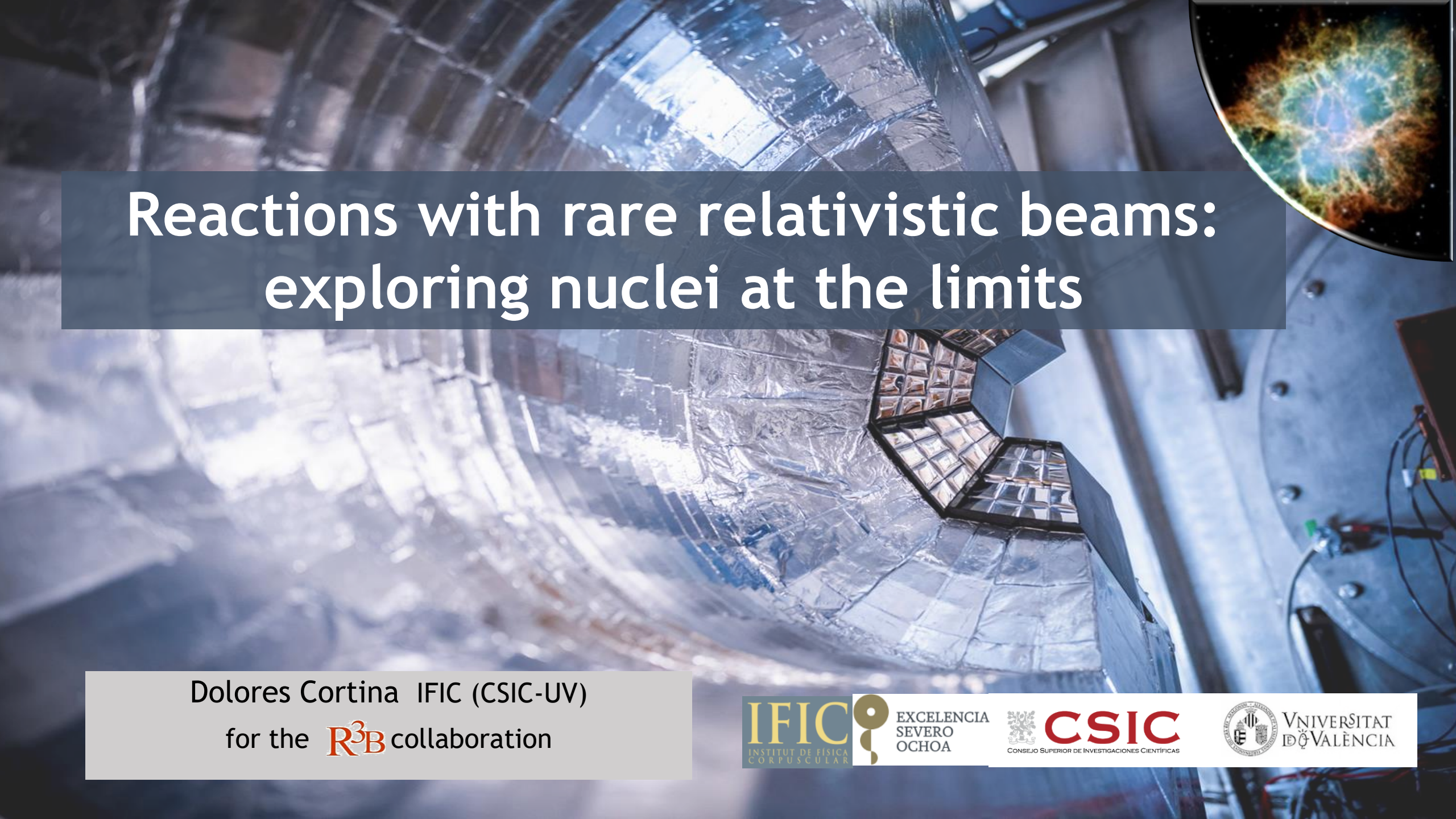


Reactions with rare relativistic beams: exploring nuclei at the limits

Dolores Cortina IFIC (CSIC-UV)

for the R3B collaboration

Index

Introduction for the non-experts
- What are exotic nuclei ?
- How we conduct our experiments ?
- Why do we need relativistic beams?

R3B @ NUSTAR

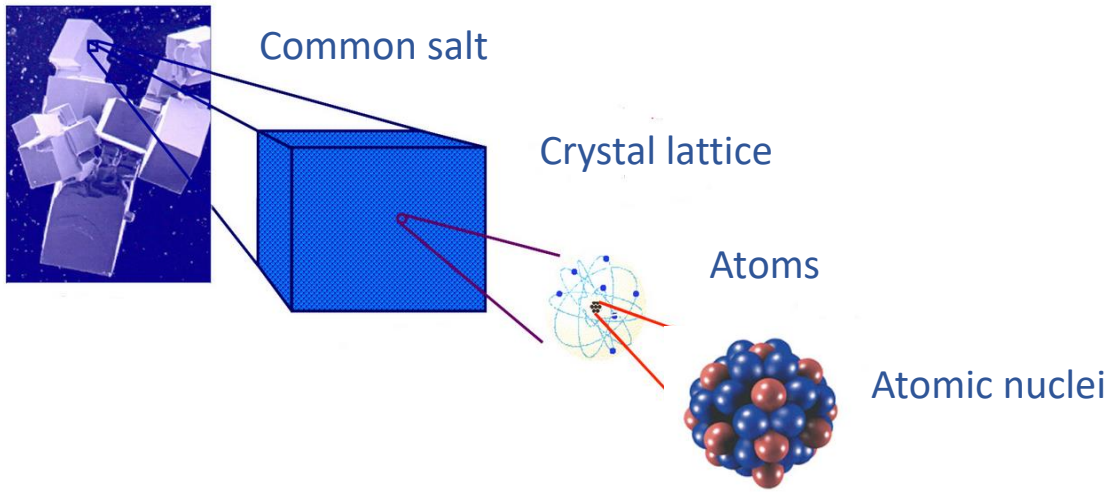
Selected examples of the R3B Research program
- Nuclear structure at the limits
- Fission and the origin of chemical elements

Introduction for the non-experts

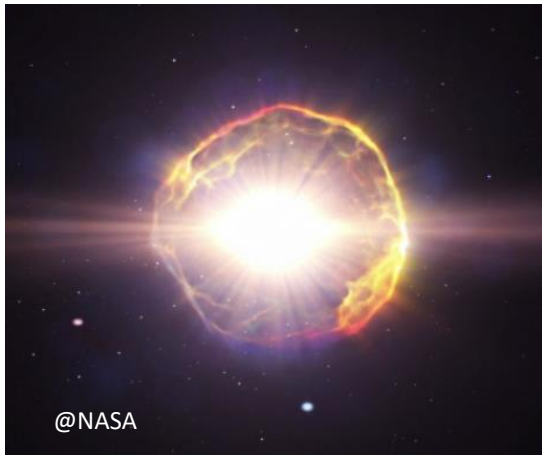
What are rare nuclei?

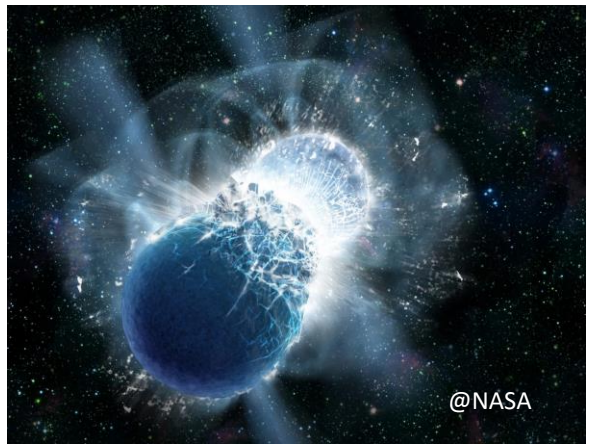
The atomic nucleus is the heart of matter

Standard matter



Astrophysical sites





Stable nuclei

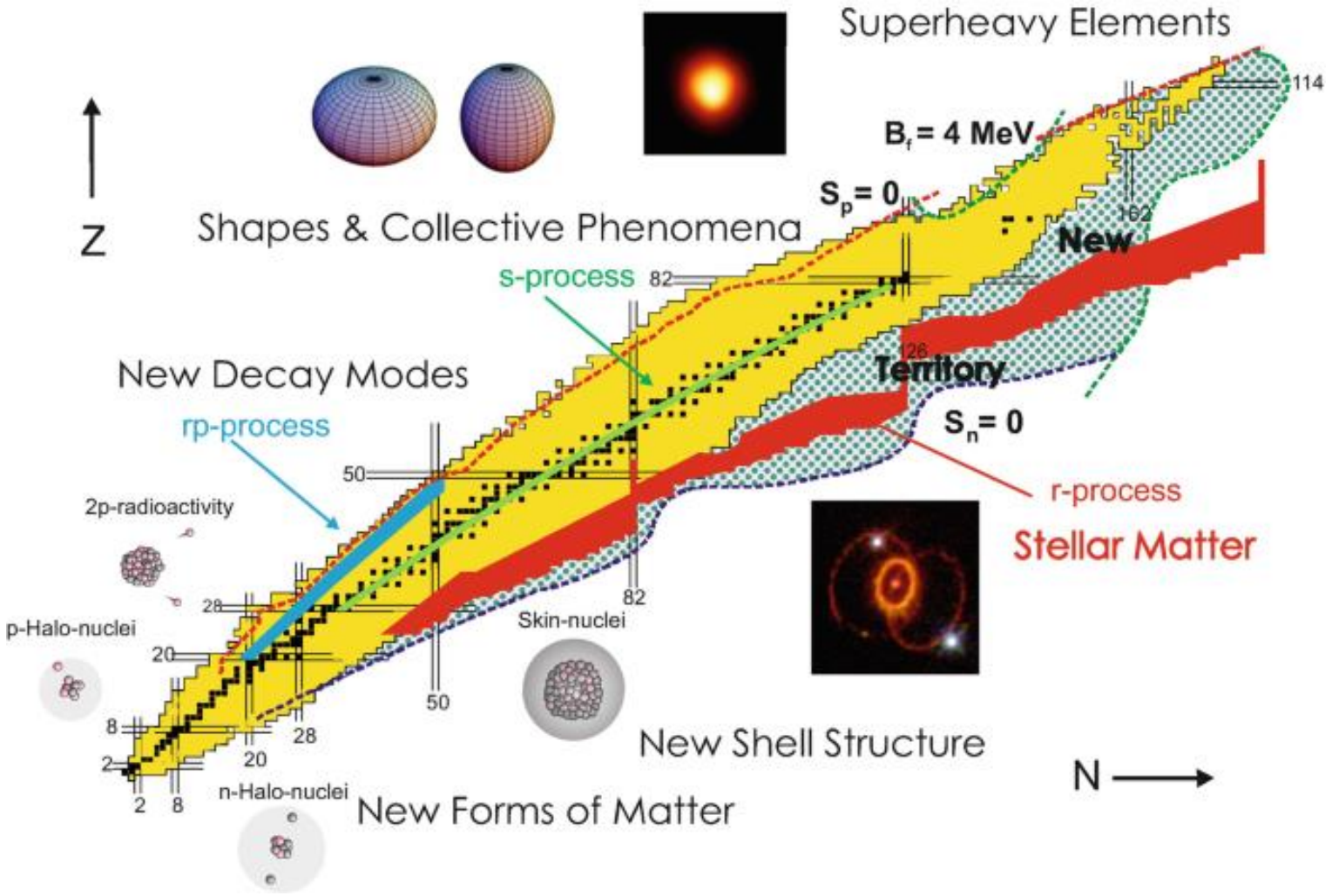
- Many body quantum system
- Made up of nucleons : protons and neutrons in a 1:1 ratio
- Well bound by the nuclear force

Unstable nuclei (rare, exotic…)

- protons and neutrons are not balanced
- Weekly bound by the nuclear force
- They have short-lives
- Important to understad how matter around us was formed

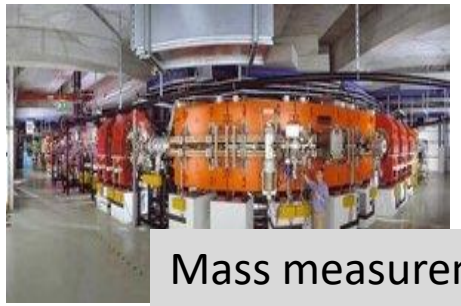
What are rare nuclei?

Some particle accelerators can produce secondary beams of exotic nuclei



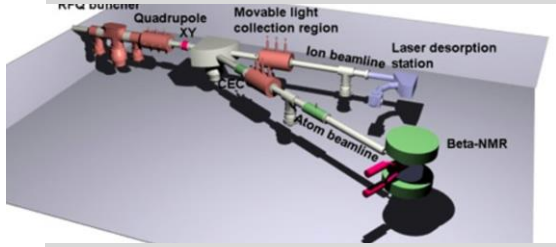
How do we conduct our experiments ?

Ground state properties:



Mass measurements

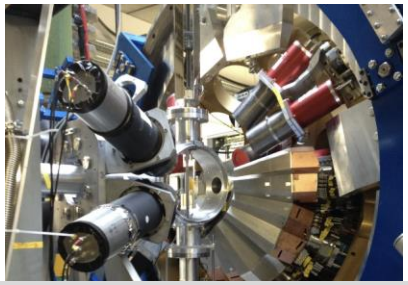
Size : mass and charge radii



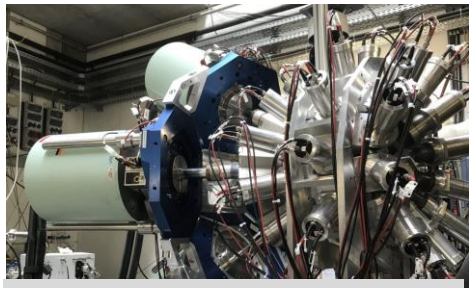
Electromagnetic moments

MATS
LasPEC
…

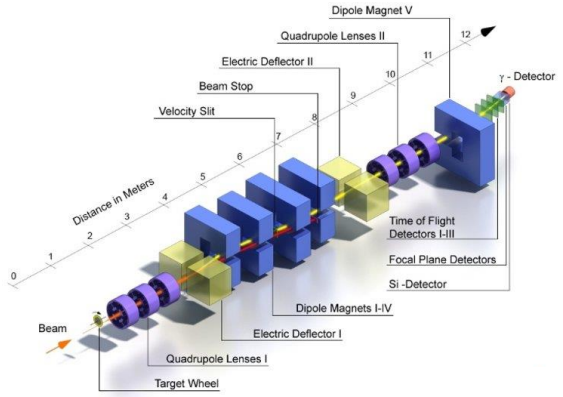
Radioactive decay:



High resolution γ spect.



Decay spectroscopy



HISPEC
DSPEC
SHE
…

Reactions:

How we conduct a reaction experiment ?

We identify the object of our study

We interact with it

Reaction

How we conduct a reaction experiment ?

We identify the object of our study.

Reaction

Detection

Full kinematics : We collect any kind of fragments in which the vase has been broken into

High resolution: The fragments have well-defined edges

High efficiency: I have a broom and dustpan adapted to the size of my fragments.

Large acceptance: I sweep a sufficiently large surface area to ensure that all fragments are collected.

How we conduct a reaction experiment ?

We identify the object of our study.

Reaction

Detection

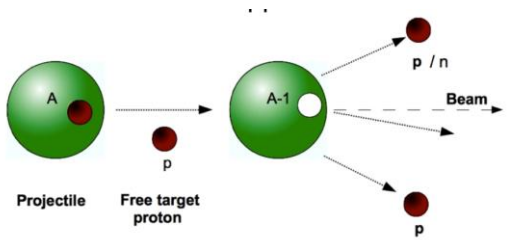
Reconstruction

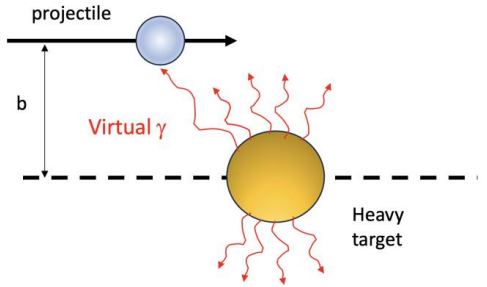
Higher the resolution, efficiency and acceptace better the reconstruction !

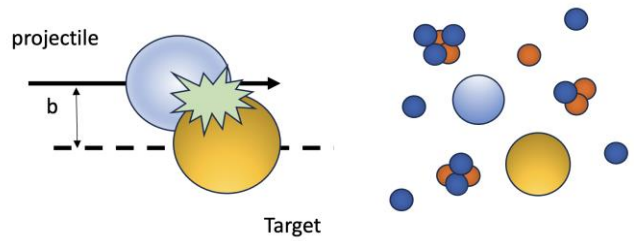
Why relativistic projectiles ?

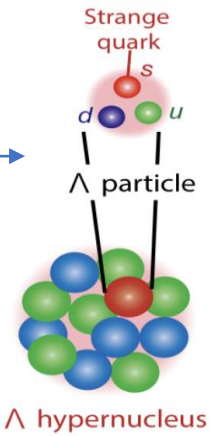
Reaction mechanisms

- Knockout – QFS
  - Single particle states
  - deeply bound/ unbound states
  - NN correlations
  - Fission
- Coulex
  - Collective excitations (GDR, Fission …)
- Charge exchange reactions
- Fragmentation
  - Equation of state
- Subnucleonic degrees of freedom
  - Nucleon resonances in nuclei
  - Hypernuclei









Why relativistic projectiles ?

Reaction mechanisms

- Knockout – QFS
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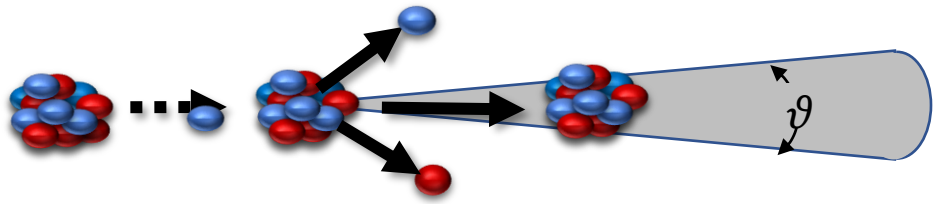
- Charge exchange reactions
- Fragmentation
  - Equation of state
- Subnucleonic degrees of freedom
  - Nucleon resonances in nuclei
  - Hypernuclei

Methodology

- Complete kinematics
- Missing mass
- Invariant mass
- Calorimetry
- Gamma Spectroscopy

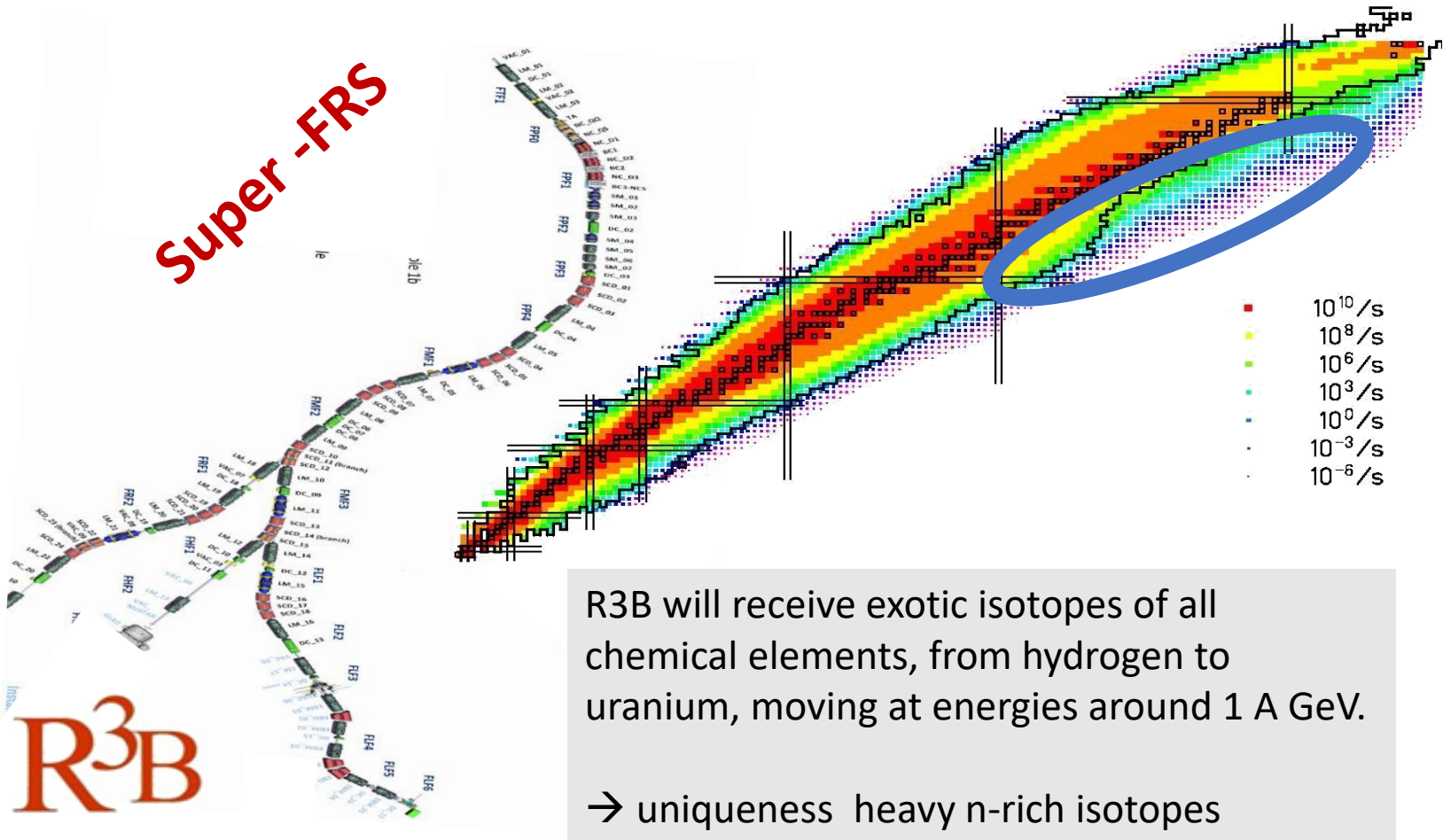
Experimental advantages

- The target thickness can be increased.
- The kinematics of the reaction products is forward focussed
- The geometrical acceptance of the detectors is large



The experimental Facility

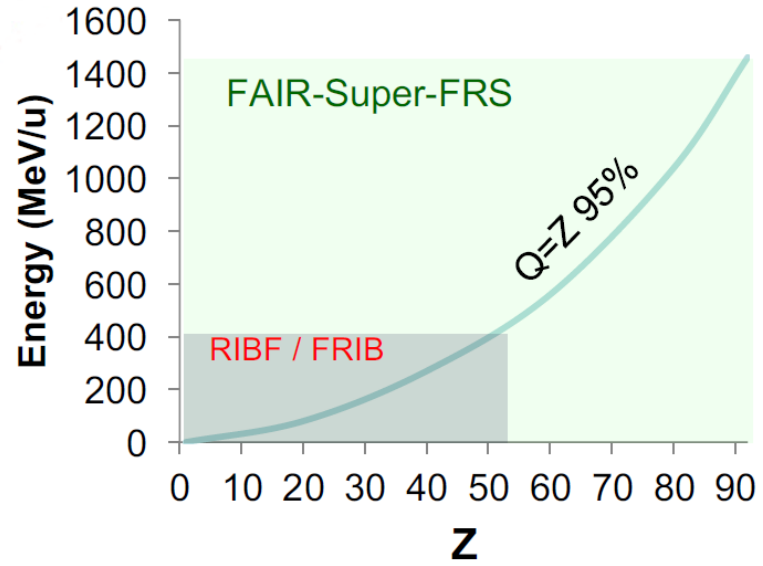
R3B @ NUSTAR



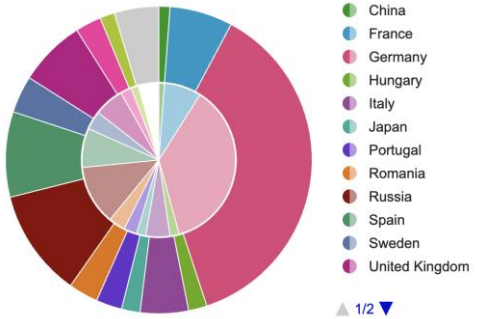
R3B will receive exotic isotopes of all chemical elements, from hydrogen to uranium, moving at energies around 1 A GeV.

→ uniqueness heavy n-rich isotopes

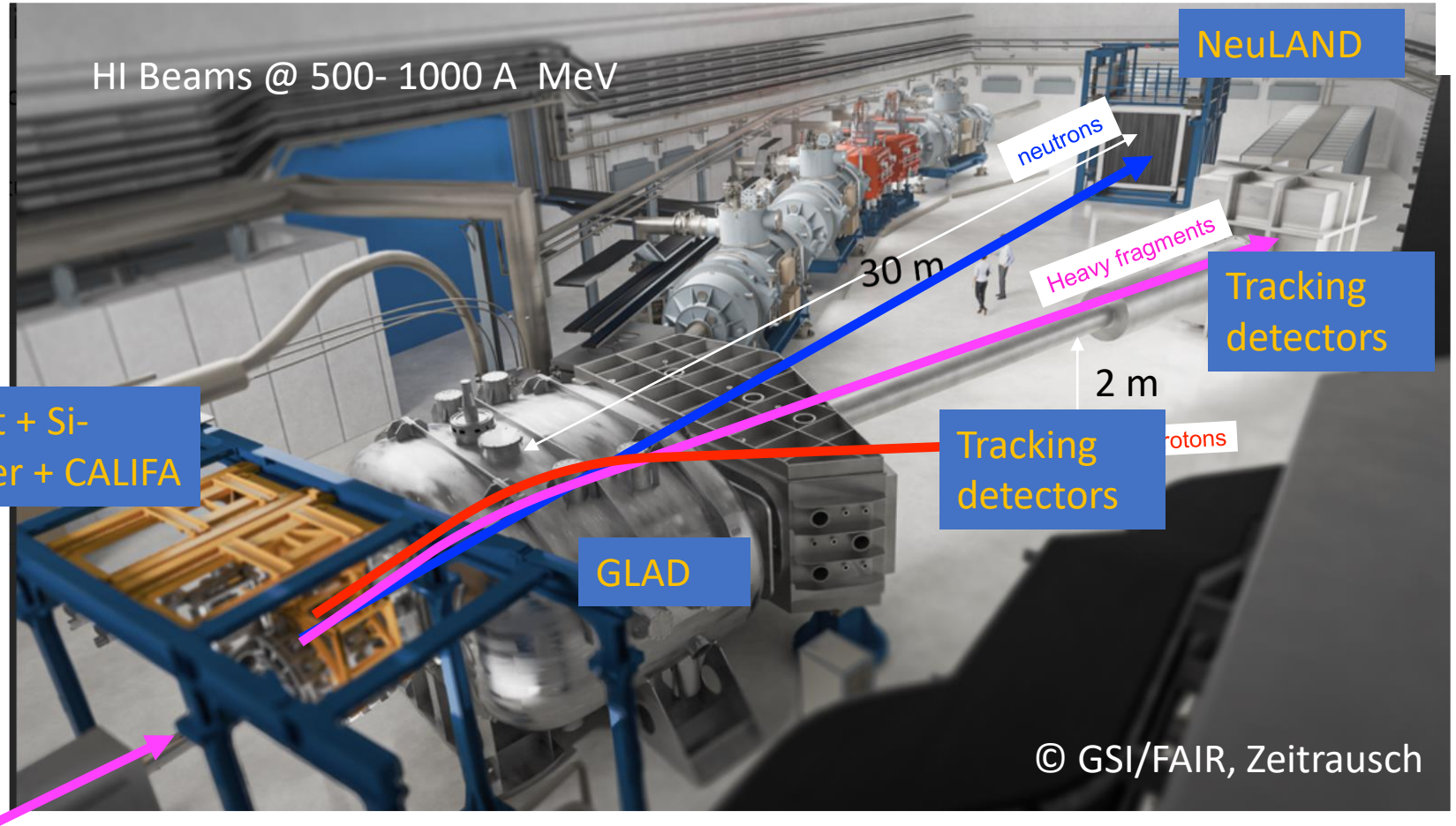
For the production of radioactive beams the main improvement
→ a factor 1000 in intensity



R3B experiment



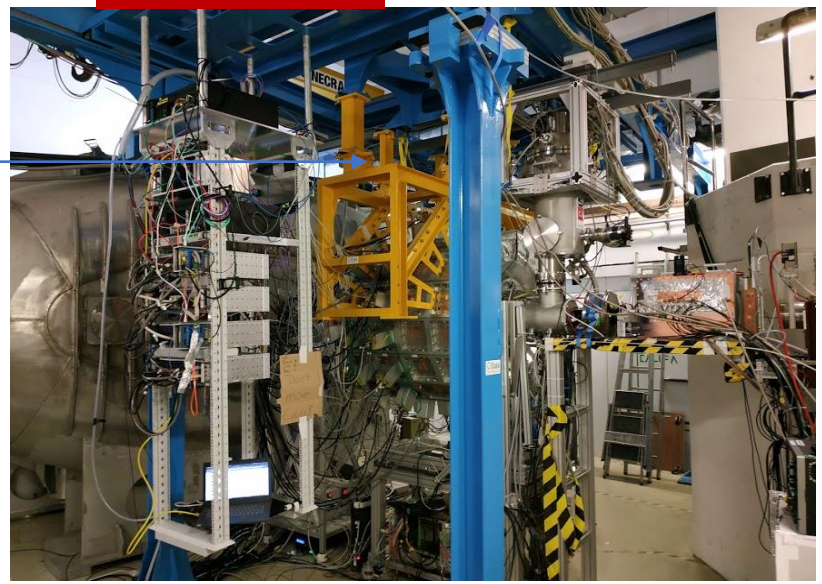
Reactions with **R**elativistic **R**adioactive **B**eams



is a modular and versatile setup for kinematically complete measurements of reactions with high-energy RI beams

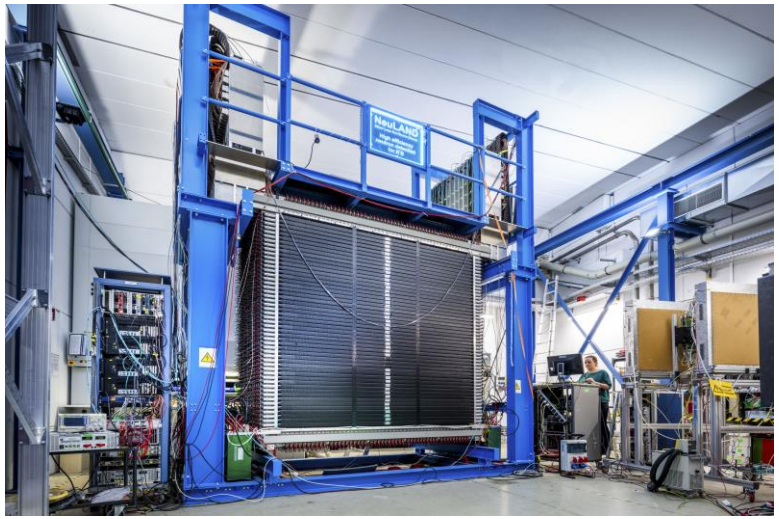
R^3B in Cave C

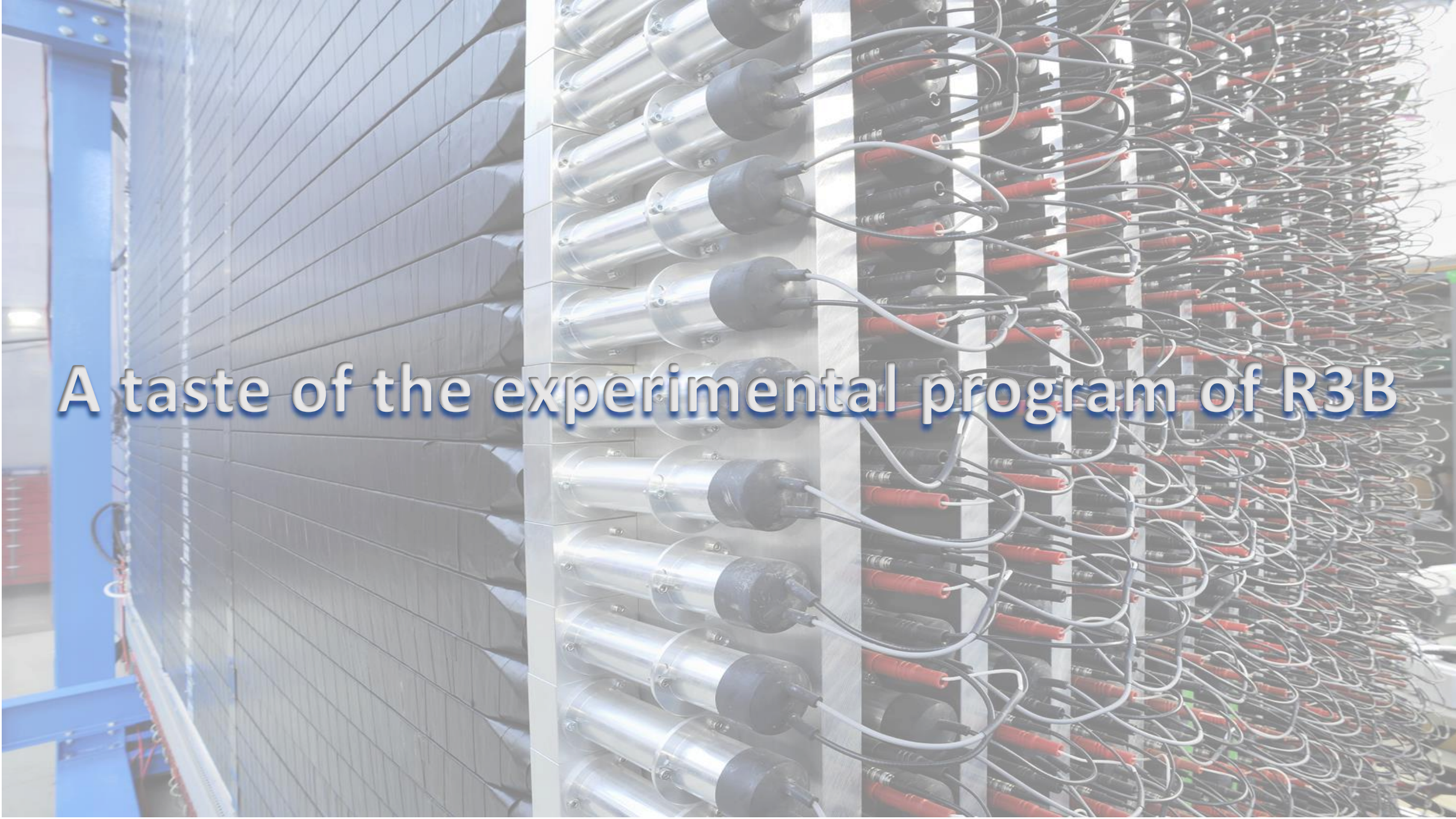
2015 - 2020



R³B in Cave C

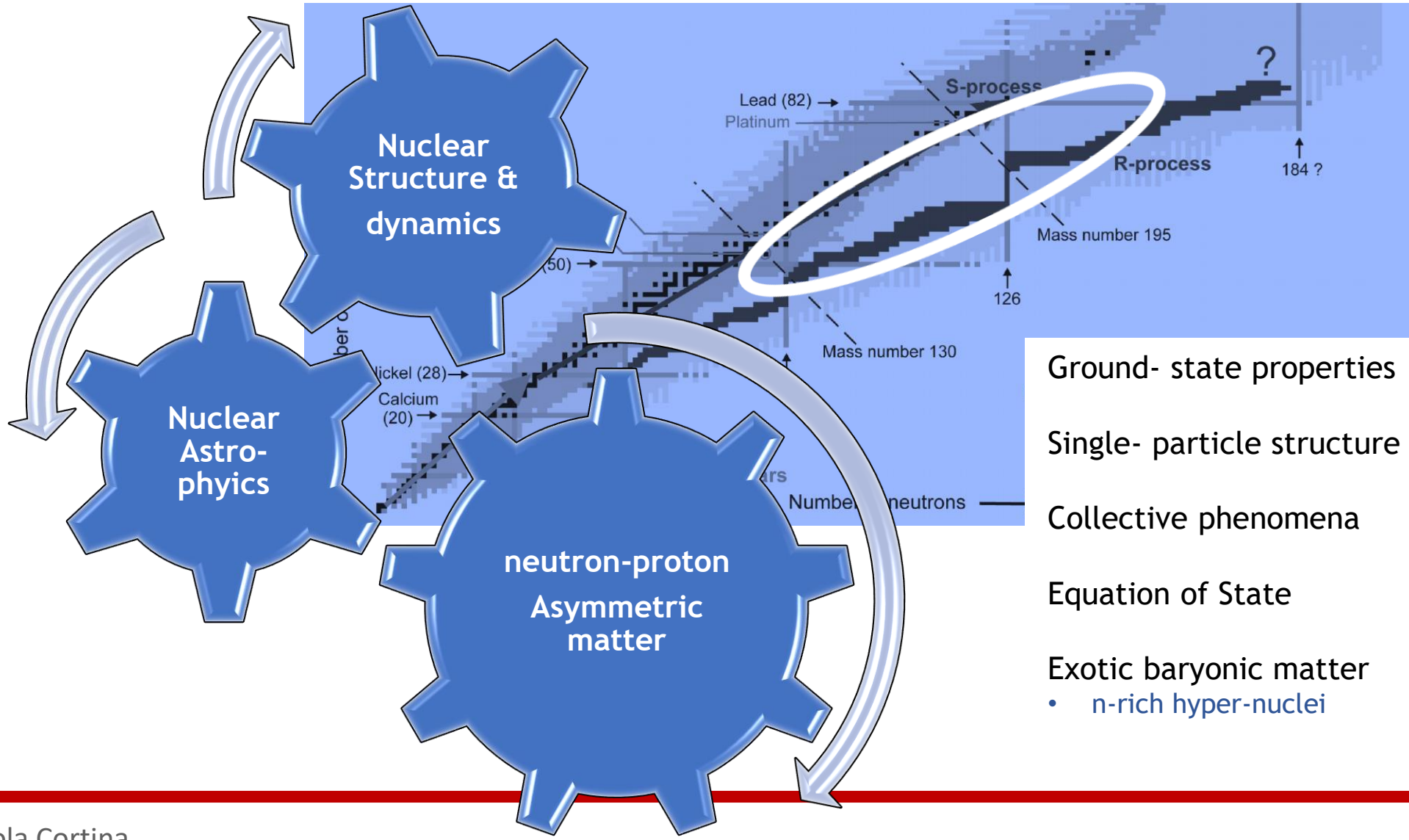
2020 - 2025





A taste of the experimental program of R3B

Broad Research Program



Ground- state properties

Single- particle structure

Collective phenomena

Equation of State

Exotic baryonic matter

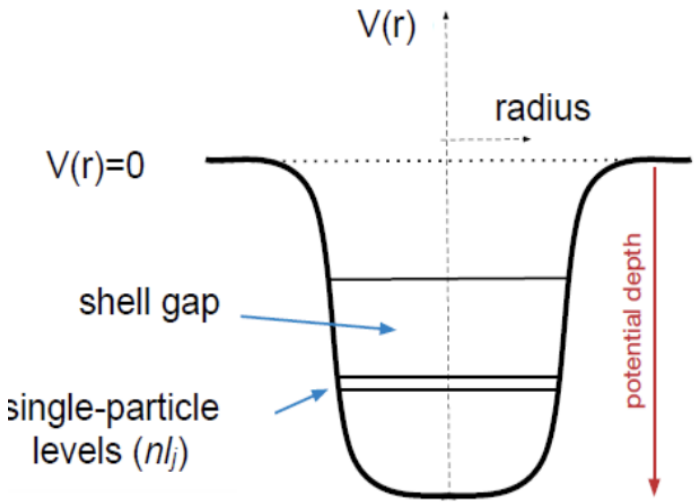
- n-rich hyper-nuclei

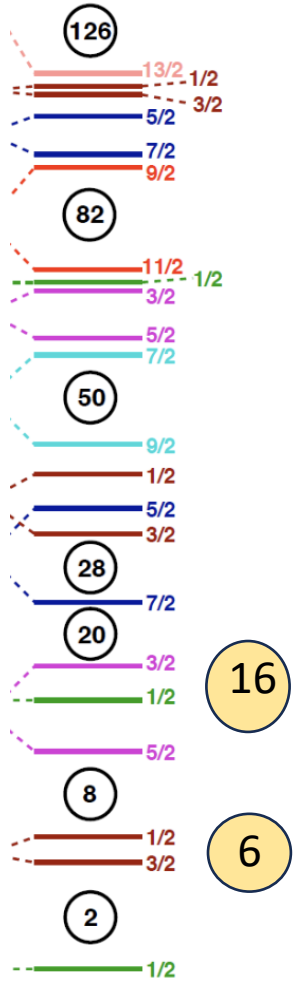
A) Single particle structure: Shell evolution

Our knowledge and understanding of the complex structure of the nuclei is based on what is known as the **Shell model** : mean field + residual

The most striking fingerprint is the organisation of the energy single-particle nucleon levels, grouped into shells that give origine to the magic numbers

→ associated to extra-stability





The nuclear interaction can be divided in several parts:

- Central
- Spin-orbit (SO)
- Tensor

The imbalance ratio N /Z modifies the ¨weight¨ of these contributions

→ magic numbers can change

Study the Shell evolution with the isospin

→ Use of knockout in QFS regime

A) Single particle structure: Shell evolution

Our knowledge and understanding of the complex structure of the nuclei is based on what is known as the **Shell model** : mean field + residual

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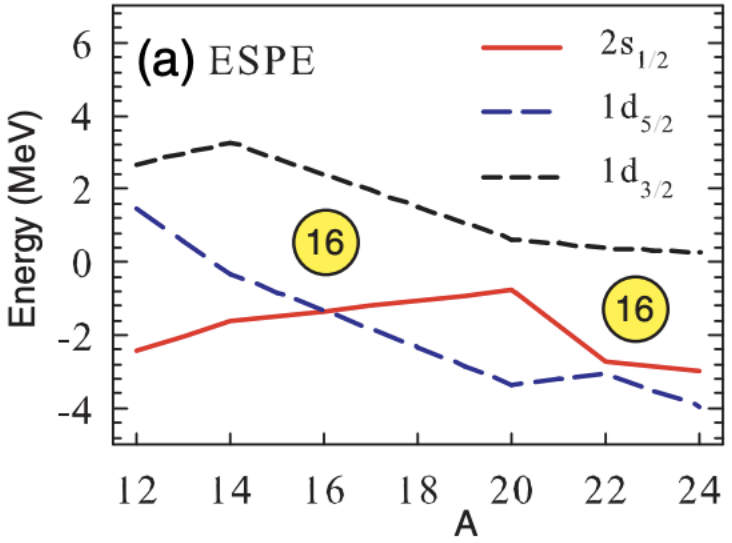

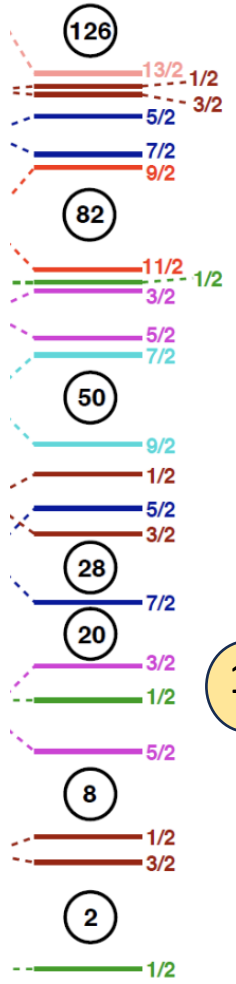

16

The nuclear interaction can be divided in several parts:

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- Spin-orbit (SO)
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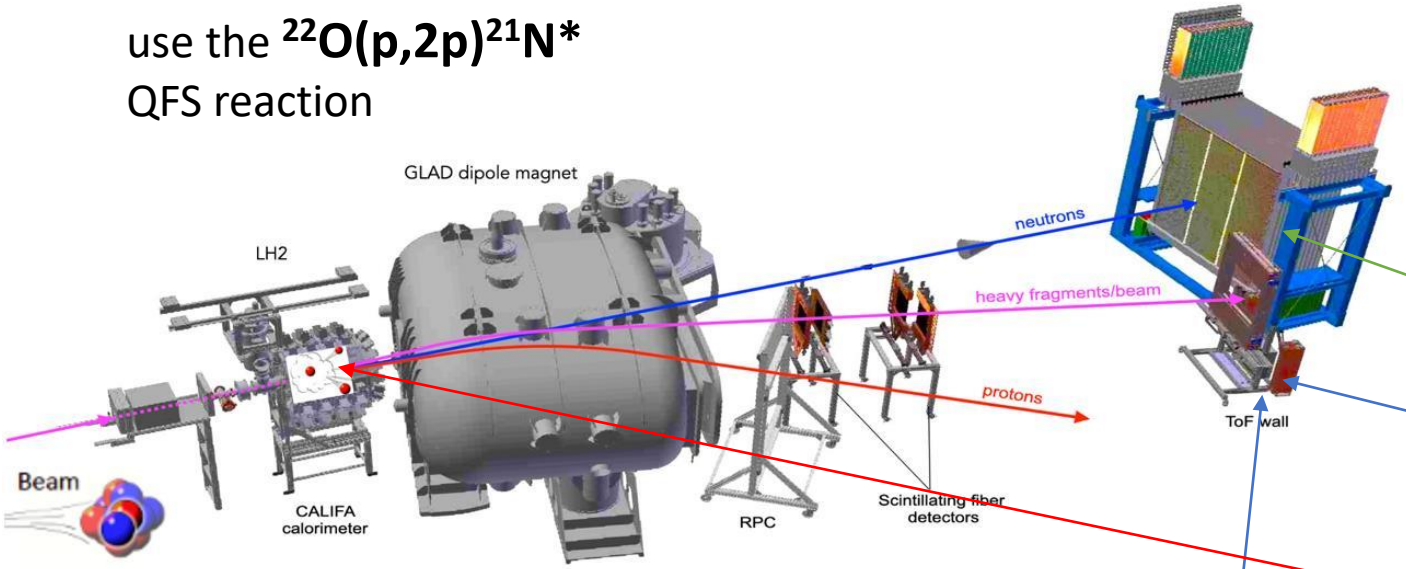
Study the Shell evolution with the isospin

→ Use of knockout in QFS regime

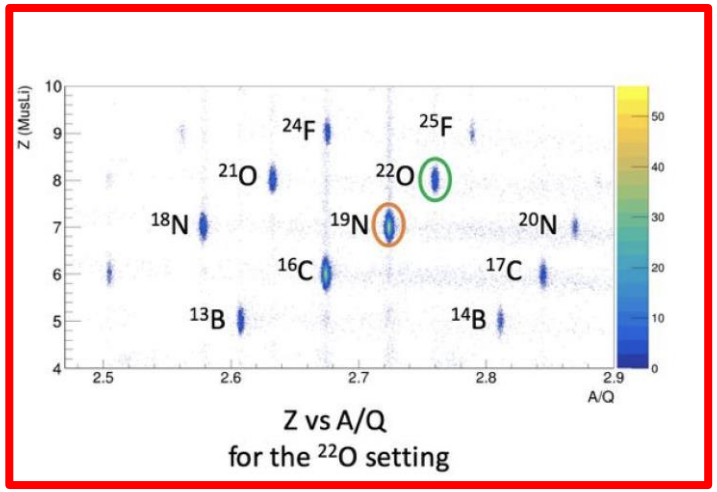
A) Single particle structure: Shell evolution

use the $^{22}O(p,2p)^{21}N^*$ QFS reaction



Study of the tensor force in the O, (C) isotopic chain using QFS reactions

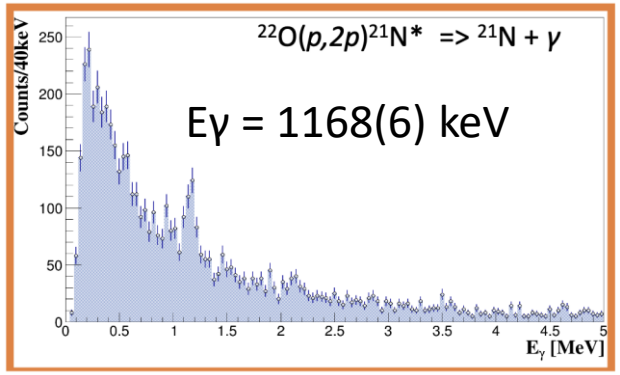
To determine how the Z = 6 gap (first proton spin-orbit splitting) evolves from stability to the dripline, ^{16}O to ^{22}O



Z vs A/Q
for the ^{22}O setting

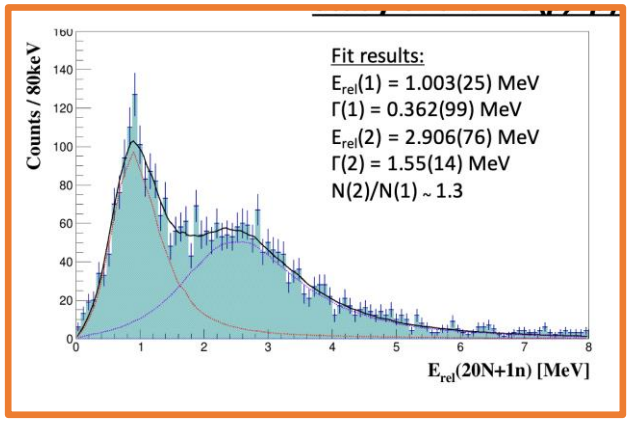
^{21}N + γ

To bound



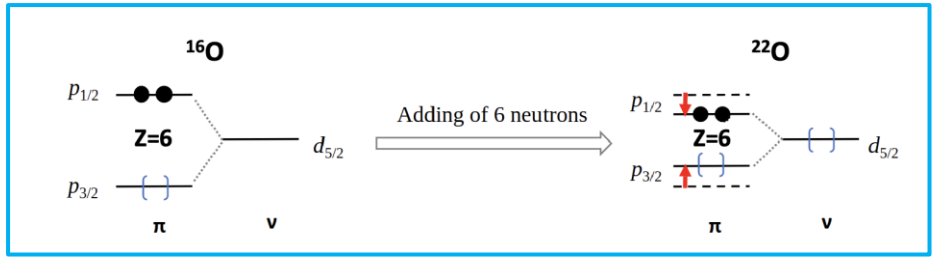
^{20}N + n

To unbound

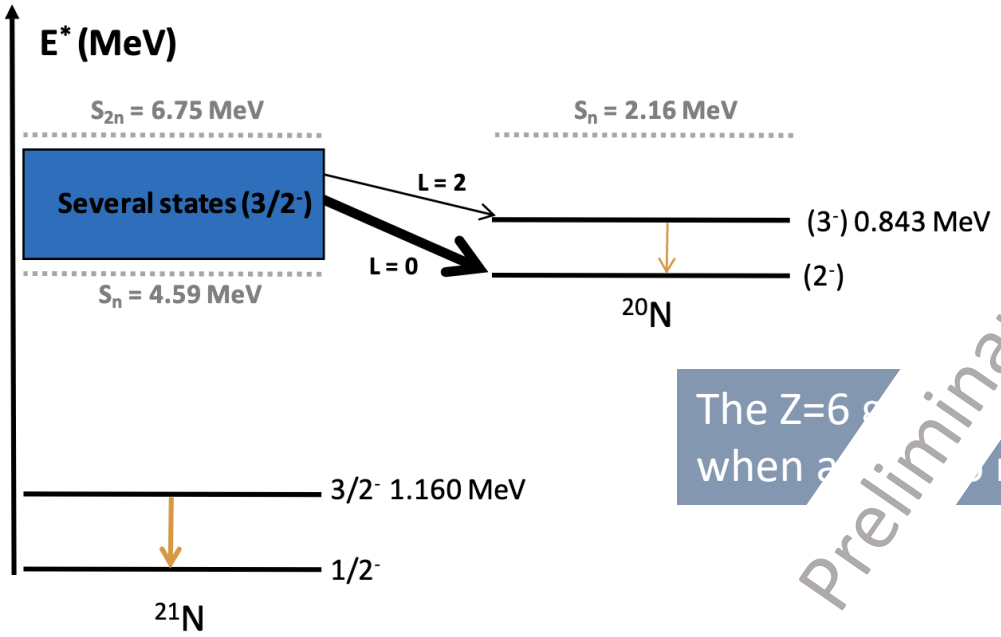


Study of the tensor force contribution in the O isotopic chain using QFS reactions

To determine how the Z = 6 gap (first proton spin-orbit splitting) evolves from stability to the dripline, ^{16}O to ^{22}O, we need to identify 3/2- states in ^{21}N, over a wide excitation energy range, using the **^{22}O(p,2p)^{21}N*** QFS reaction

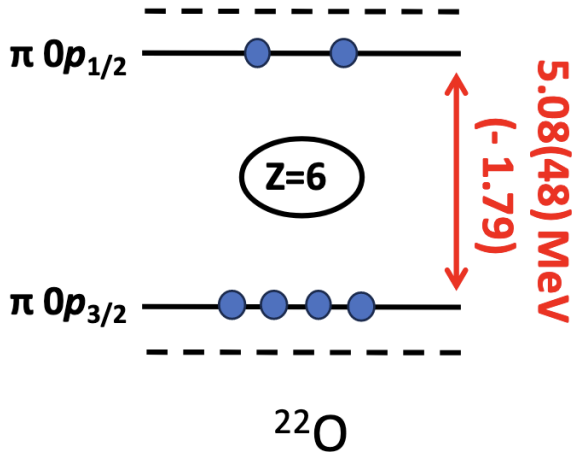


Accurate SM calculations



Preliminary results

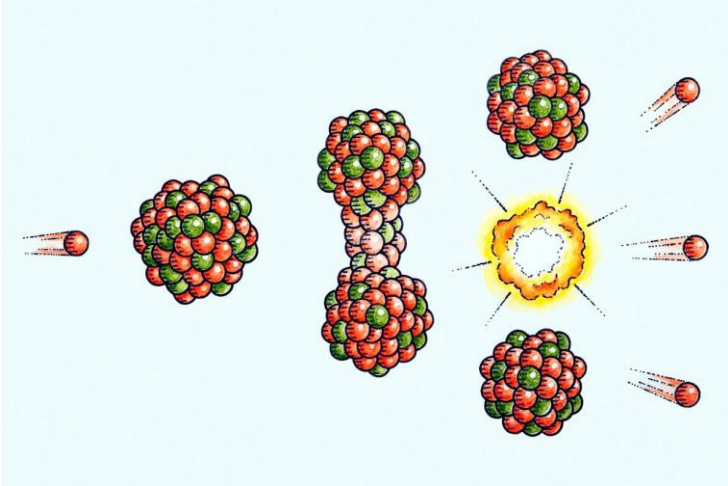
The Z=6 g… duced by 1.79(48) MeV when a… neutrons to the ^{16}O



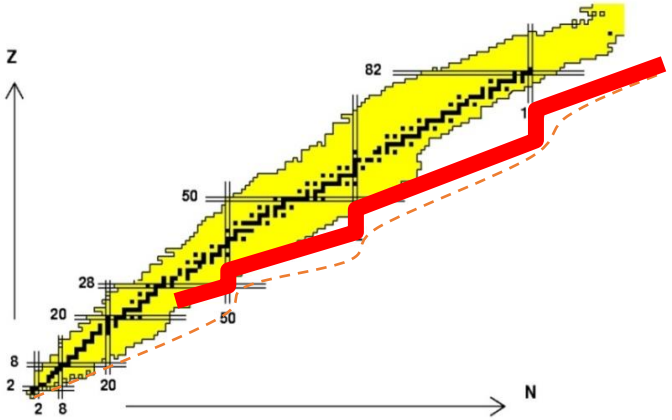
Extend the study to other nuclei in the region

A. Barrière, N. Mozumdar, M. Feijoo et al.

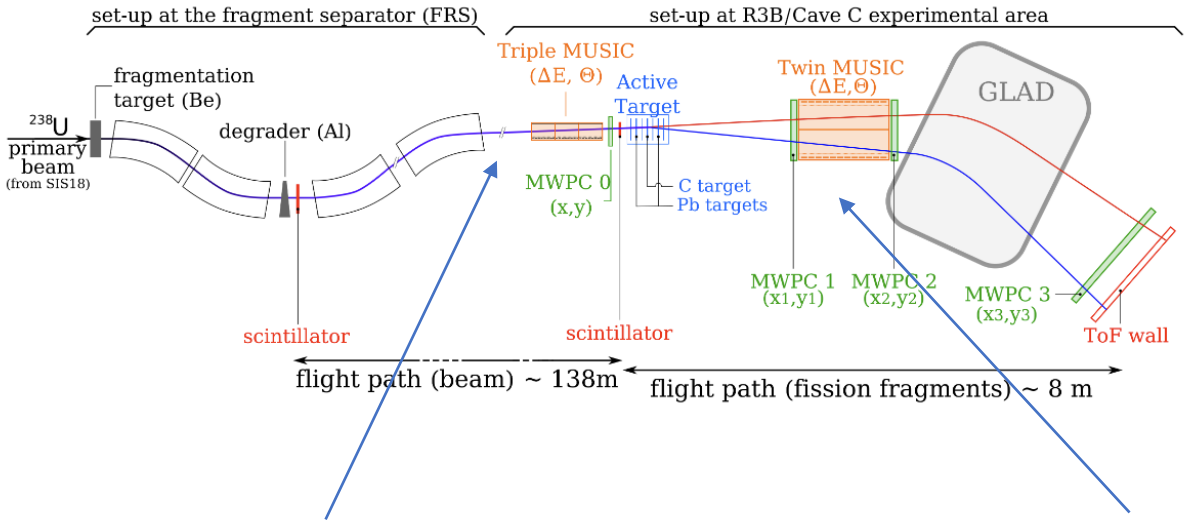
B) Fission studies



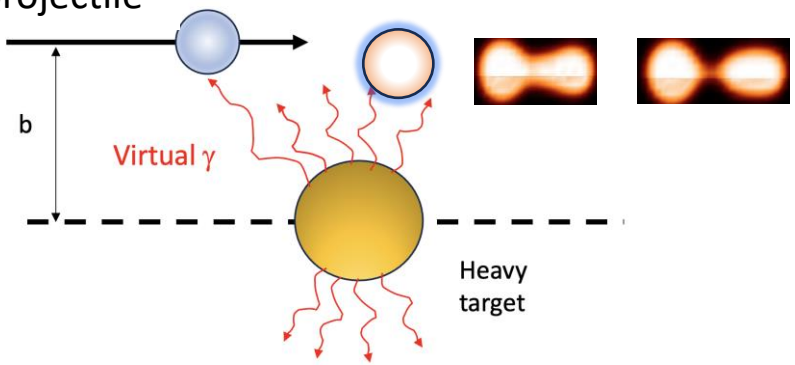
- Interplay of microscopic and macroscopic effects: Dynamic evolution of compound nucleus. Nuclear shells at extremes
- Nuclear fission is used in nuclear power plants to generate electricity . Understanding fission can help improve the performance of nuclear reactors. Knowing fission Z and A distributions is relevant to evaluate heat after shutdown
- Nuclear fission is relevant to astrophysics. Acts as feedback mechanism during the r-process : element abundancies
- Nuclear fission can help us understand the stability of superheavy elements



B) Fission studies using Coulex

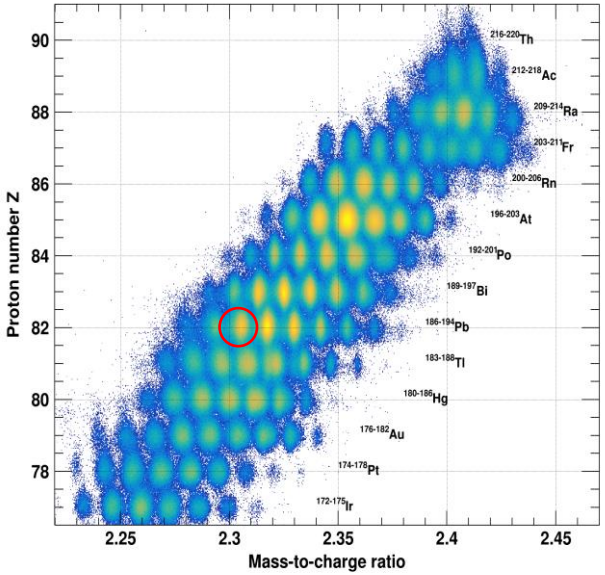


Heavy projectile

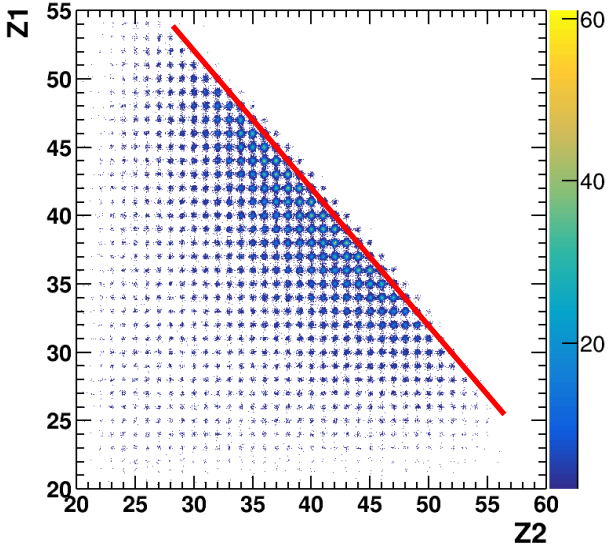


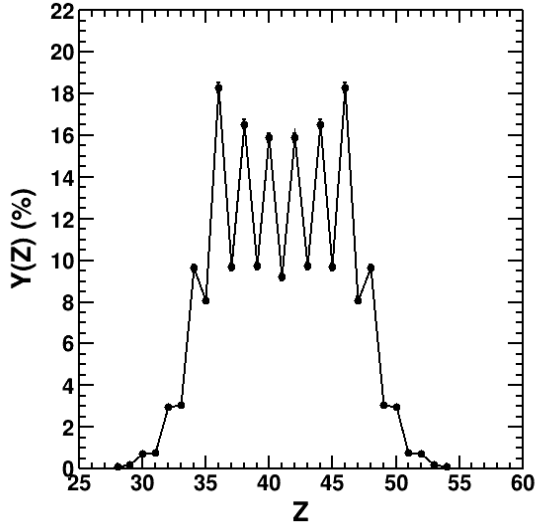
Example ^{189}Pb

Selection of Coulomb excitation event ($Z_{sum} = Z_{beam} = 82$)



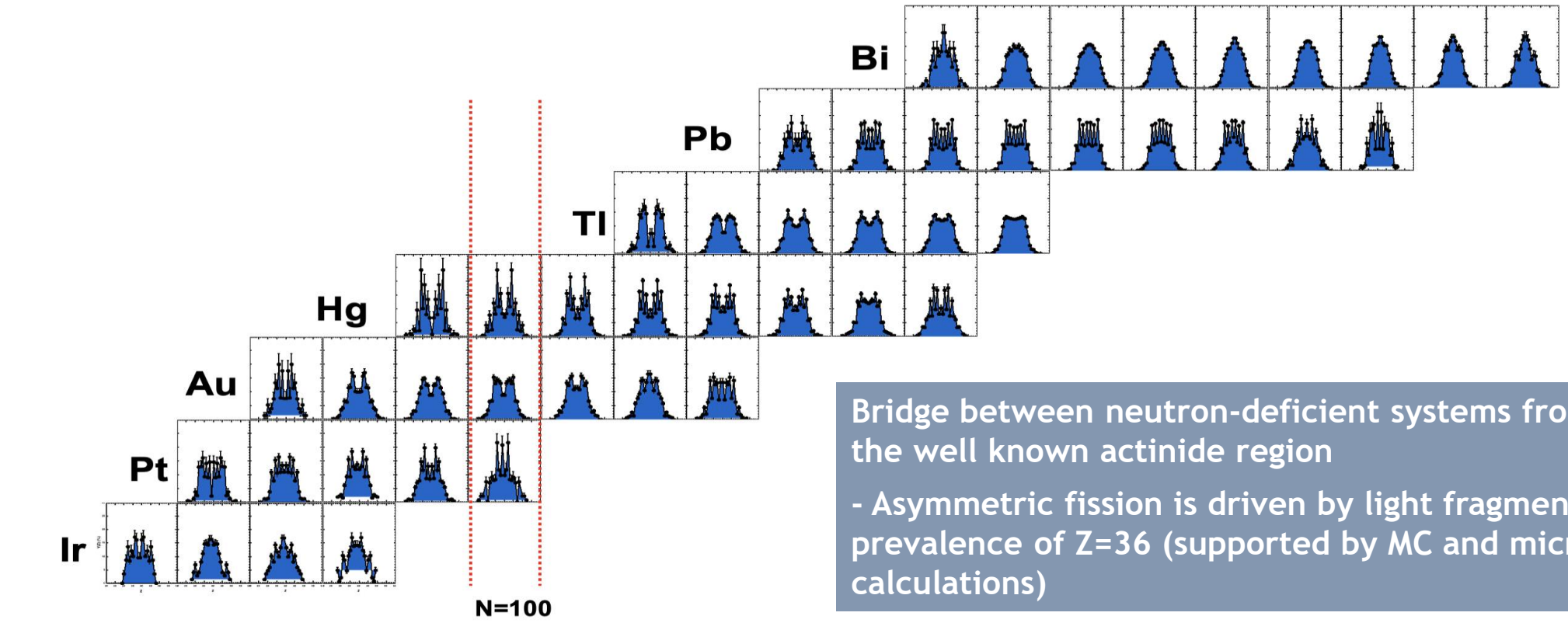
100 fissioning systems in one experiment !





Fission studies using Coulex

First mapping of this island of asymmetry



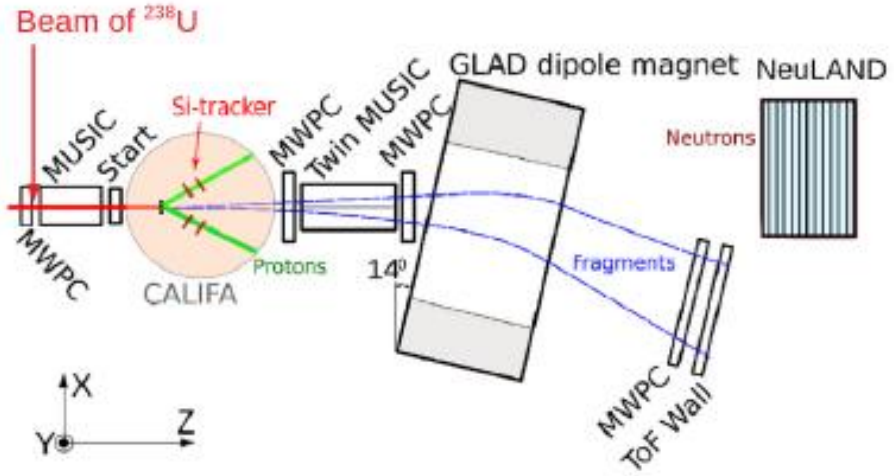
Bridge between neutron-deficient systems from Ir up to the well known actinide region

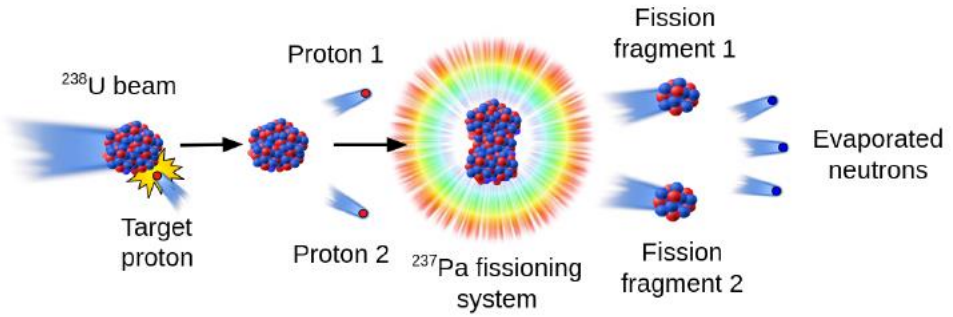
- Asymmetric fission is driven by light fragment with prevalence of Z=36 (supported by MC and microscopic calculations)

P. Morfouace et al. Accepted in Nature

Fission studies using QFS

Towards the complete characterization of the fission process





Combination of (p, 2p) and inverse kinematics

- determination of the excitation energy

of the fissioning system (missing mass spectroscopy)

- isotopic identification and TKE for the two fission fragments

- Fission barriers are important for the description of the r-process. They are expected to evolve with n-excess

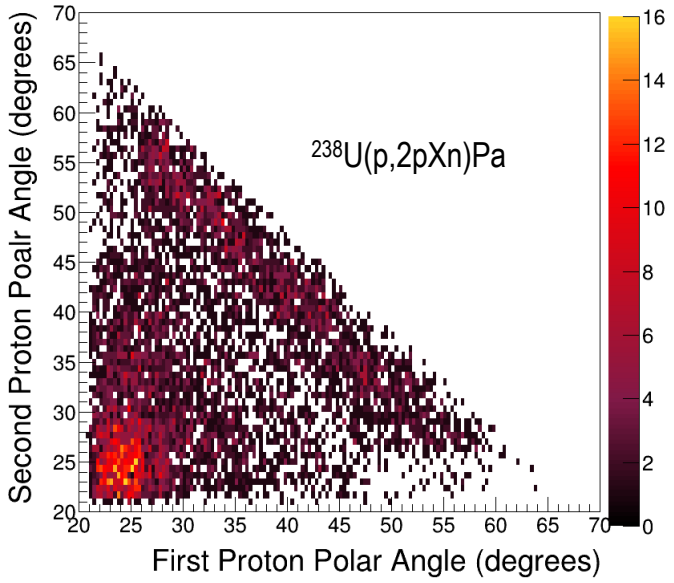
→ Proof of concept with stable nuclei

First experimental test with ^{238}U QFS (p,2p)

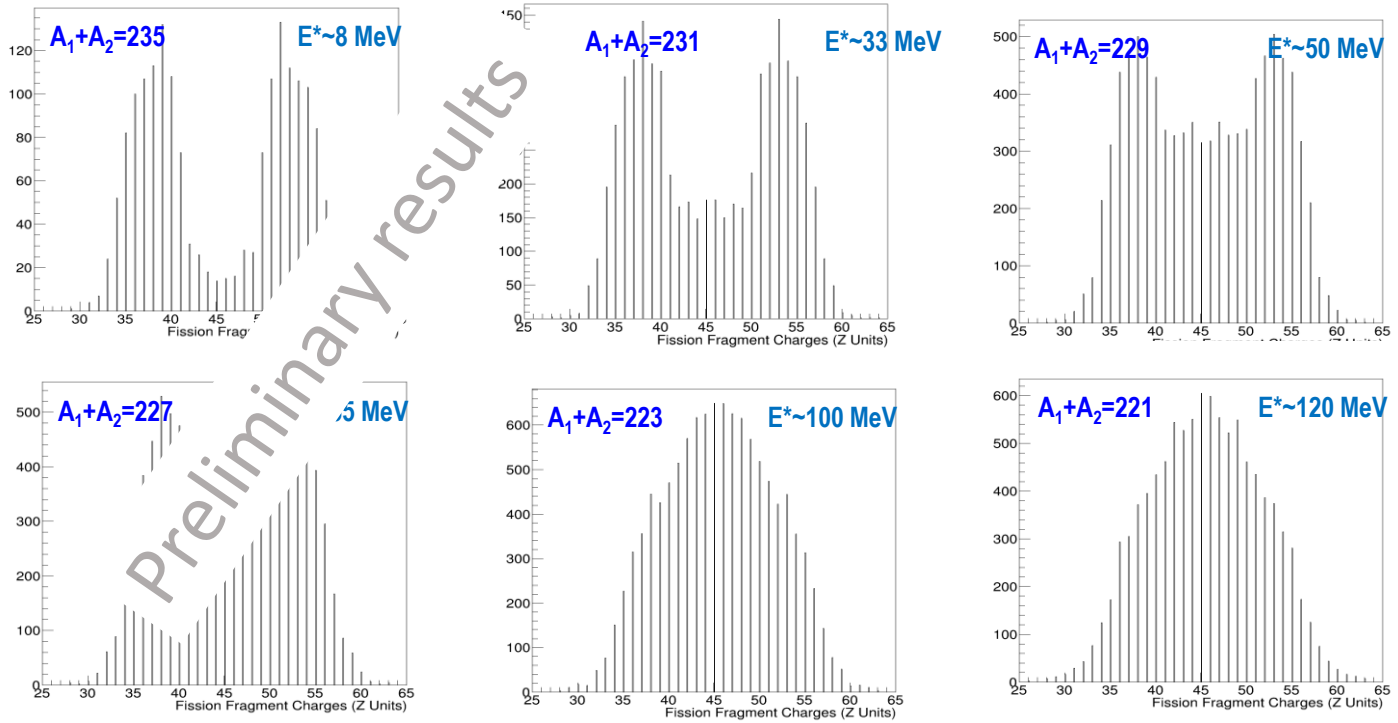
Fission studies using QFS

- Mass and charge identification of fission fragments
- Excitation energy reconstruction only posible with **CALIFA**
- Dependence of the **charge and mass yield with the excitation energy**

A clear transition from asymmetric to symmetric fission when decreasing the total mass (increasing the excitation energy).



Angular correlations between the protons from (p,2p) reactions



First step towards the measurement of fission barriers for r- process (unstable) nuclei

G. García, A. Graña et al.

Summary and Outlook

The combination of relativistic radioactive beams and a high acceptance, high efficiency and high resolution device constitutes a versatile and powerful tool to learn about nuclear matter : structure, dynamics, astrophysics

We are laying the groundwork for the development of a broad research programme using reactions induced by exotic projectiles, which would contribute to gain knowledge in different facets of nuclear matter, dynamics and interaction (i.e: single-particle properties, the role of correlations between nucleons, understanding of reaction mechanisms…)

¨Right size¨ to develop PhD Project
Many possibilities to contribute to instrumentation

Very exciting period. Ready to recieve FAIR beams in 2028

Sumary