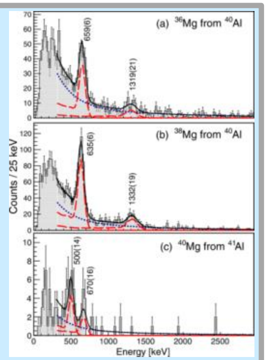


Steady increase of Beam Current @ RIKEN (Japan)

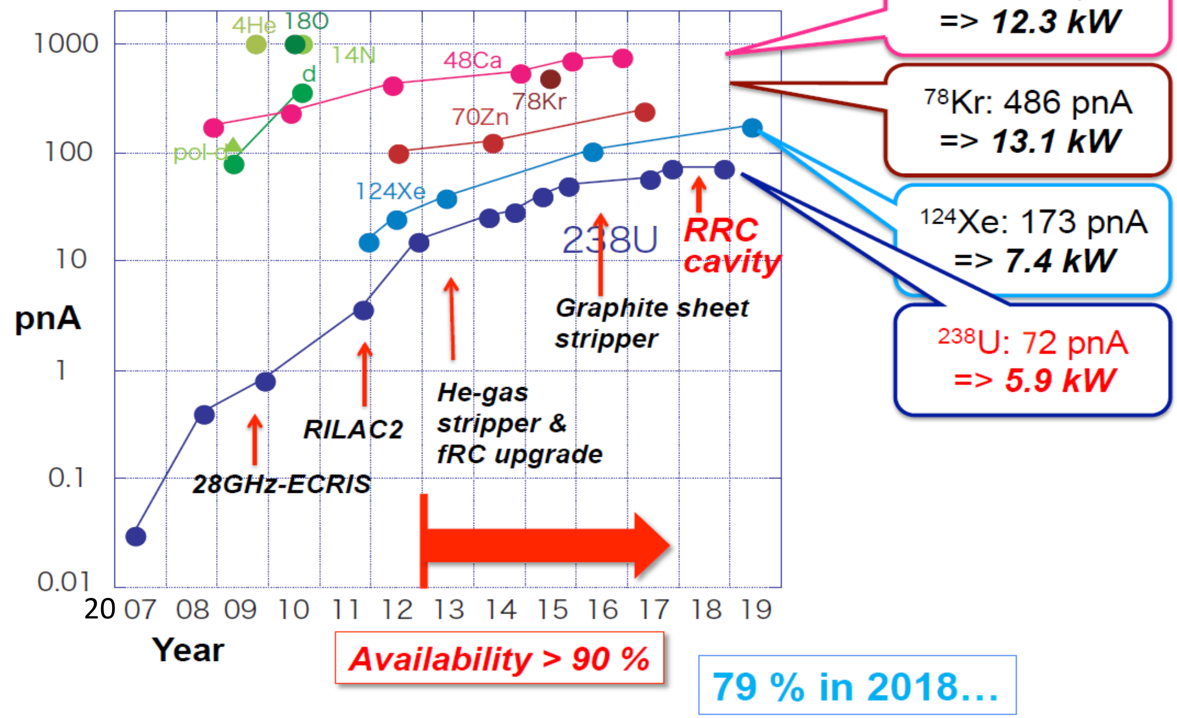
^{40}Mg (N=28) is largely deformed.

The origin is a mystery.

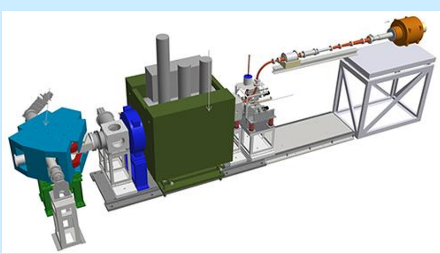
No theory can reproduces the data.



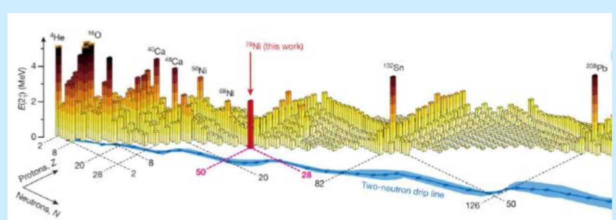
RIBF accelerator performance



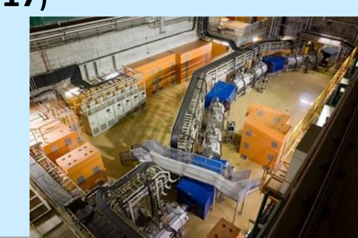
Quest for heavier super-heavies (Z=113)
Success in producing and accelerating high intensity vanadium beam
- Cleared the way for producing element 119 – (2017)



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

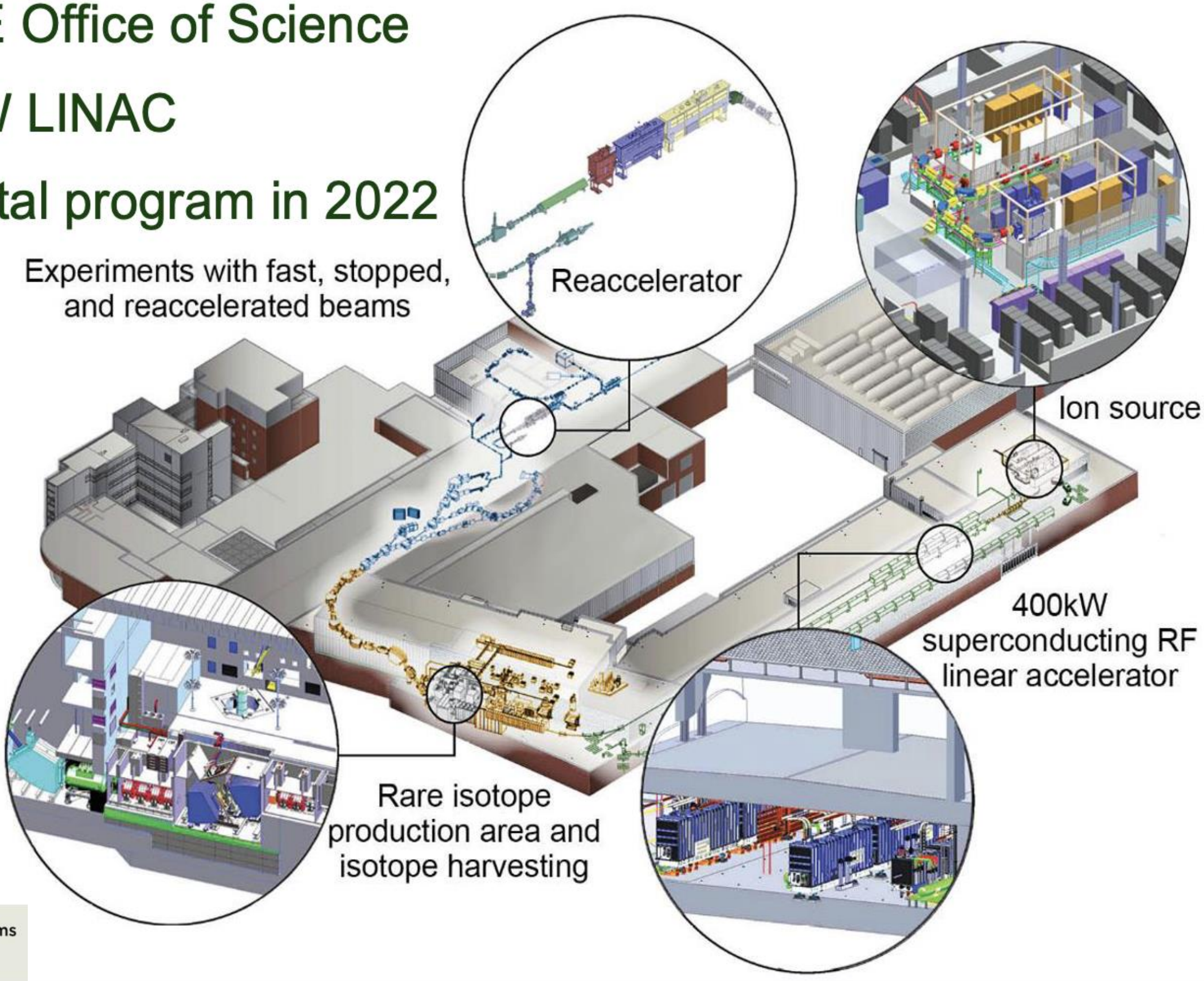


73 new isotopes discovered at RIKEN's RI Beam Factory (2017)



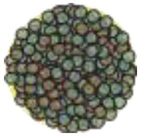
Facility for Rare Isotope Beams, FRIB

- Supported by DOE Office of Science
- 200 MeV/u 400 kW LINAC
- Start of experimental program in 2022
- Equipment
  - Fast
  - Stopped
  - Reaccelerated

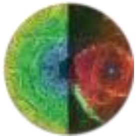


FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

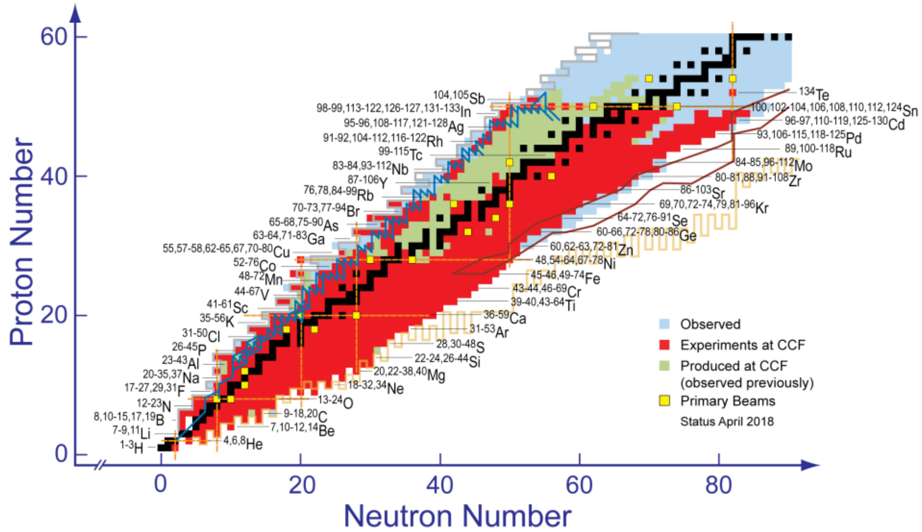
Physics Program

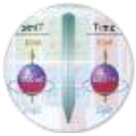


- Properties of atomic nuclei
  - Develop a predictive model of nuclei and their interactions
  - Many-body quantum problem: intellectual overlap to mesoscopic science, quar dots, atomic clusters, etc.



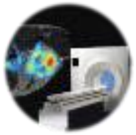
- Astrophysics: What happens inside stars?
  - Origin of the elements in the cosmos
  - Explosive environments: novae, supernovae, X-ray bursts …
  - Properties of neutron stars





Tests of laws of nature

- Effects of symmetry violations are amplified in certain nuclei



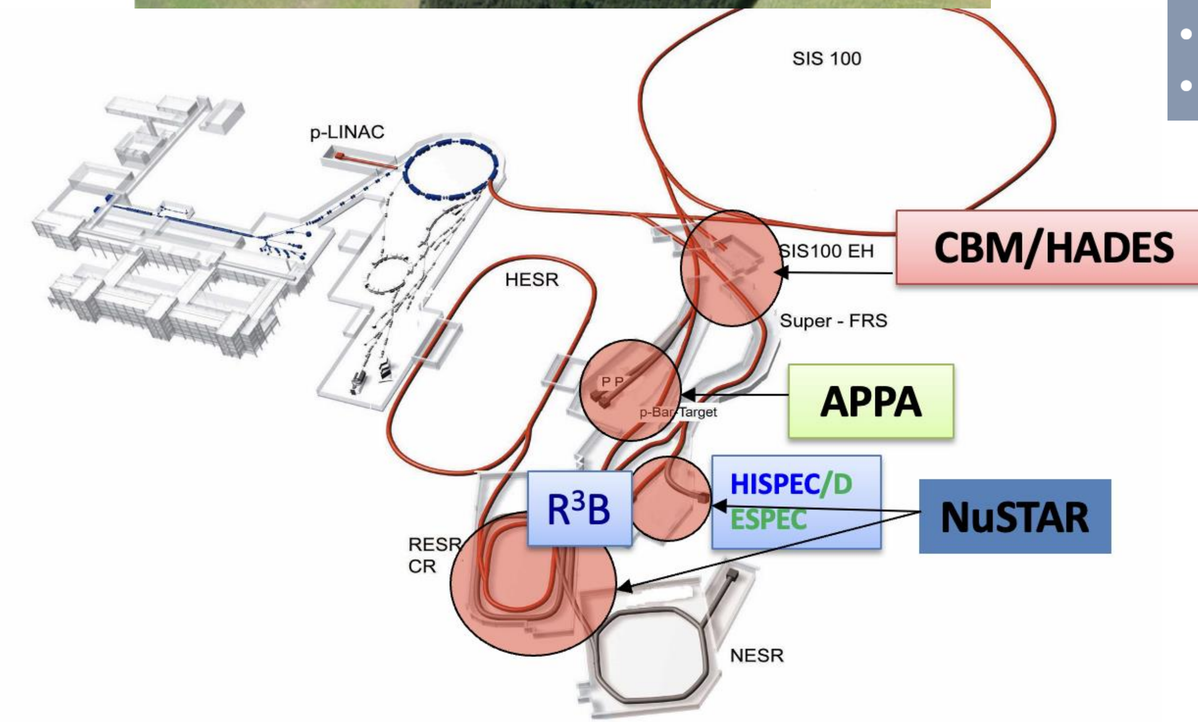
Societal applications and benefits

- Medicine, energy, material sciences, national security

Design parameters U^{28+}	SIS18	SIS100
Energy	200 MeV/u	1.5 GeV/u
Ions per cycle	1.5×10^{11}	5×10^{11}
Repetition rate	2.7 Hz	0.3 Hz

Gain factors (compared with GSI):

- 100-1000 x intensity
- 10 x energy
- antiproton beams
- system cooler storage rings

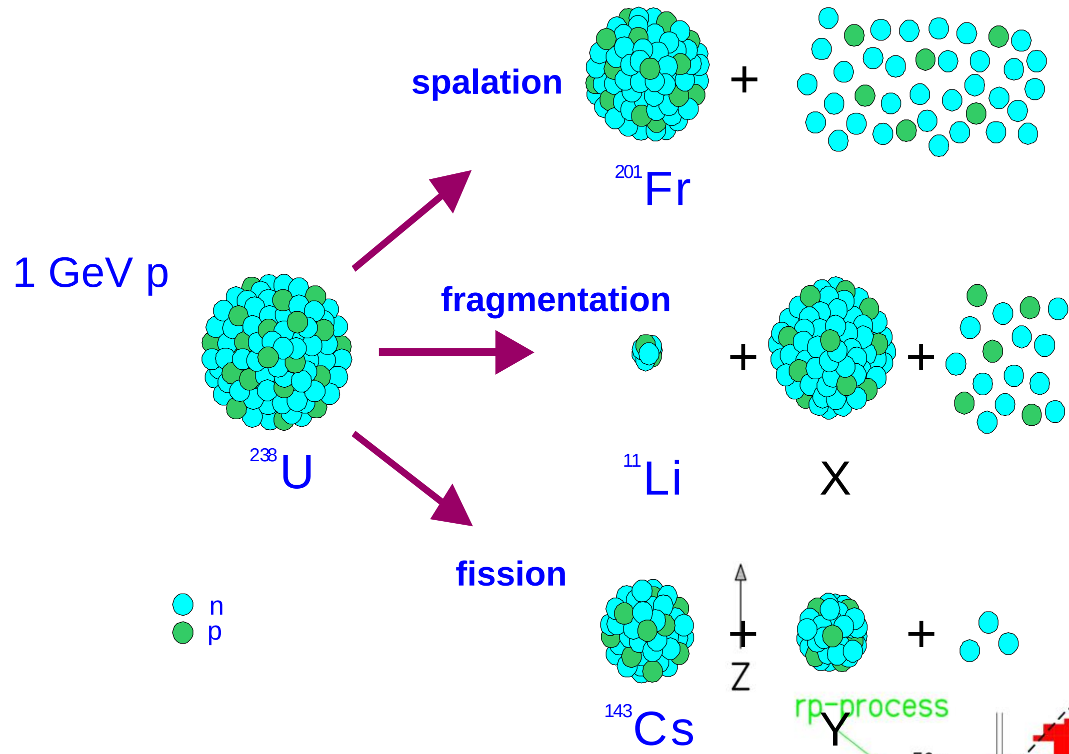


Talk by
Olof Tengblad

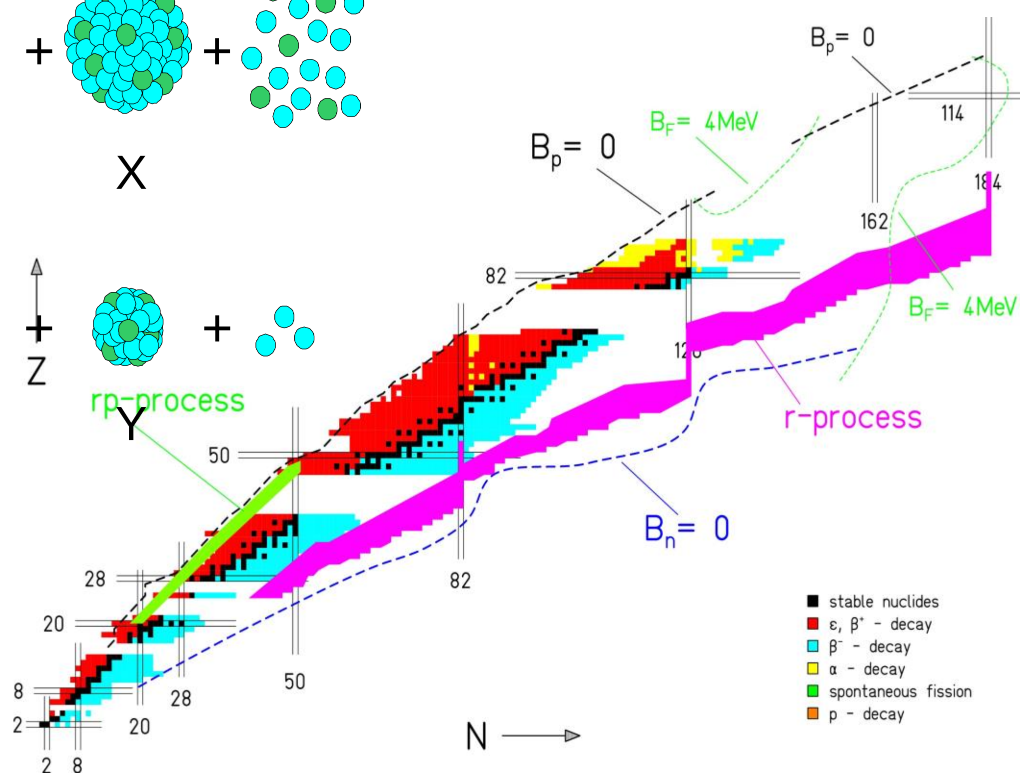
✓ **Nuclear Structure and Astrophysics: NUSTAR**

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

Isotope production



Nuclei chart @ ISOLDE



Exotic ion production

Gaps

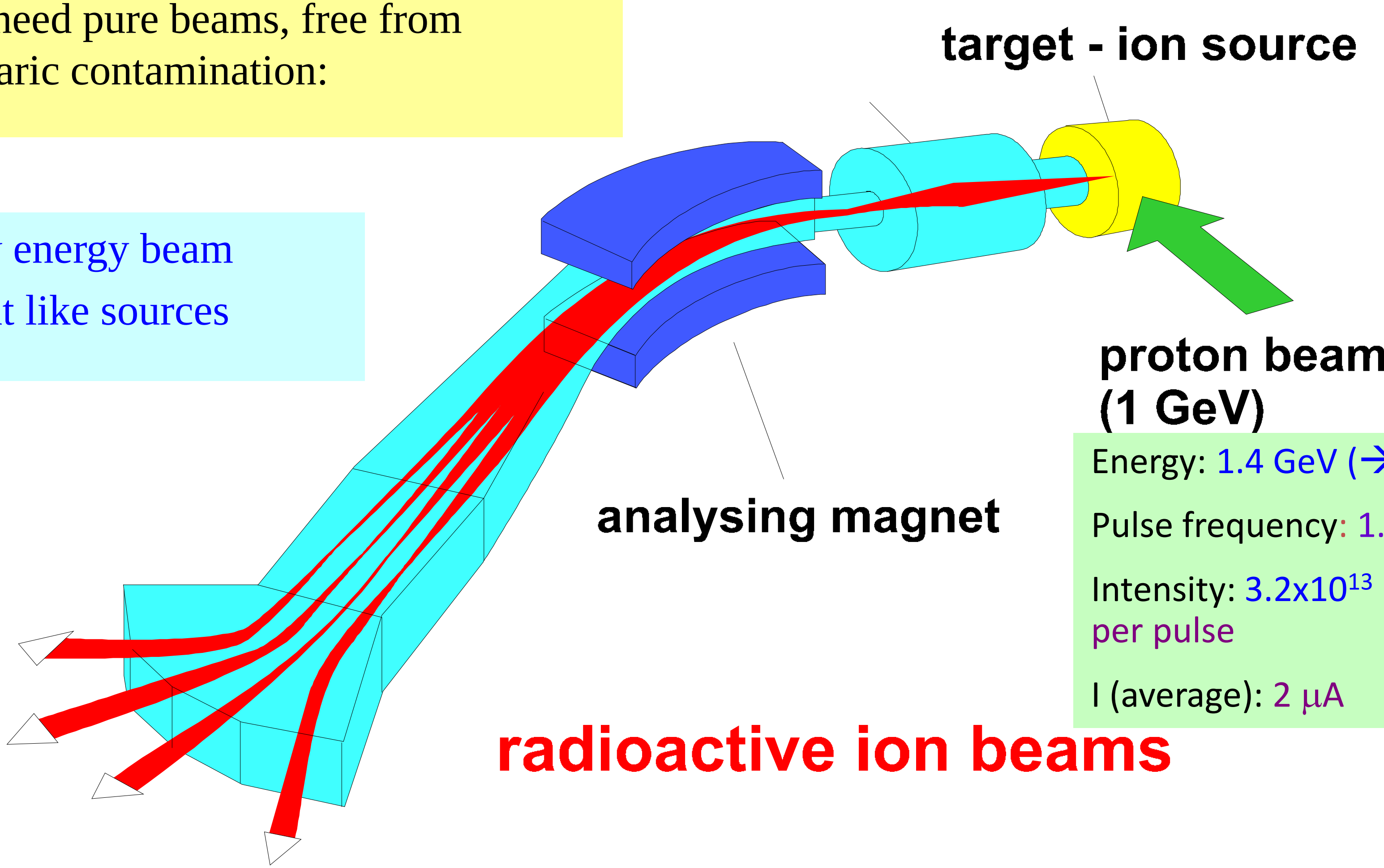
Long chain of isotopes

ISOLDE Isotope Separation On-Line

We need pure beams, free from isobaric contamination:

Low energy beam

Point like sources



Energy: 1.4 GeV (→ 2 GeV)

Pulse frequency: 1.2 s

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

I (average): 2 μA

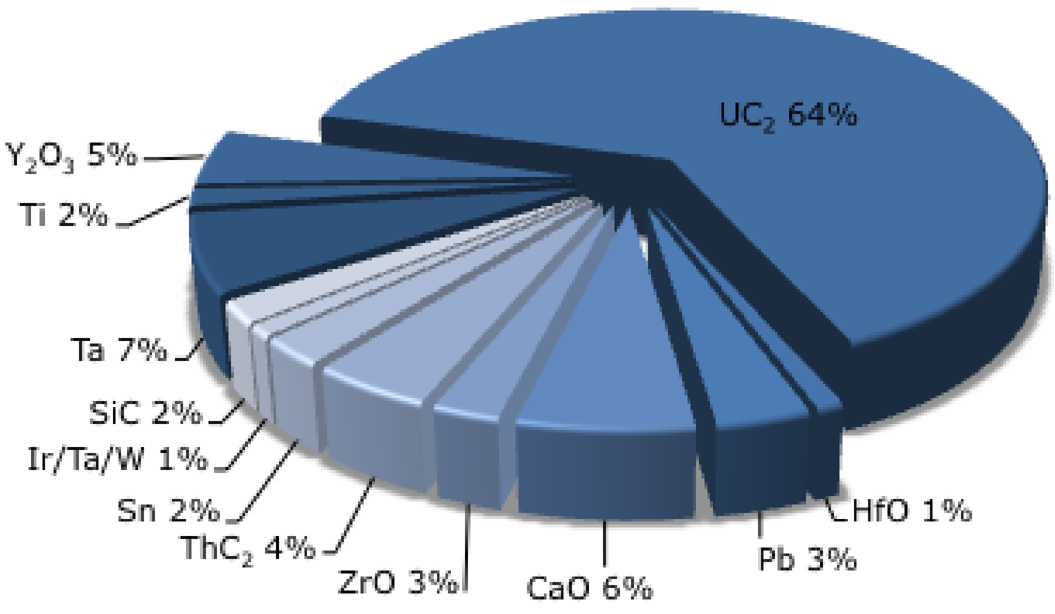
Target – Ion-source matrix: a chemical laboratory

RIB intensity [s^{-1} µA^{-1}]; Proton beam Intensity [s^{-1} µ A^{-1}]; Avogadro Numb.; Diffusion+ Effusion Efficiency

$$I = \int \sigma(E)\ \Phi(E, x)\ \rho(x)\ N/A\ dx\ \varepsilon_{diff+eff}\ \varepsilon_{ion}$$

Cross section [cm^2]; Target density [g cm^{-3}]; Target Atomic Mass [g]; Ionization Efficiency

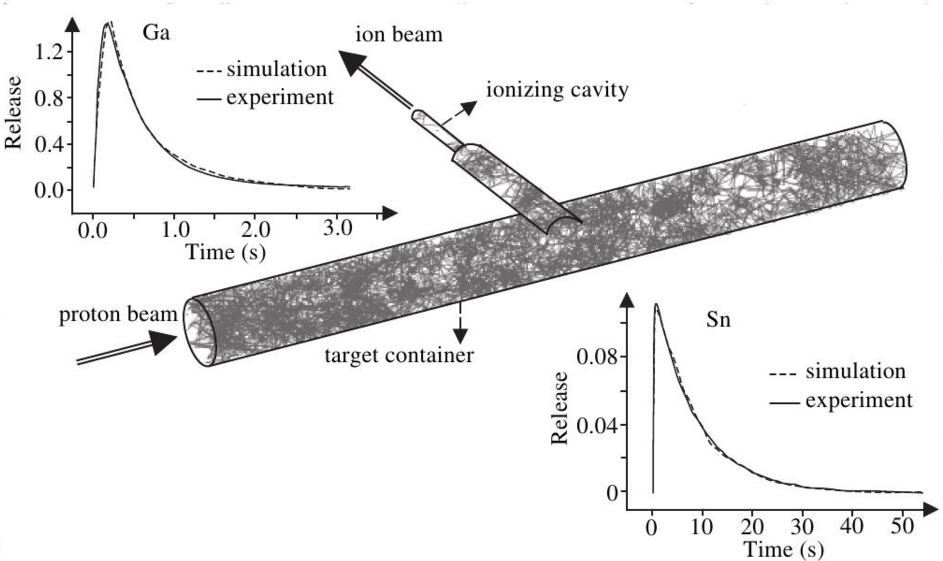
Use in 2011 @ ISOLDE

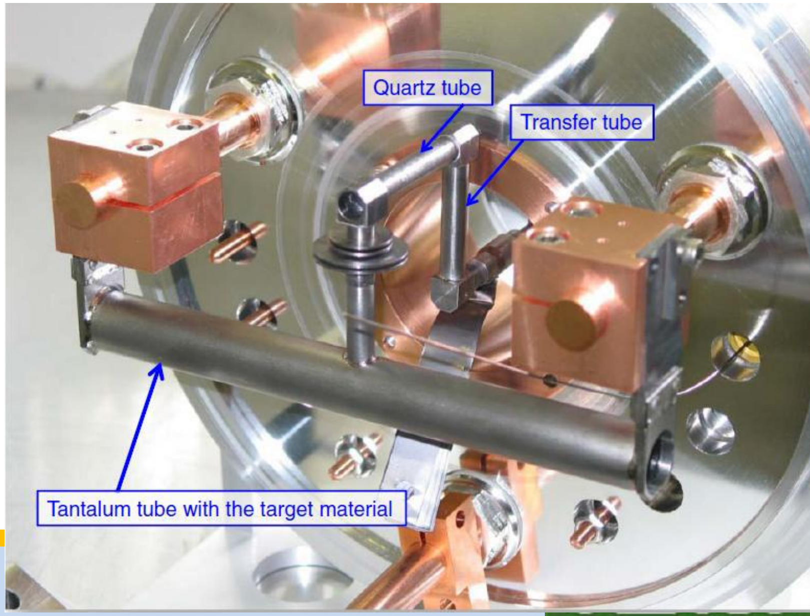


- Container: 20 x 2 cm cylinder of Ta
- Material:
  - Liquid La, Pb, Sn
  - Metal foil/powder Nb, Ti,
  - Oxides CaO, MgO
  - Carbides SiC, UC, ThC
- Ion-source
  - Surface
  - Plasma
  - Laser
- Fluorination CF4 or SF6

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

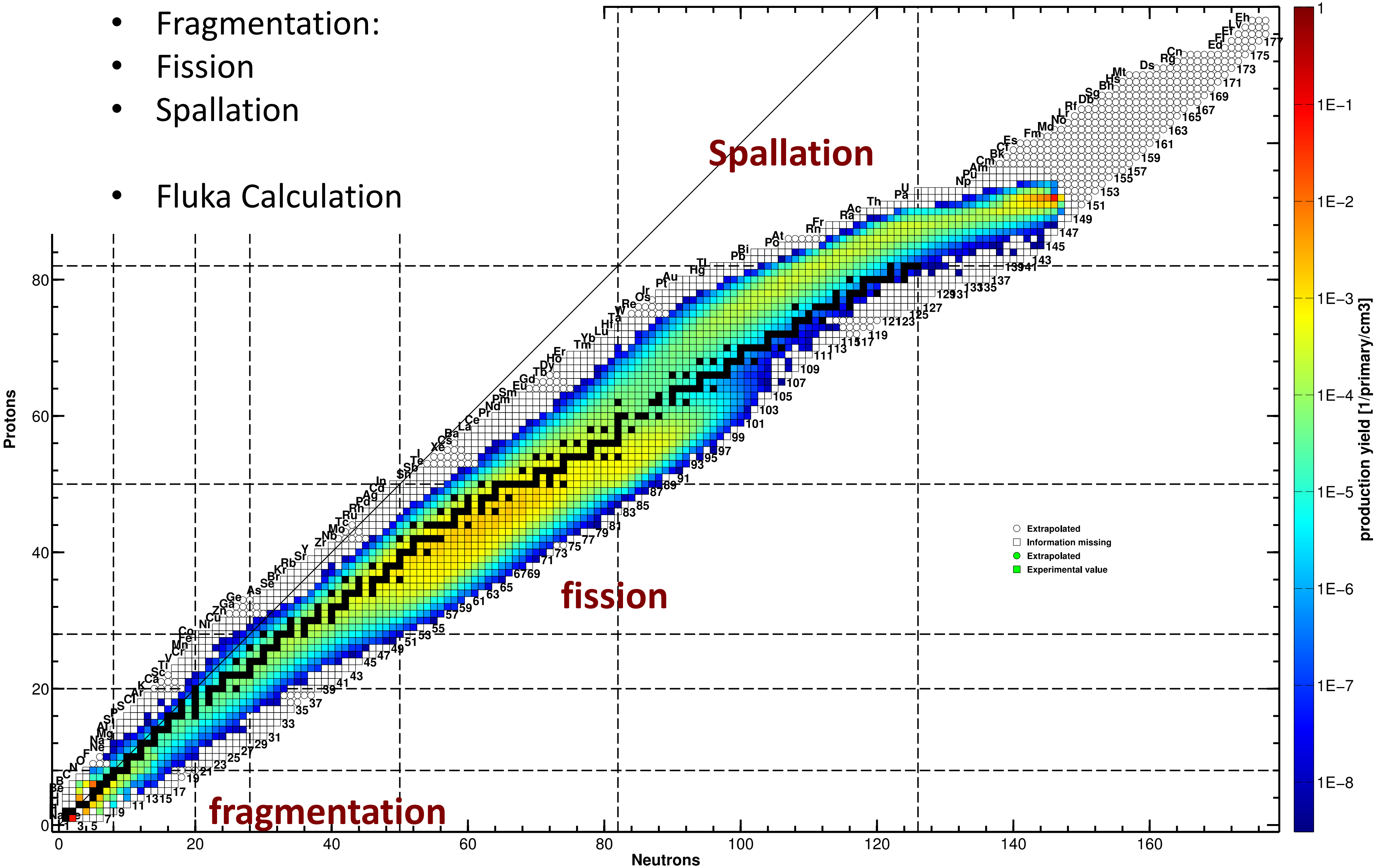




Monte Carlo Simulation of ISOLDE production

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

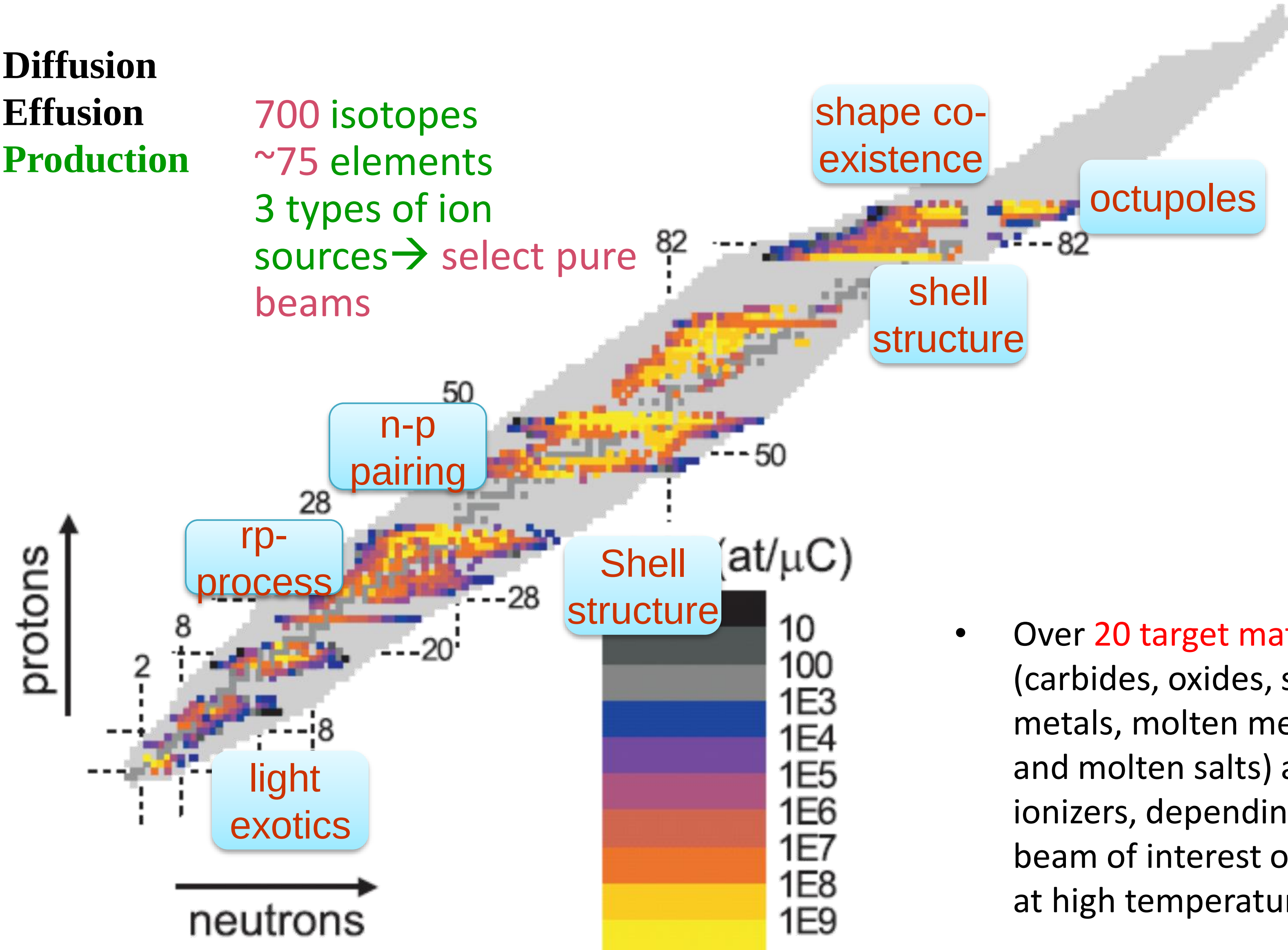
P beam on UC-Target



ISOLDE Main potential

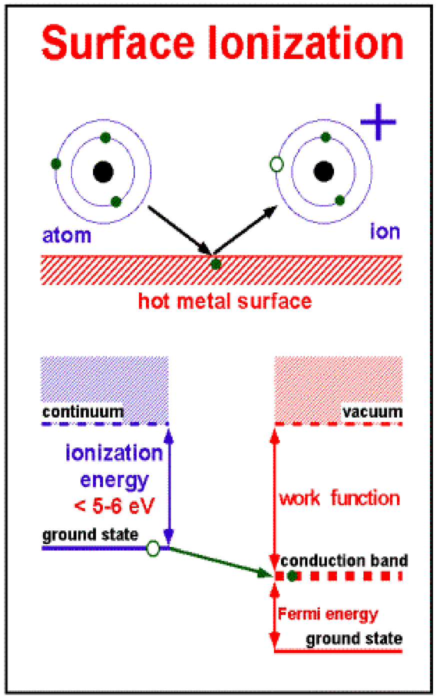
- **Diffusion**
- **Effusion**
- **Production**

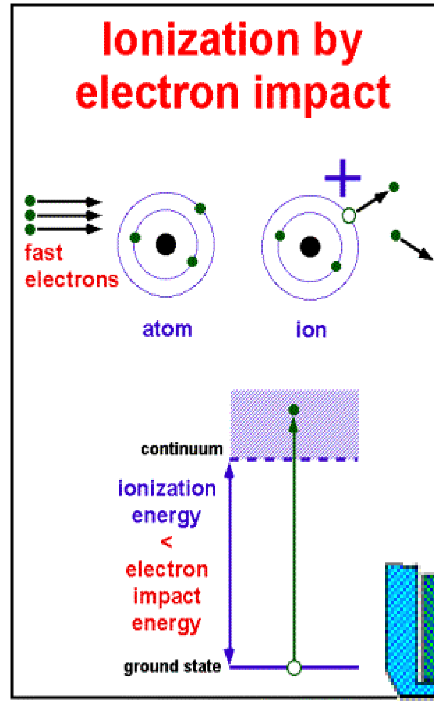
700 isotopes
~75 elements
3 types of ion sources→ select pure beams

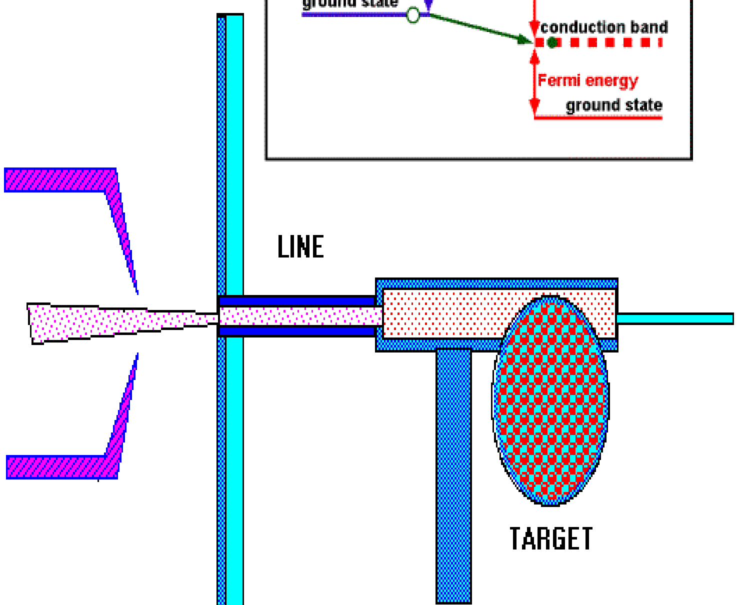


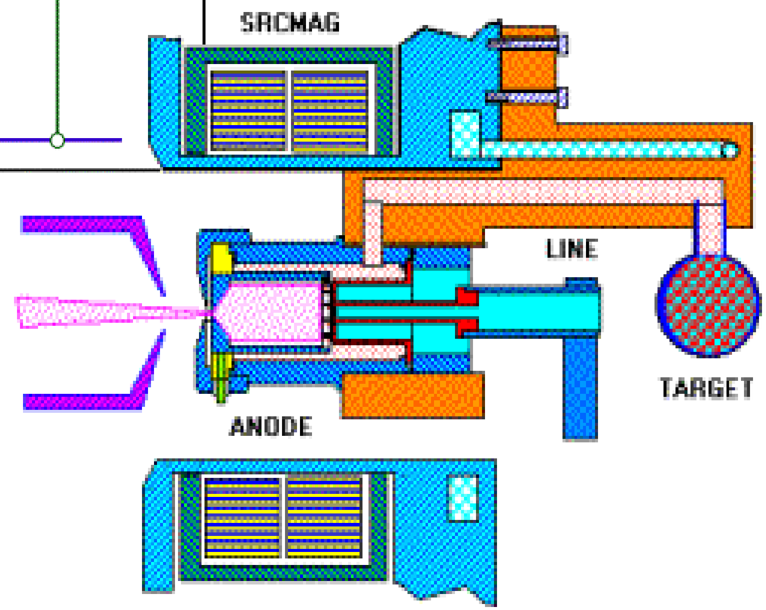
- Over 20 target materials (carbides, oxides, solid metals, molten metals and molten salts) and ionizers, depending on beam of interest operated at high temperature

Surface & plasma ionization



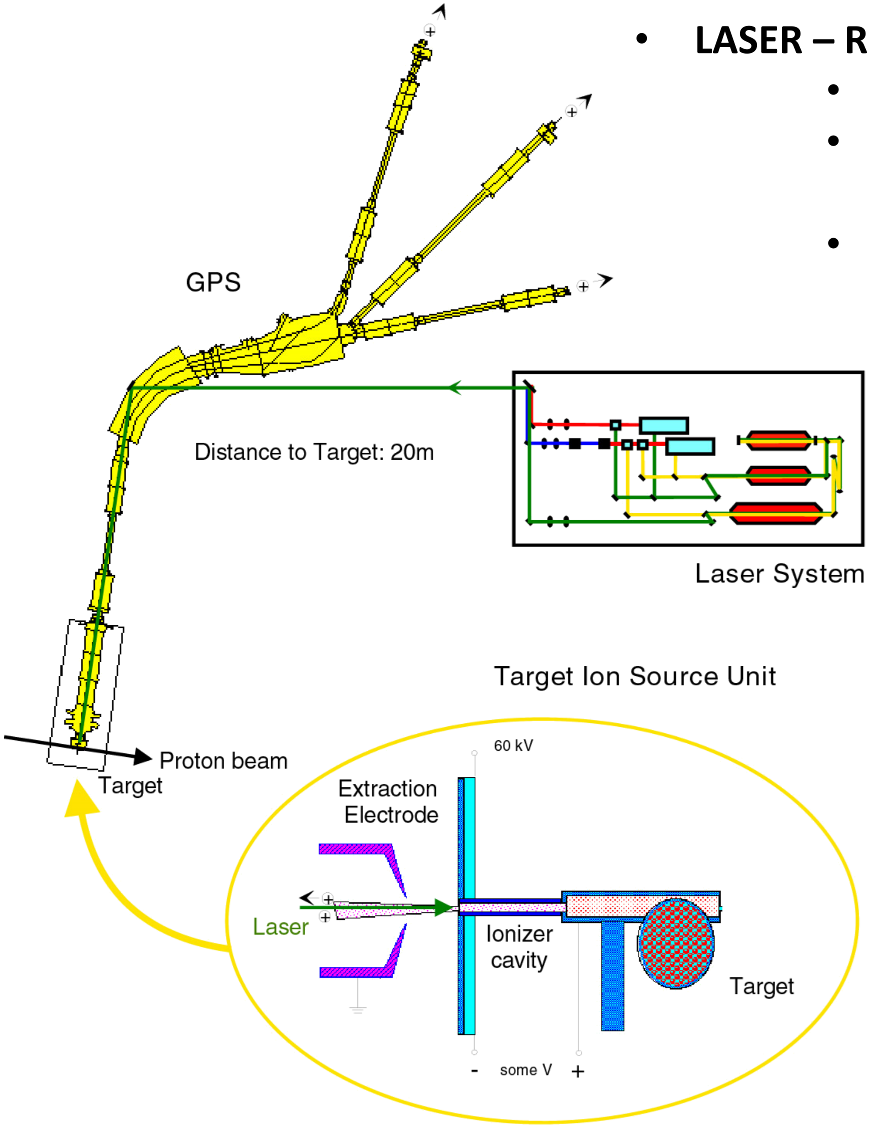


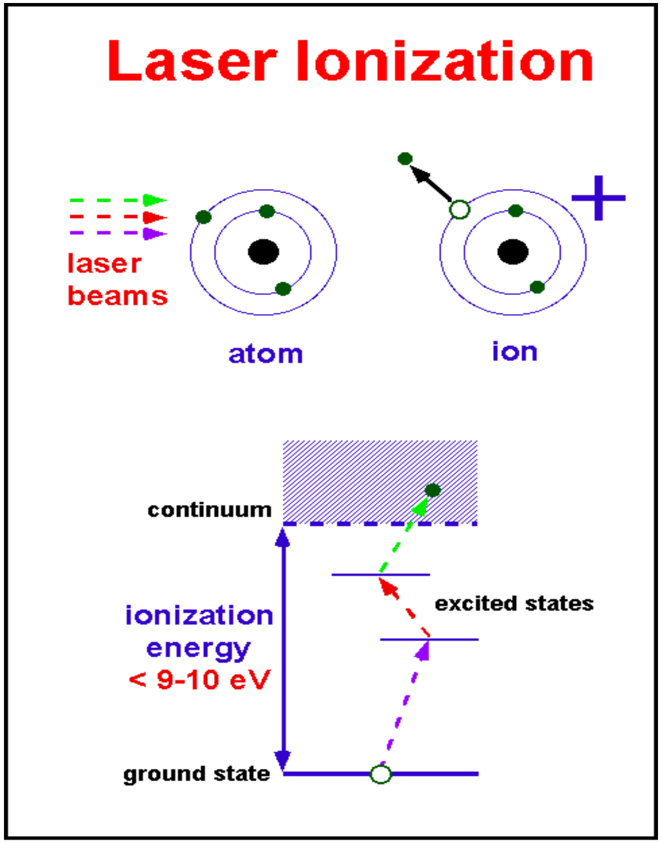




Laser Ionization source

- **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

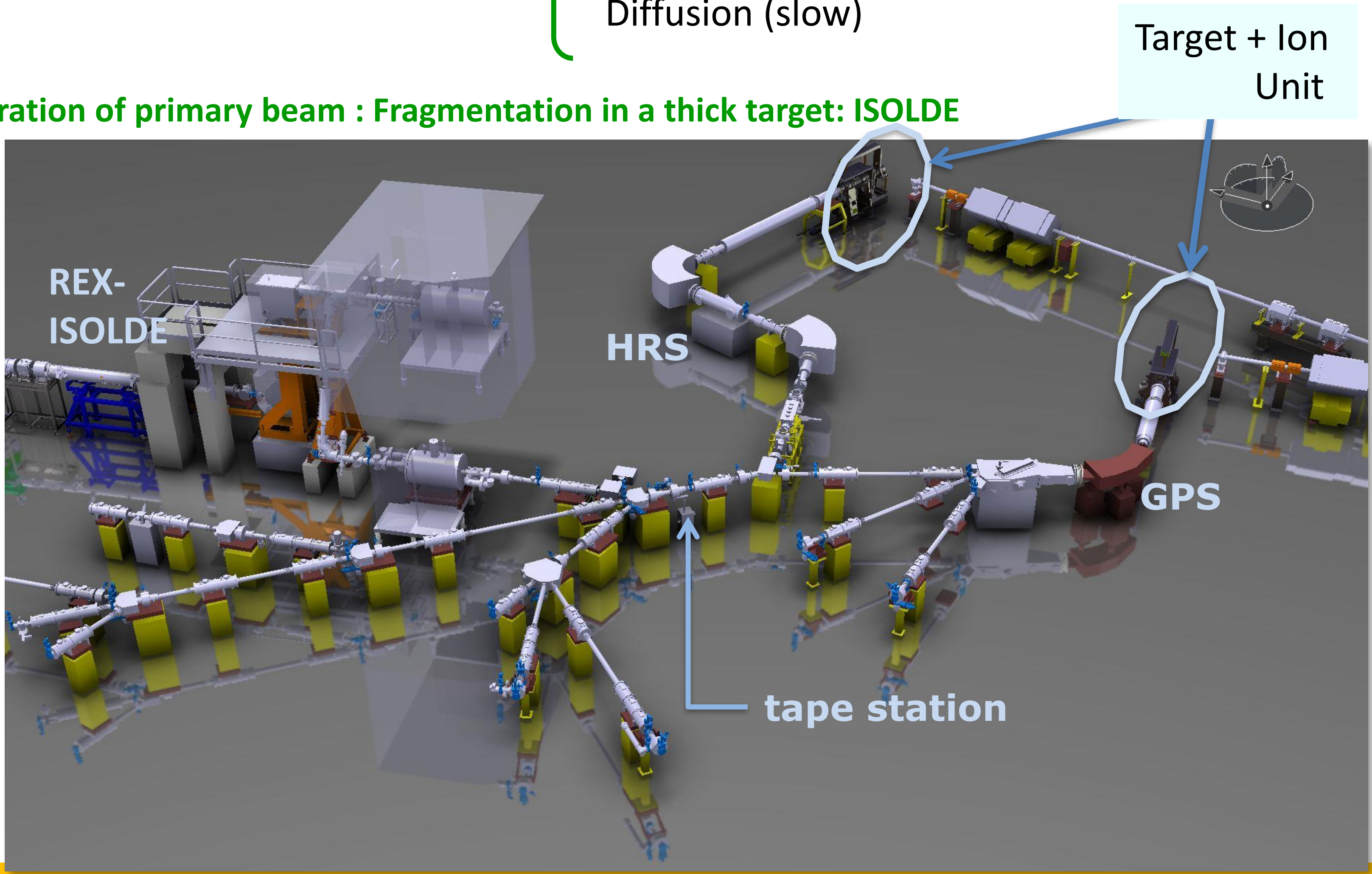




Separation @ ISOL

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

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

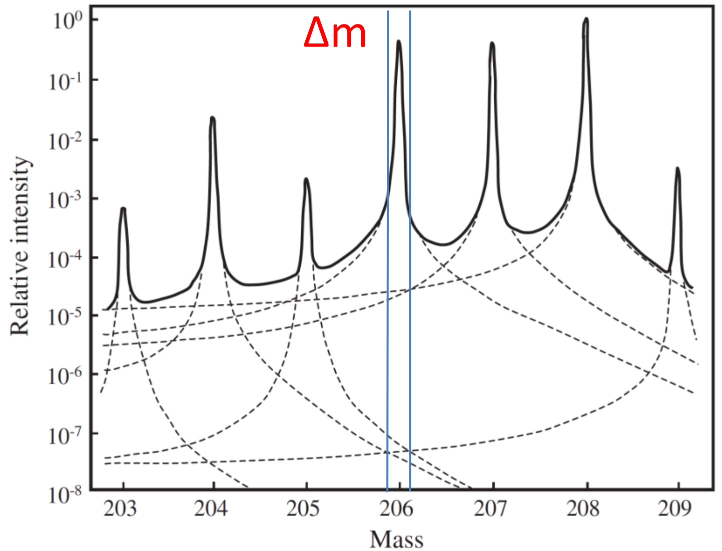


Mass separators @ ISOLDE

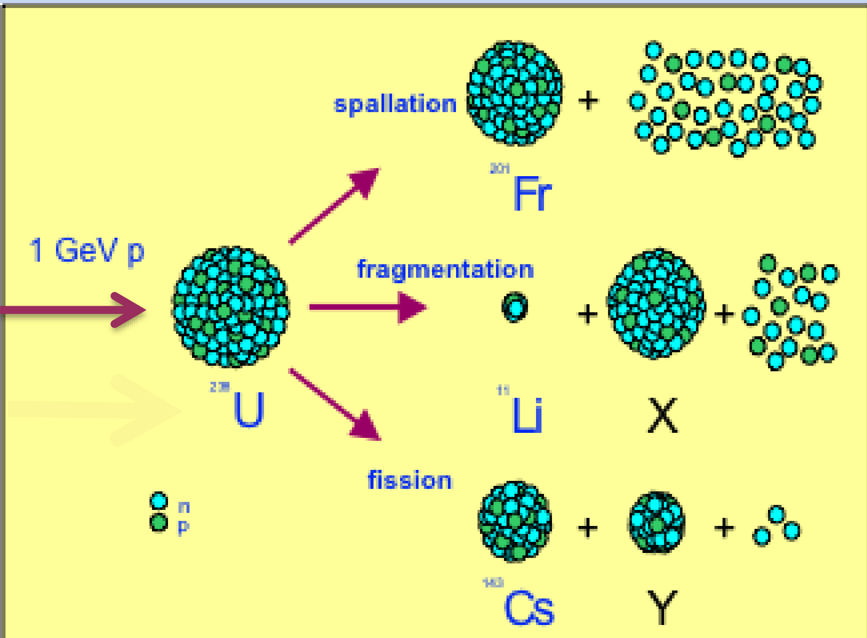
- The radioactive ions are accelerated at 20 – 60 kV and sent to the separating magnets.

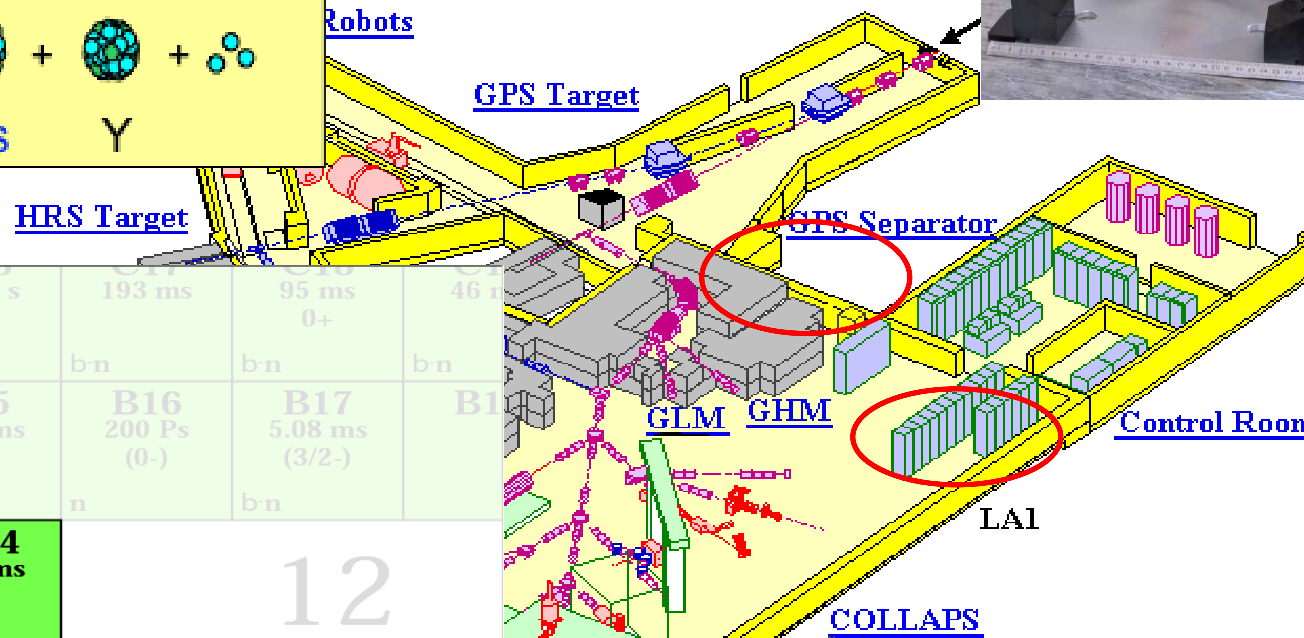
- GPS (General Purpose)
  - Magnetic dipole + electrostatic switchyard
  - Can separate simultaneously 3 masses
  - $m/\Delta m = 1000$

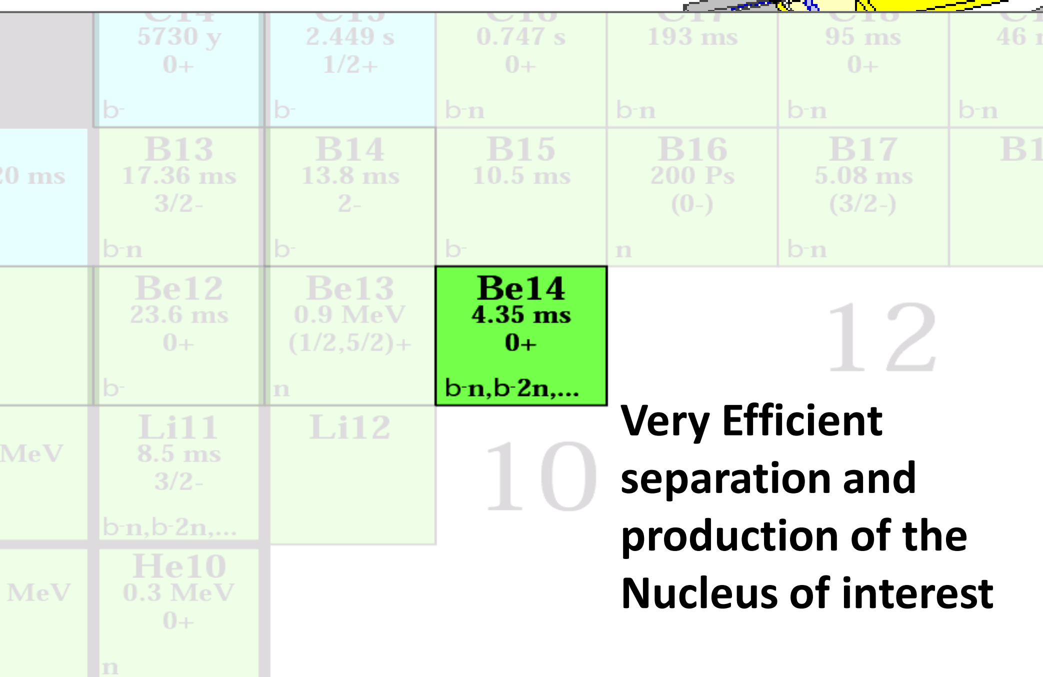
- HRS (High Resolution)
  - 2 Magnetic dipoles
  - Separation power
  - $m/\Delta m = 5000$



…election @ ISOLDE







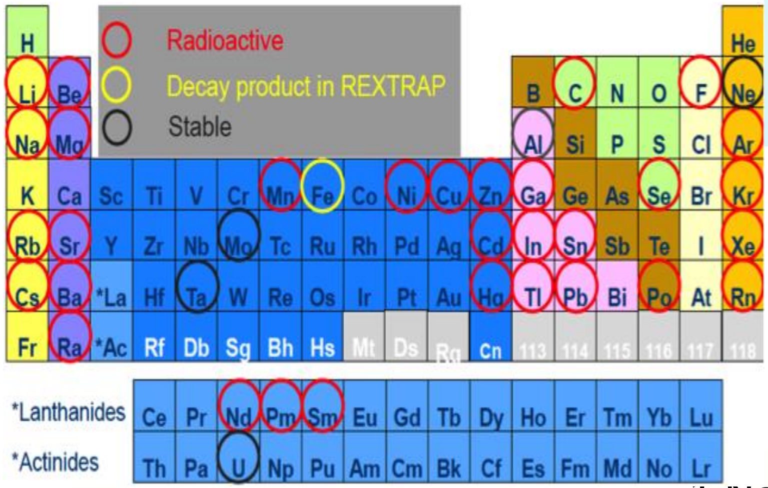
Very Efficient separation and production of the Nucleus of interest

IEM

Post-accelerator: REX-ISOLDE → HIE-ISOLDE

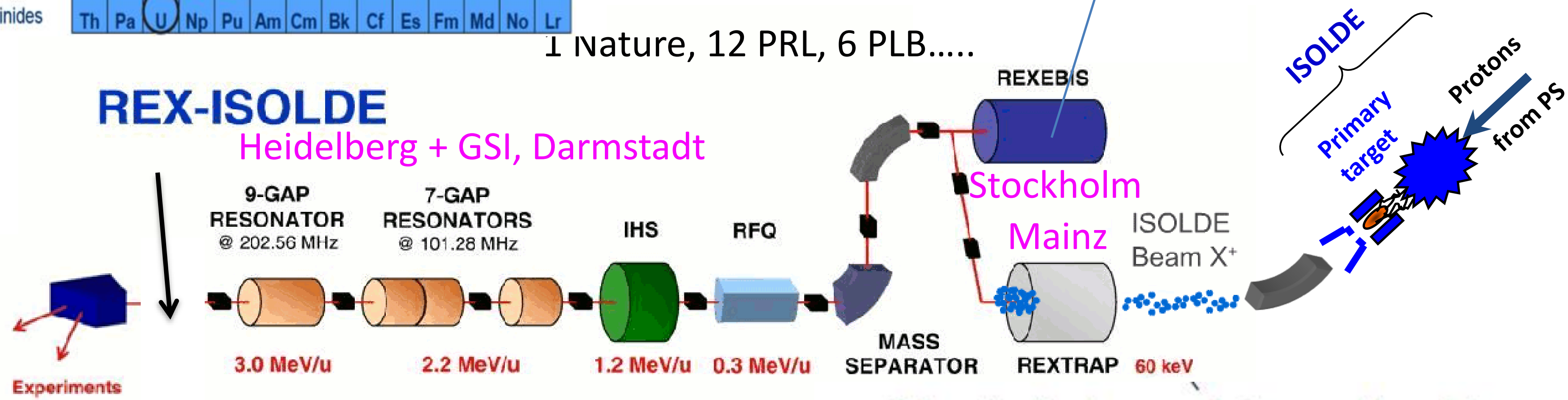
REX-ISOLDE started in 2001
HIE-ISOLDE 2014

Total efficiency : 1 -10 %



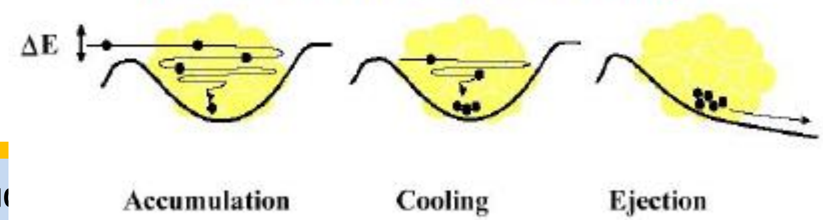
1 Nature, 12 PRL, 6 PLB…..

Charge Breeding
1^+ to $A/Q = 2 - 4.5$

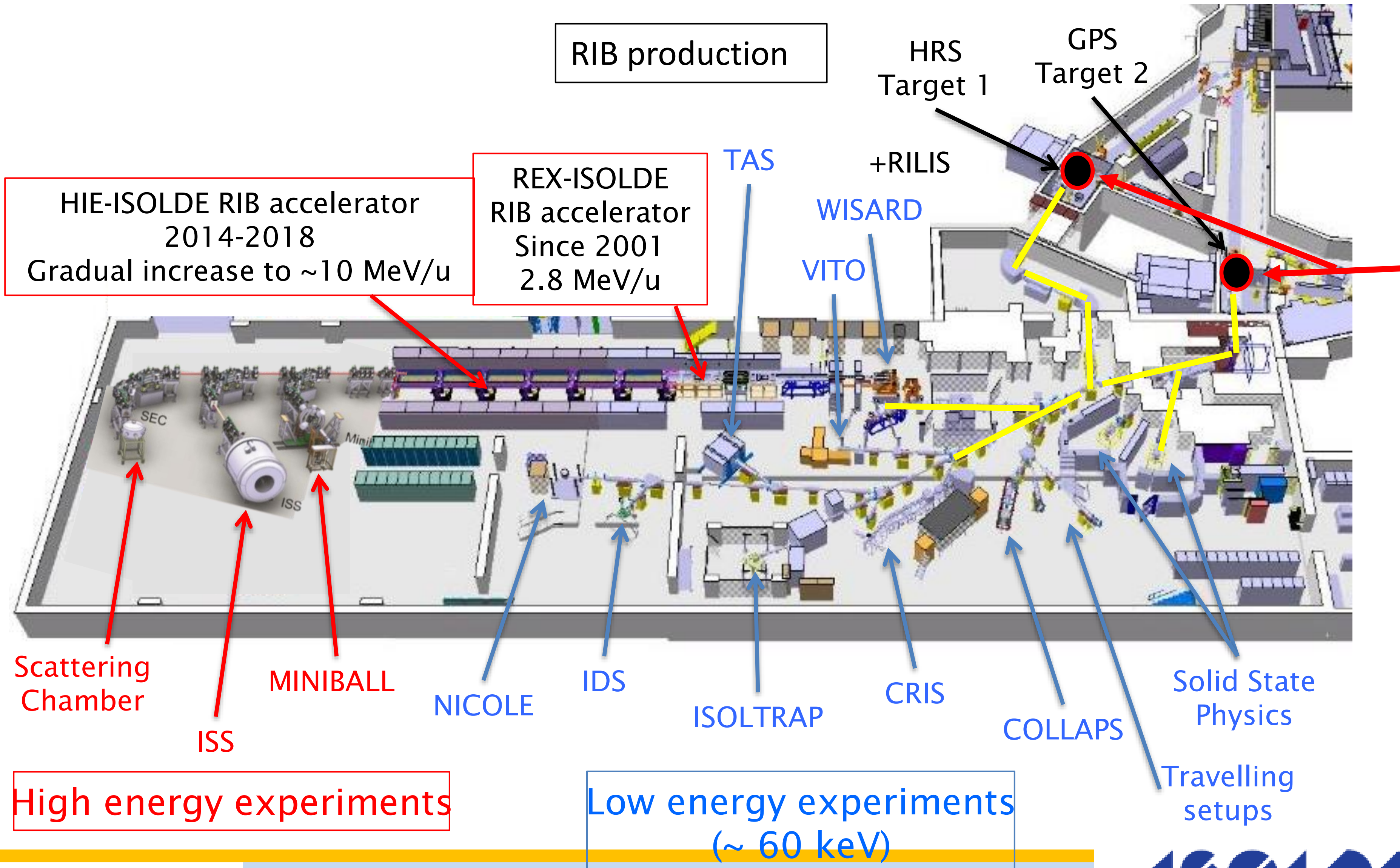


* longitudinal accumulation and bunching
* transverse phase space cooling

* 6 cavities
* 100 and 200 MHz, ~100 kW
* 300 keV/u to 3 MeV/u



The ISOLDE facility and set-ups



Summary: Two production Methods

Primary Target

extraction

ionisation

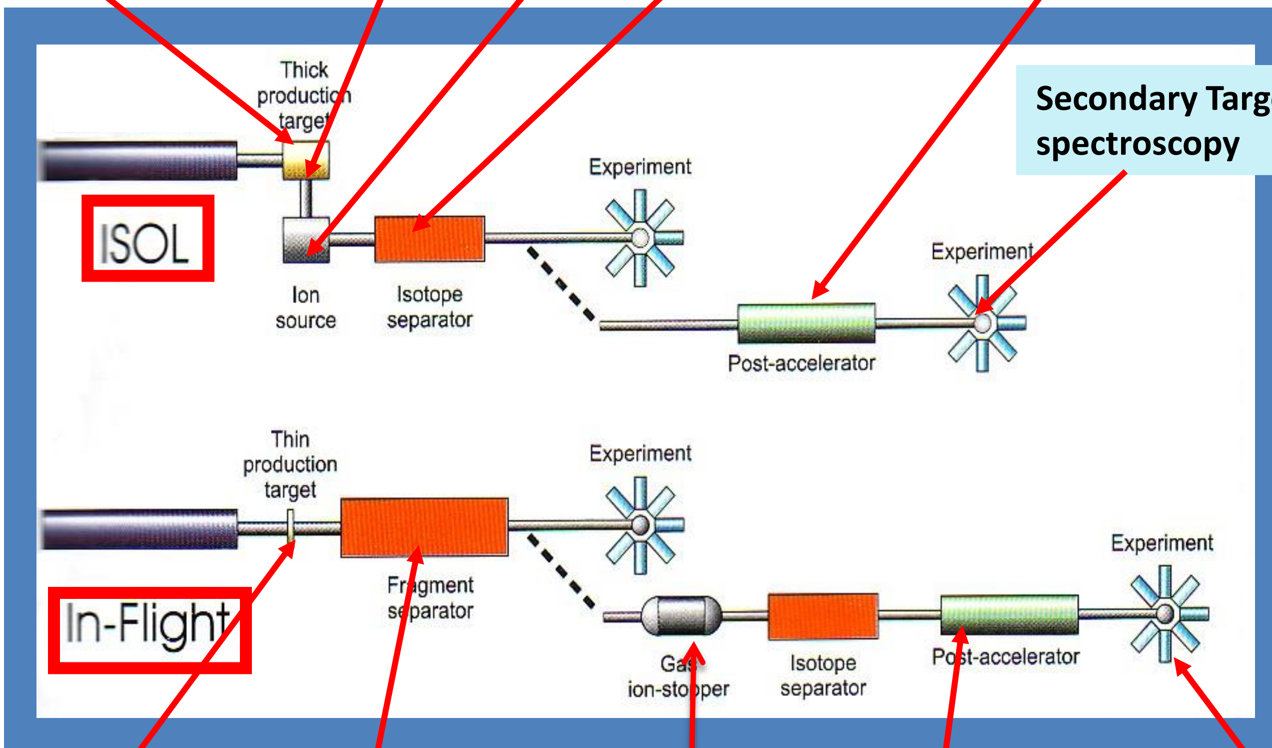
séparation

post-accelerator

Secondary Target
spectroscopy

driver accelerator

driver accelerator
ions 100 MeV - 1 GeV/u



fragmentation / fission

Fragment Separator

De-acceleration

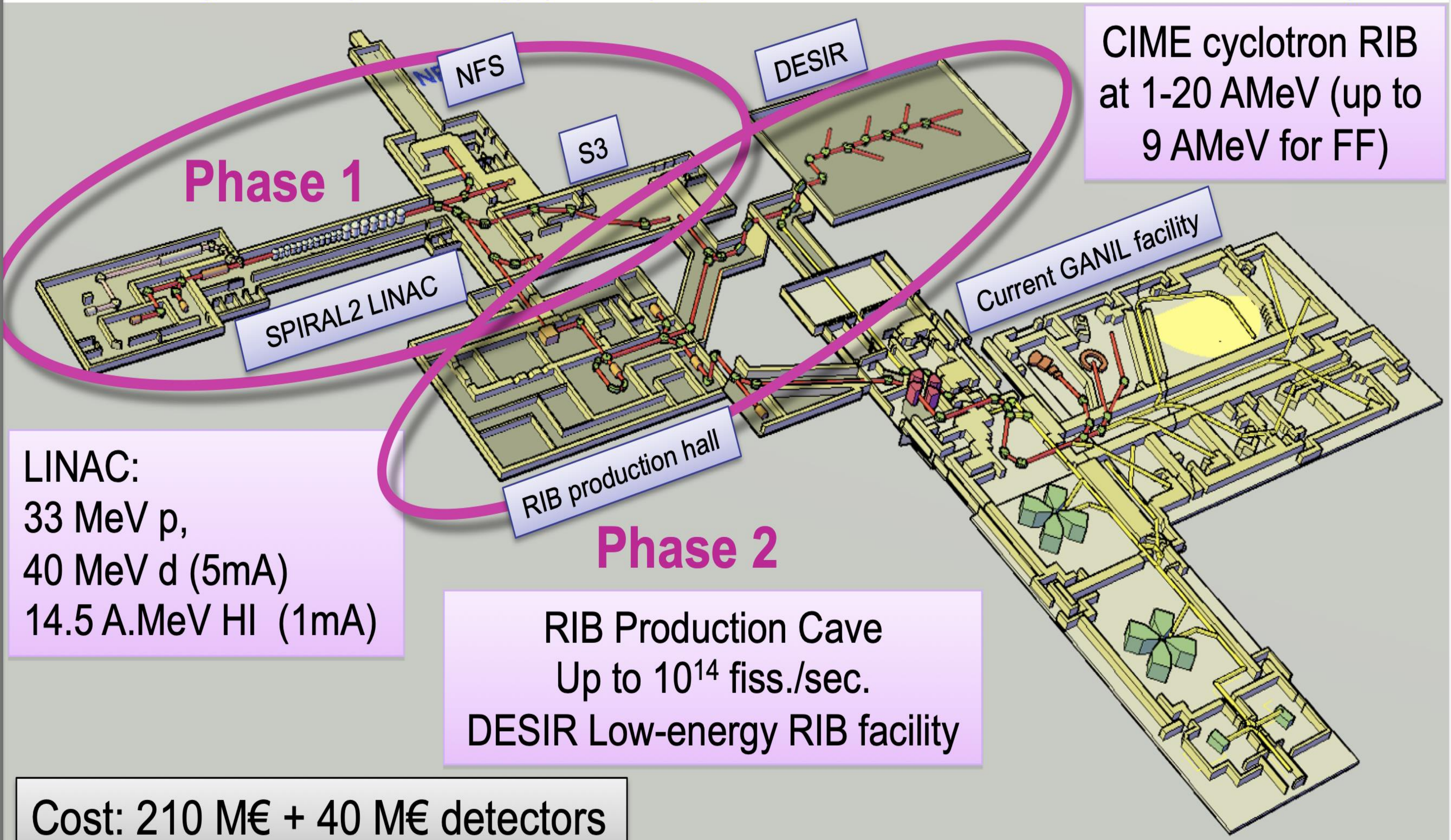
Post-accelerator

Secondary Target
Spectroscopie

SPIRAL2 Project

Phase 1: High intensity stable beams + Experimental rooms (S^3 + NFS)

Phase 2: High-intensity low-energy (DESIR) & post-accelerated Radioactive Ion Beam facility



CIME cyclotron RIB at 1-20 AMeV (up to 9 AMeV for FF)

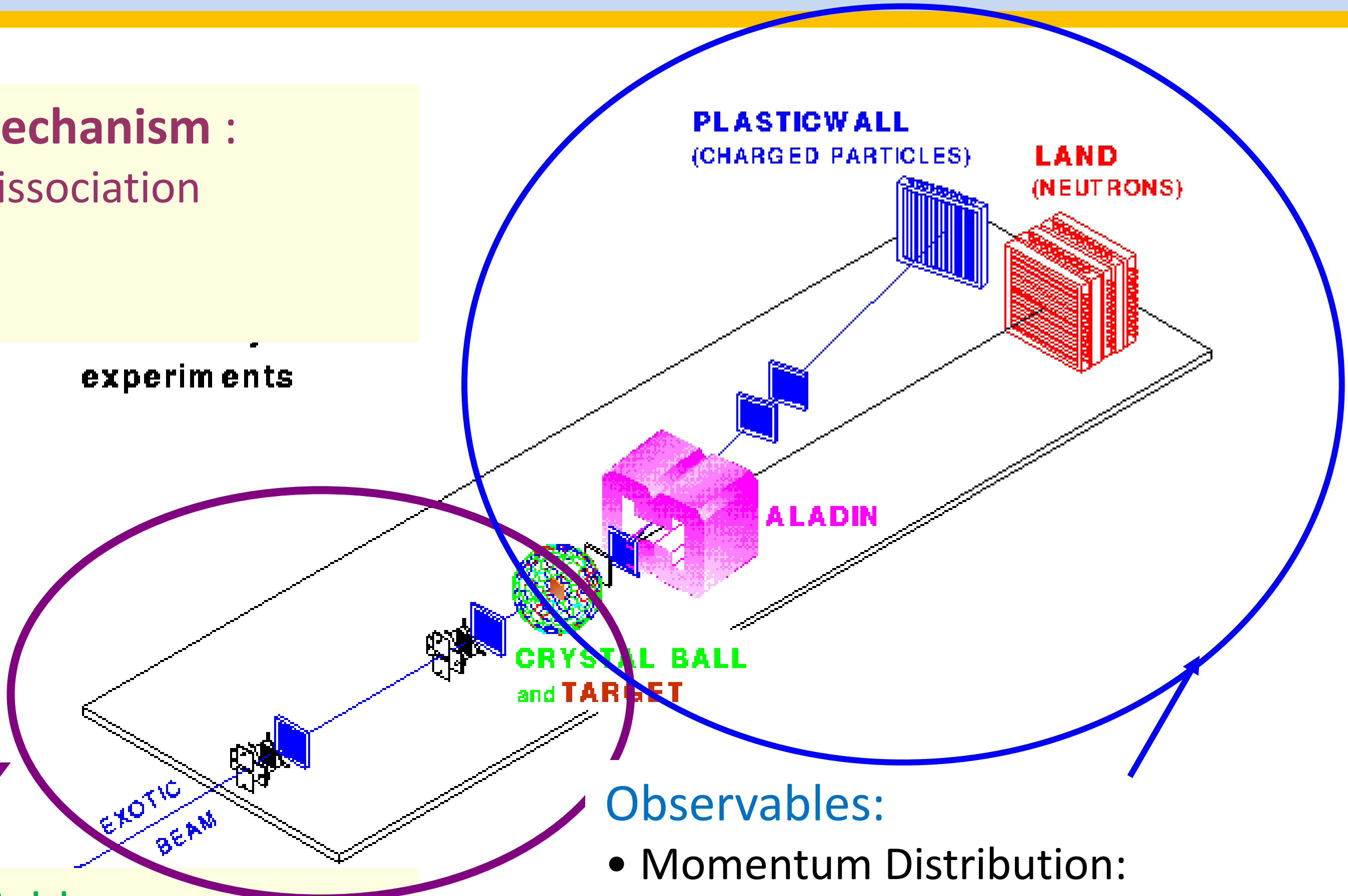
LINAC:
33 MeV p,
40 MeV d (5mA)
14.5 A.MeV HI (1mA)

RIB Production Cave
Up to 10^{14} fiss./sec.
DESIR Low-energy RIB facility

Cost: 210 M€ + 40 M€ detectors

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