Nuclear reactions at high-energy

A personal view

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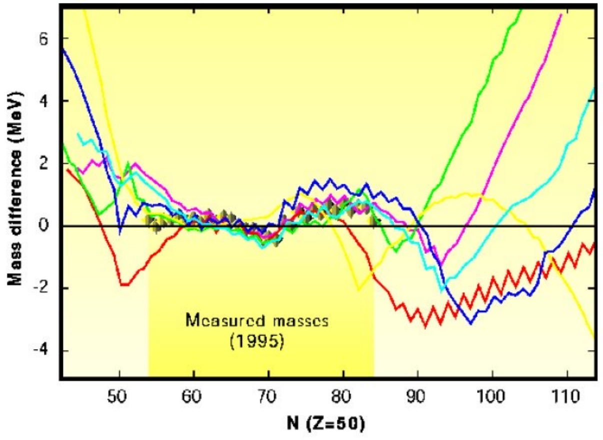
Experimental investigation of the atomic nucleus

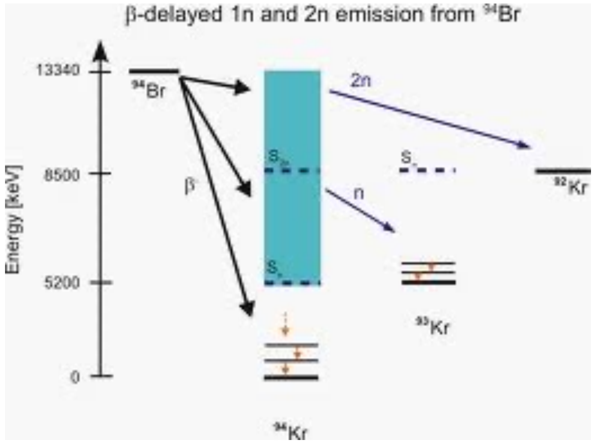
Ground-state properties.

- masses
- size: matter and charge radial distributions, deformation
- electromagnetic moments



Radioactive decays.

- decay properties
- beta-delayed gamma emission
- beta-delayed particle emission

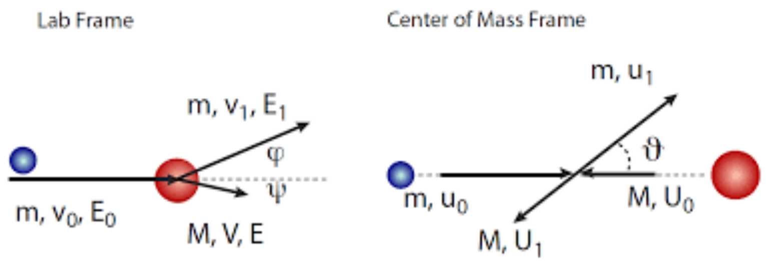


Nuclear reactions.

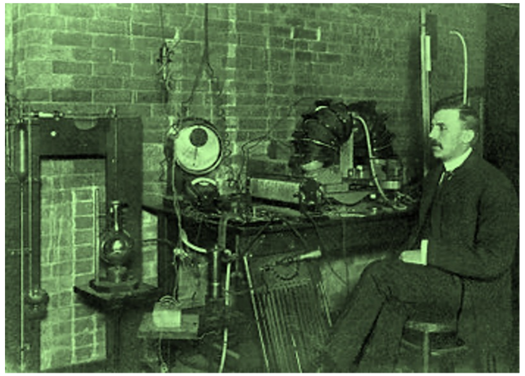
- direct reactions
- compound nucleus reactions

Early Nuclear Reactions

Nuclear reactions are the process in which two nuclei collide to produce one or more nuclides that are different from the nuclide(s) that initiated the process.

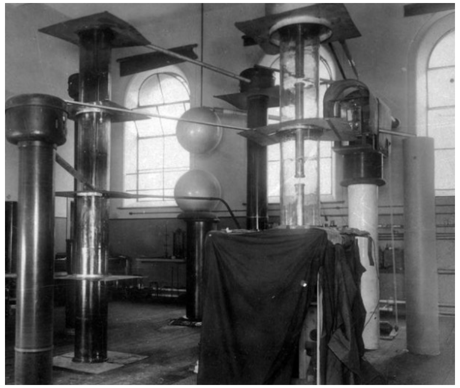


→ they have been the subject of study since the early days of our field



- The earlier scattering experiments by Rutherford, Geiger and Marsden led to important clues about atomic structure
- The first observation of an induced nuclear reaction was achieved by Rutherford in 1919

$$^{14}N + \alpha \rightarrow {}^{16}O + p$$

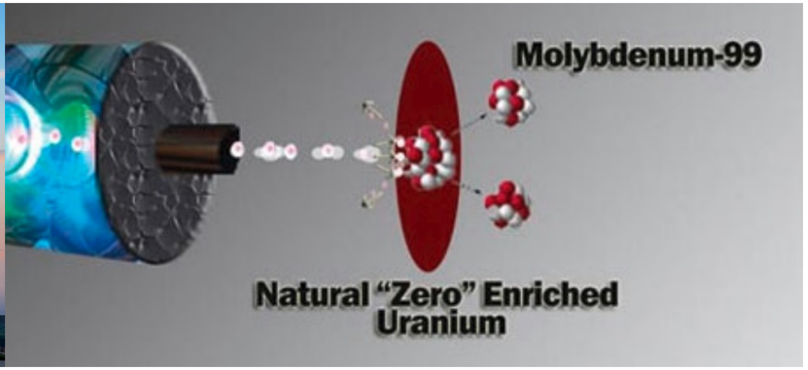


- In 1932 a fully artificial nuclear reaction (@ Cavendish) was achieved by Cockcroft and Walton, who used accelerated protons against ^{7}Li, to split the nucleus into two α particles.

Why Nuclear Reactions ?

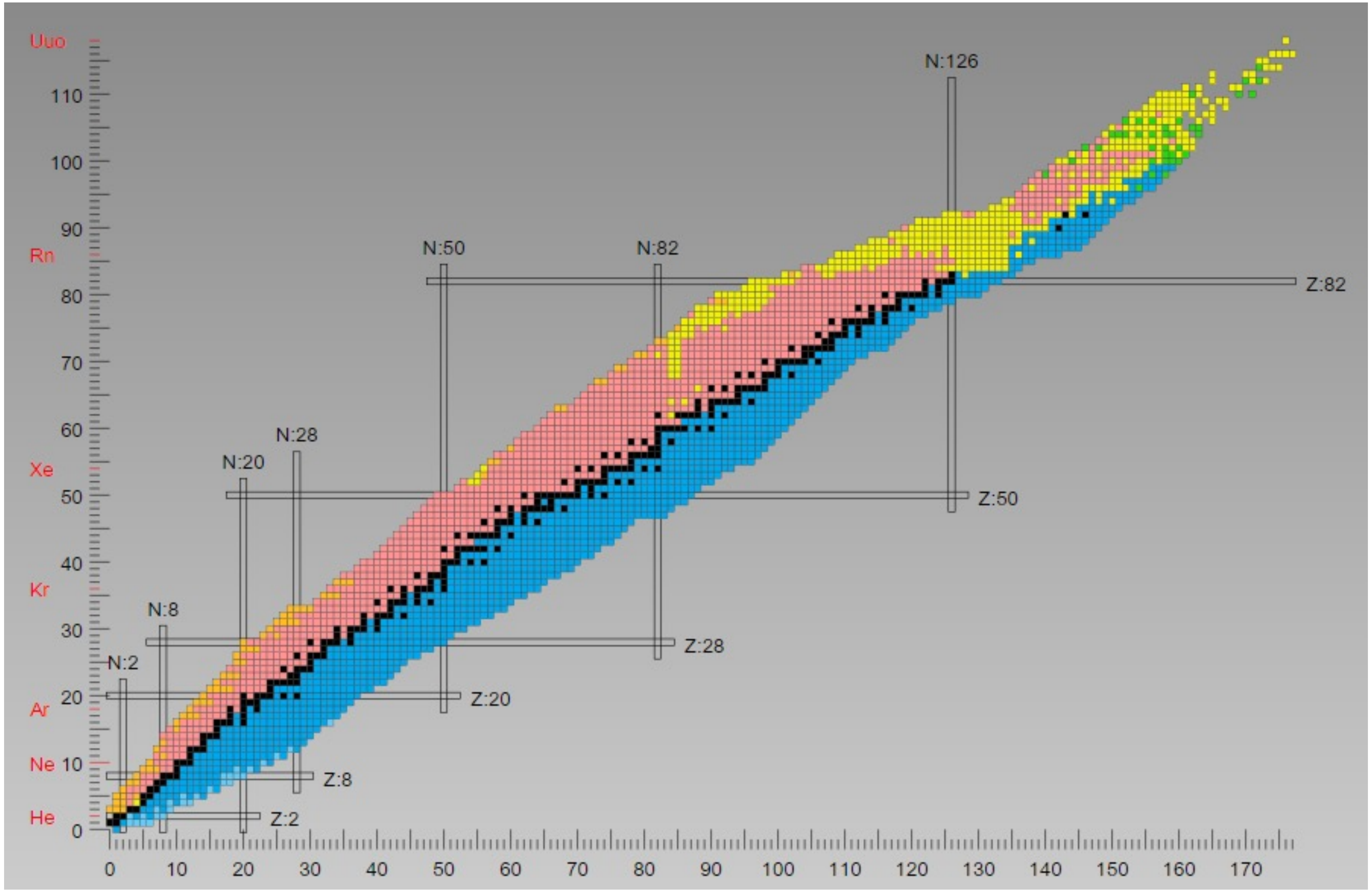
To improve our knowledge of such a complex quantum system as it is the atomic nucleus and to exploit this knowledge for different applications

- To improve our knowledge of nuclear interaction
- To understand the reaction mechanisms
- To extract information about nuclear structure
- To learn about nuclear dynamics



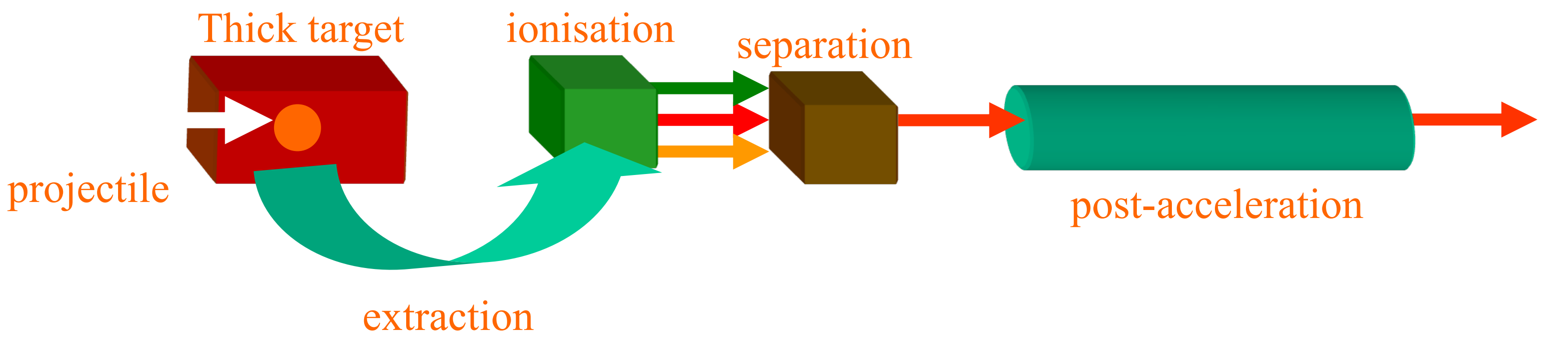
Nuclear reactions are behind phenomena studied in our labs but also in stellar environment, energy production and many important applications

Nuclear Reactions induced by RIB

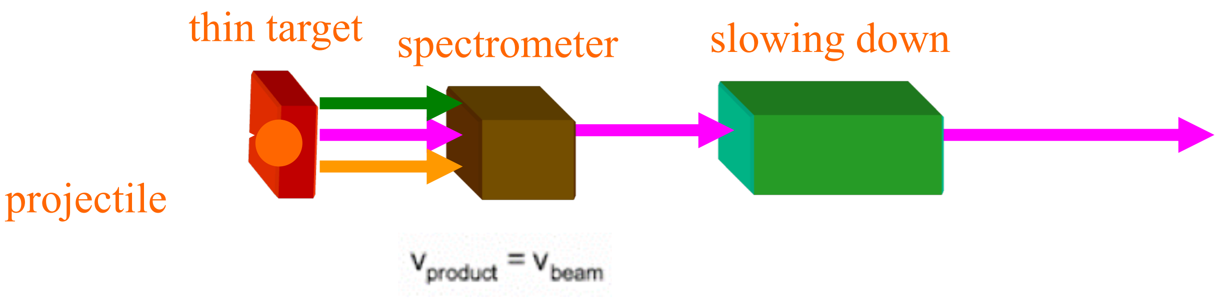


Rare Ion Beam Production

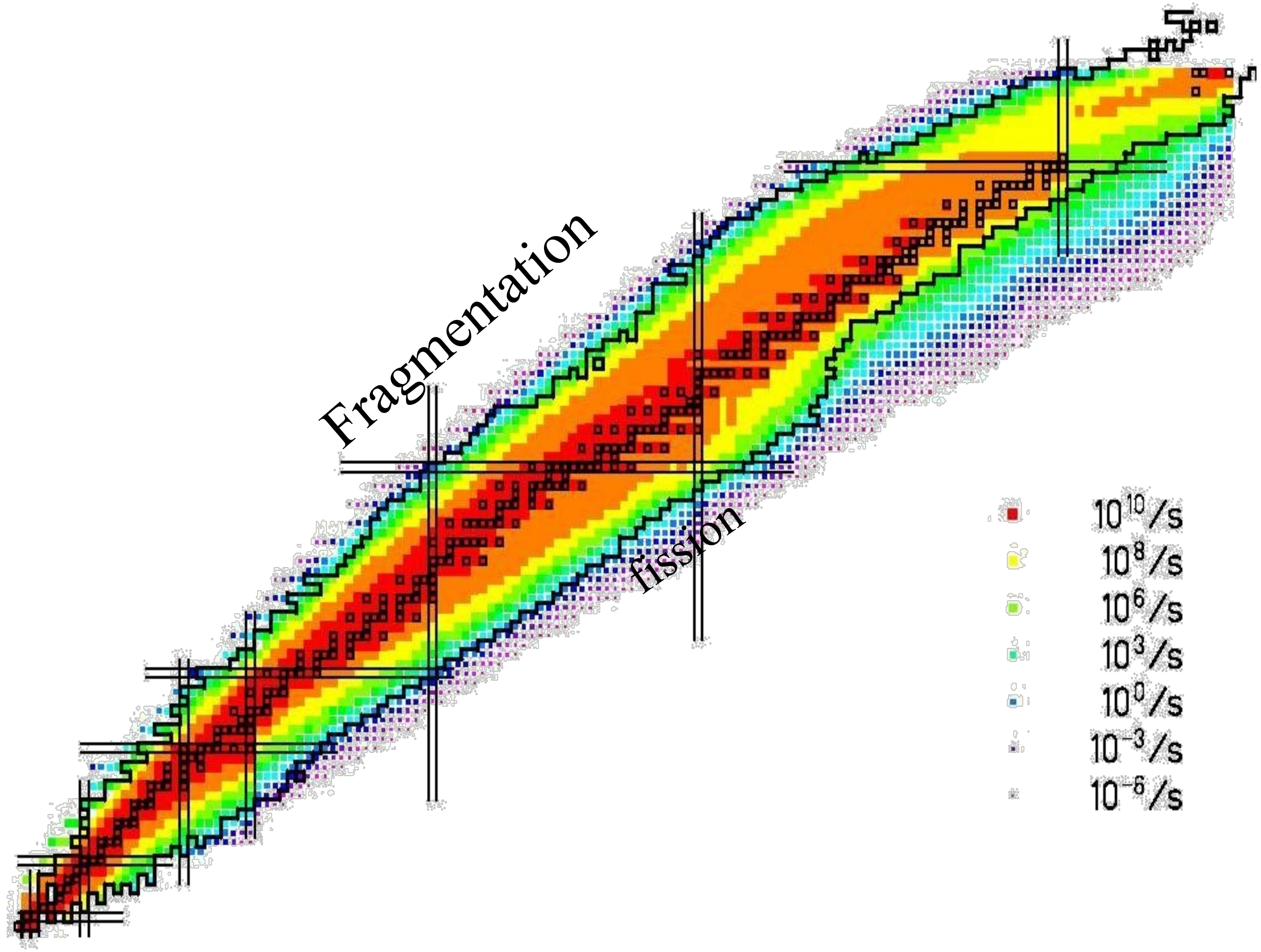
Isotopic separation on line: ISOL



In-flight projectile fragmentation

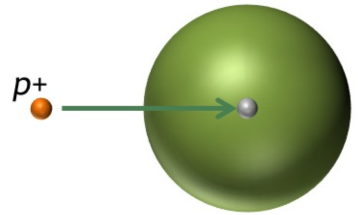


Rare Ion Beam Production



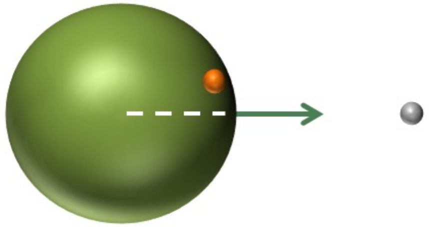
From Direct kinematics

The study nucleus is the target (stable)

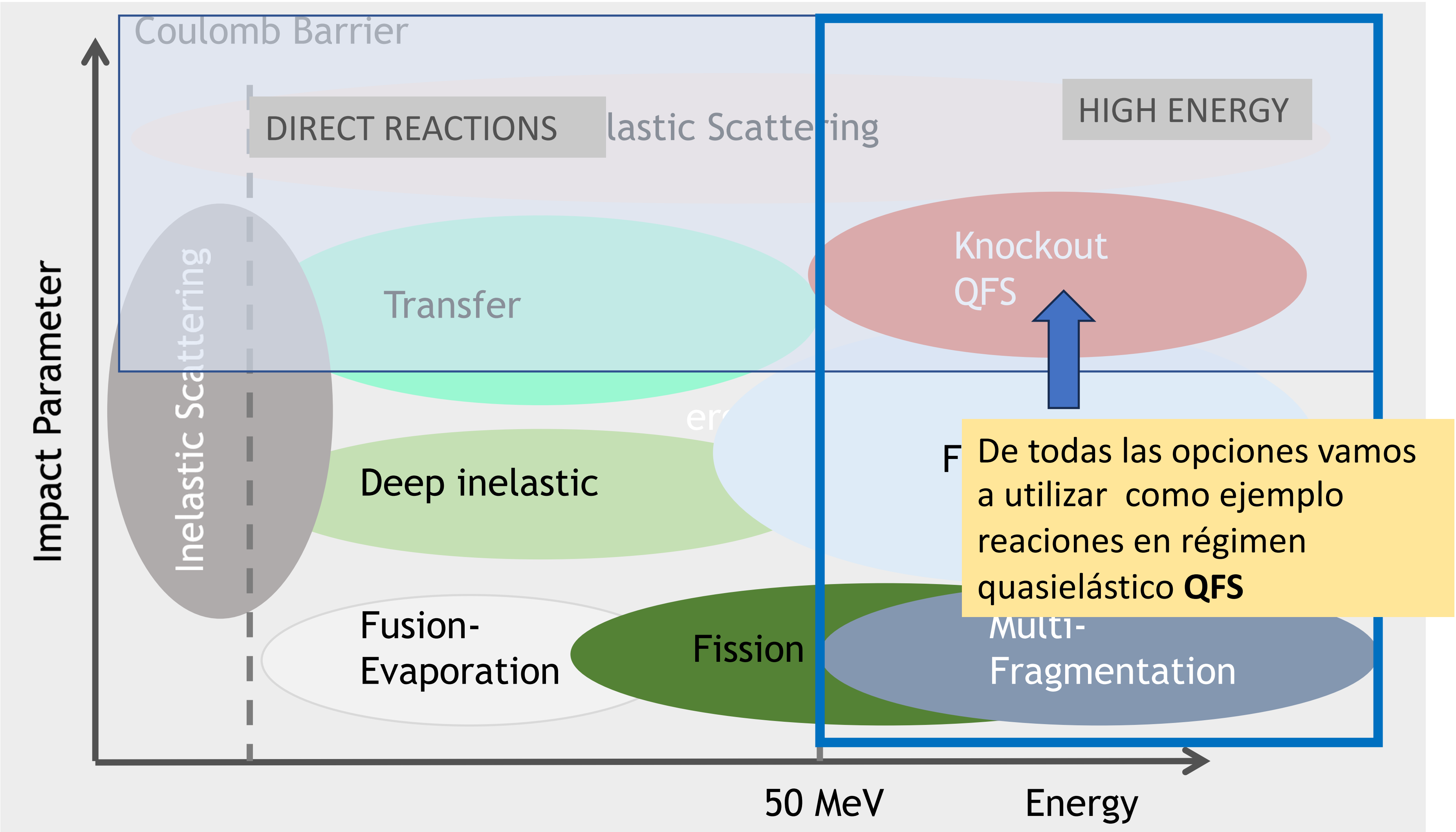


To Inverse kinematics

The study nucleus is the projectile



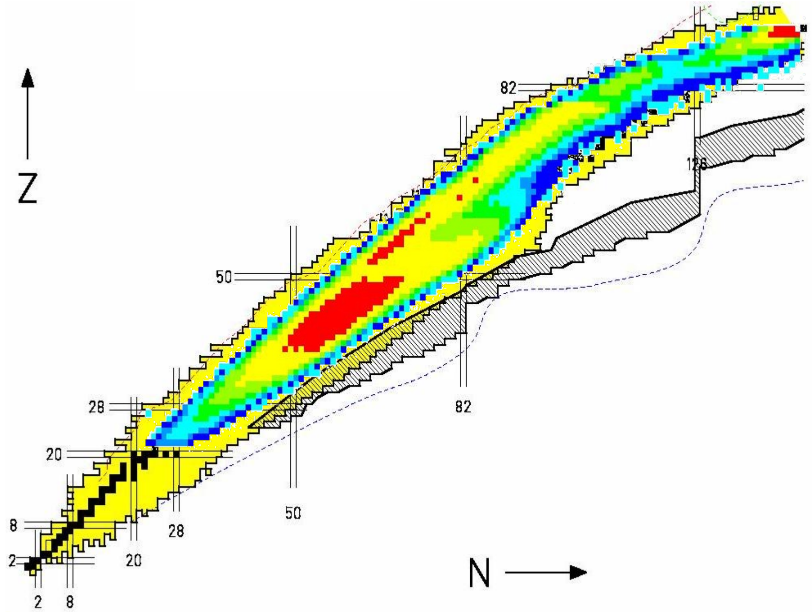
Nuclear Reactions Classification



Experimental advantages of ion reactions at high energy

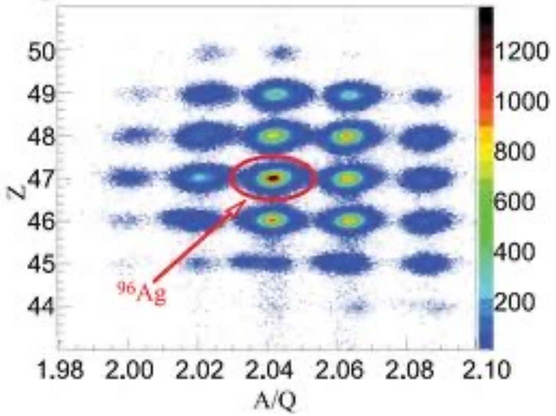
- Production of a large variety of species

In principle one can produce any fragment



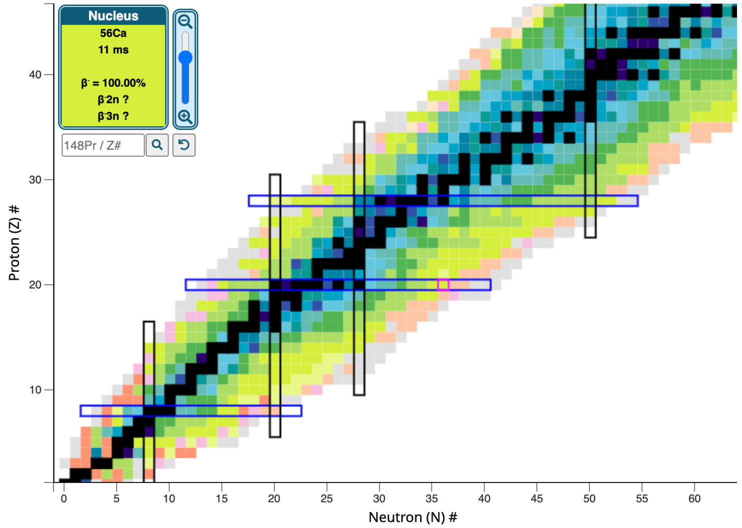
- Cocktail beam

Several isotopes can be studied simultaneously



- The exotic projectiles are studied **in-flight**

Short half-lives (μs)

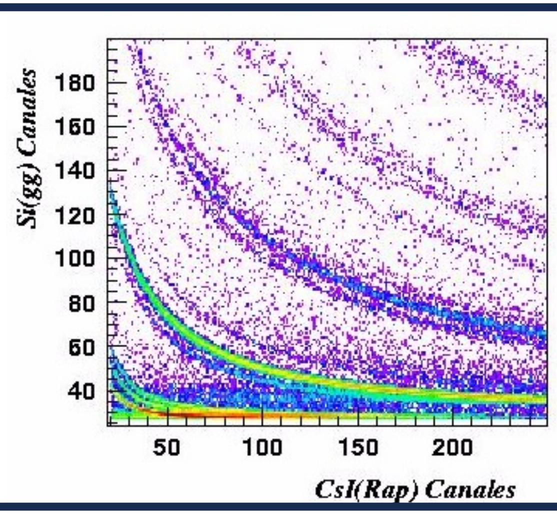


Experimental advantages of ion reactions at high energy

- Improved charge identification of reaction ejectiles

$$\frac{dE}{dx} = f(Z^2, A, \beta\gamma)$$

The energy deposition of ions with Z > 40
and E < 1 A MeV in the Bragg peak.

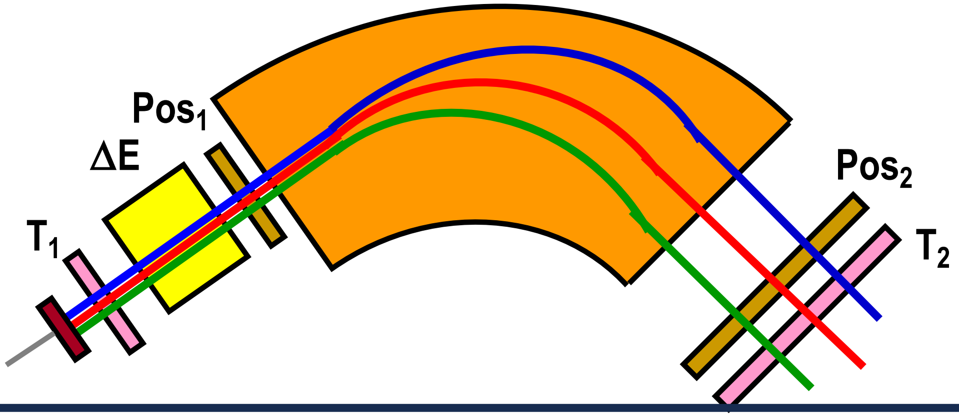


- Heavy ejectiles fully identified in Z and A

$$B\rho \propto \frac{A}{q}\beta\gamma$$

$Pos_1, Pos_2 \rightarrow L_1, L_2, L_3 \rightarrow \rho_1, \rho_2, \rho_3$
$T_1, T_2 \rightarrow L_1, L_2, L_3 \rightarrow \beta\gamma_1, \beta\gamma_2, \beta\gamma_3$
$\Delta E_1, \Delta E_2, \Delta E_3$ (q=Z) $\rightarrow Z_1, Z_2, Z_3$

} A_1, A_2, A_3



Experimental advantages of ion reactions at high energy

- The **target thickness** can be increased → Compensates the low cross- section

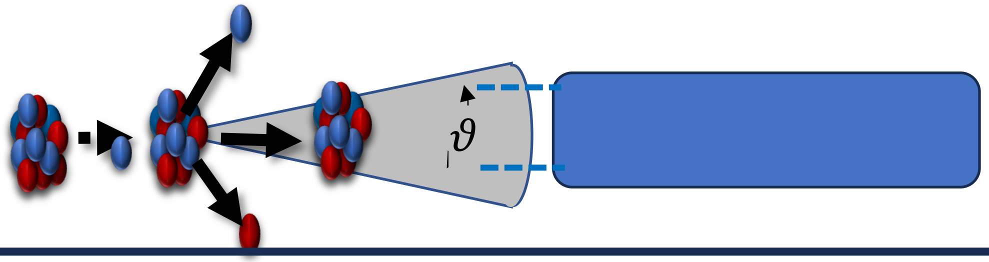
The range (R) of incoming projectiles increases with energy, and then the possible target thickness (~ 10% of R).

Typical range of projectiles

- $E<E_{fermi}$ 0.1R ~ 100 mg/cm^2
- $E>>E_{fermi}$ 0.1R ~ 1 g/cm^2

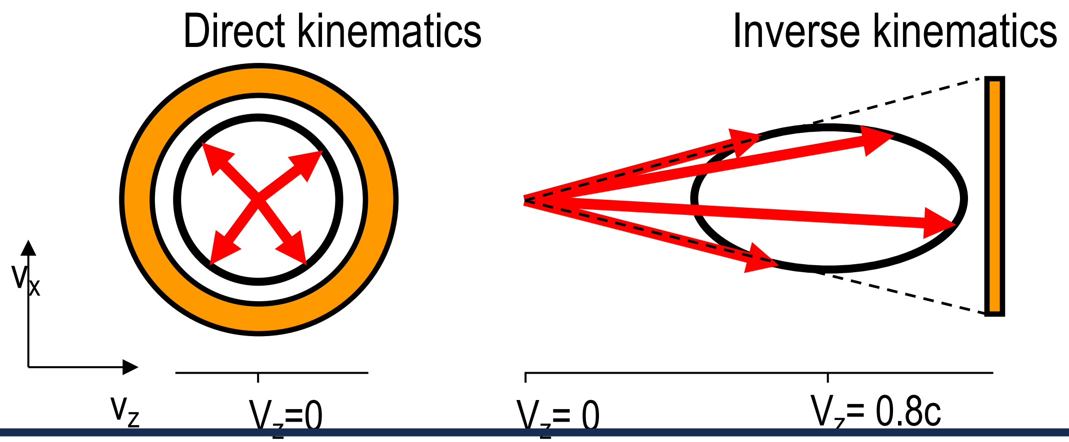
$P_{reaction} = s\ N_{projectiles}\ N_{target}$

- The reaction products are **forward focused ("easy" to analyse)** → **good transmission**



- The **geometrical acceptance** of the detectors is larger

The use of inverse kinematics moderate detector size



Simpler description of scattering at high energy regime

Elementary scattering theory

$$\frac{d\sigma}{d\Omega} \approx |f_\beta(\theta,\phi)|^2 \approx \frac{m^2}{(2\pi)^2\hbar^4}|T_{kk'}|^2$$

$$T_{kk'} = \langle \phi_{\mathbf{k}'} | V | \psi_{\mathbf{k}} \rangle$$

In case of high energy we can made use of the **Sudden or Adiabatic approximation**

The collision time τ is small compared with the characteristic period ω^{-1} of the bound target nucleon

$$\tau \approx \frac{a\ (\sim 2fm)}{v}$$

$$\hbar\omega = B$$

$$\frac{aB}{\hbar v} \ll 1$$

← higher the energy the better it works

Single-scattering approximation

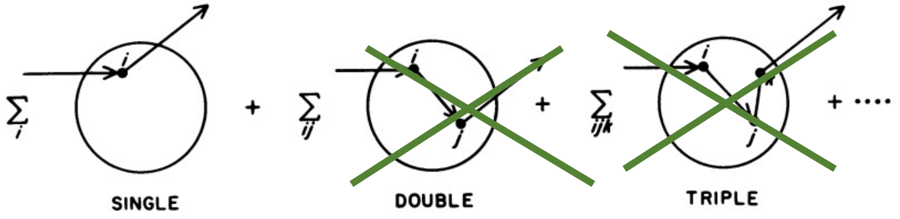
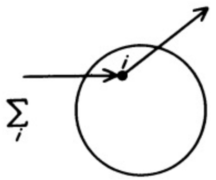


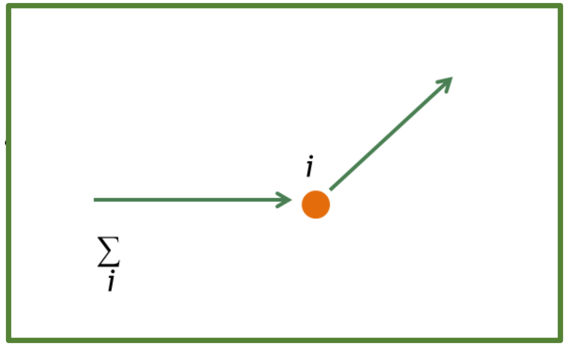
Figure 3.16 Schematic picture of the multiple scattering series. The projectile successively scatters from one, two, three . . . target nucleons

It is valid if the mean-free path Λ of the projectile within the target is larger than the target radius R

Simpler description of scattering at high energy regime

Impulse approximation





Valid assuming that the projectile energy is larger that the knockout nucleon binding energy

The interaction between projectile and knocked-out nucleon can be replace by the free scattering amplitude for this pair

- The interpretation of the main observables can be described with basic scattering theory. In the high energy regime this description remains simple → allows to get valuable nuclear structure information (they were extensively used with stable beams)

Conservation laws

- Charge : general conservation, computed by atomic numbers
- Energy and linear momentum : Dependence between scattering angle and energy

Kinematics

- Total angular momentum: Spins and relative angular momenta are computed

$$I_A + I_a + \vec{l}_{Aa} = I_B + I_b + \vec{l}_{Bb}$$

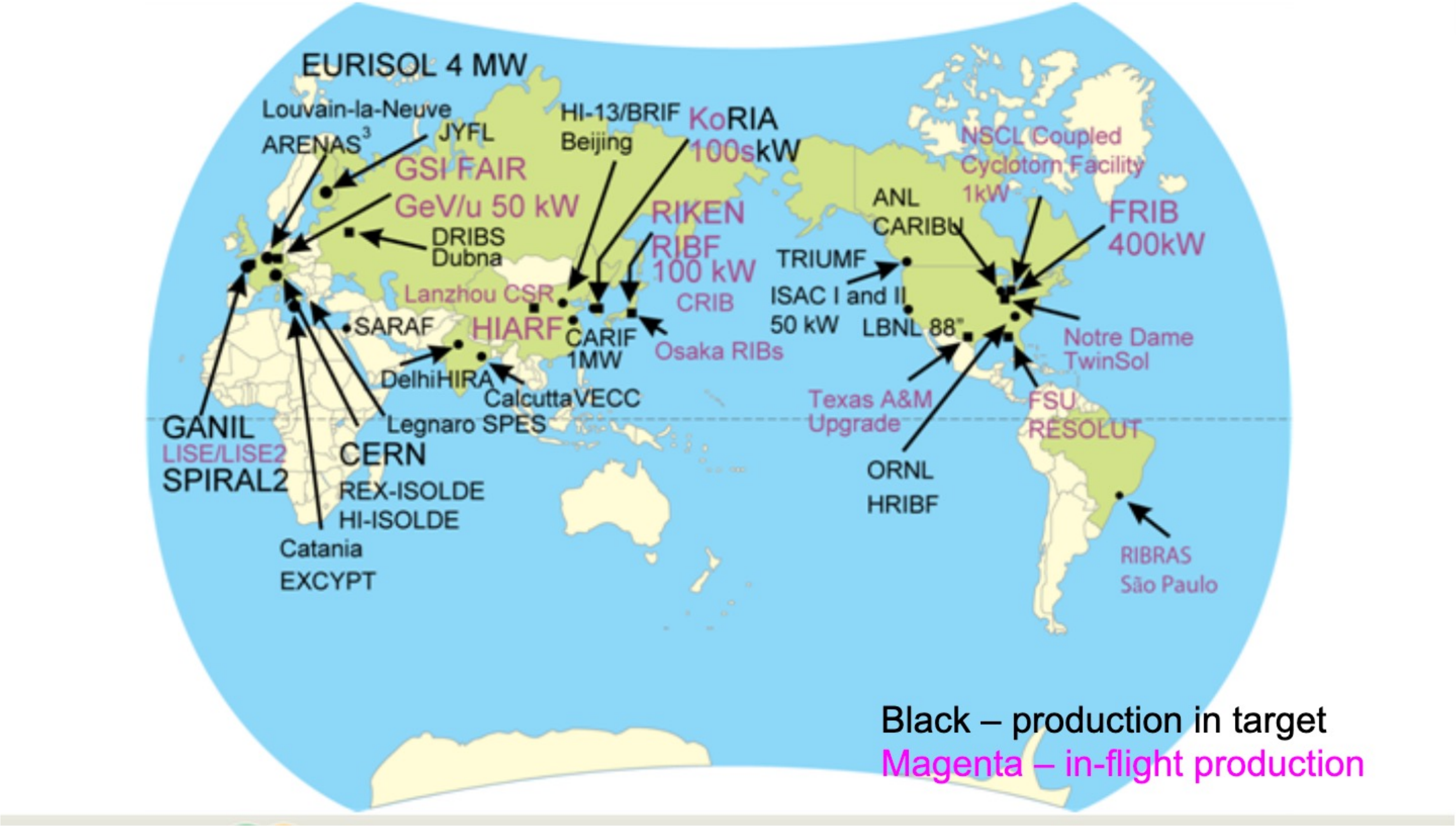
Selectivity

- Parity : specular inversion invariace

$$\pi_A \pi_a (-1)^{l_{Aa}} = \pi_B \pi_b (-1)^{l_{Bb}}$$

- Isospin: approximate law, valid for light systems (small Coulomb effect)

Worldwide RIB facilities



D.Cortina

Facility for Antiproton and Ion Research

Video drone

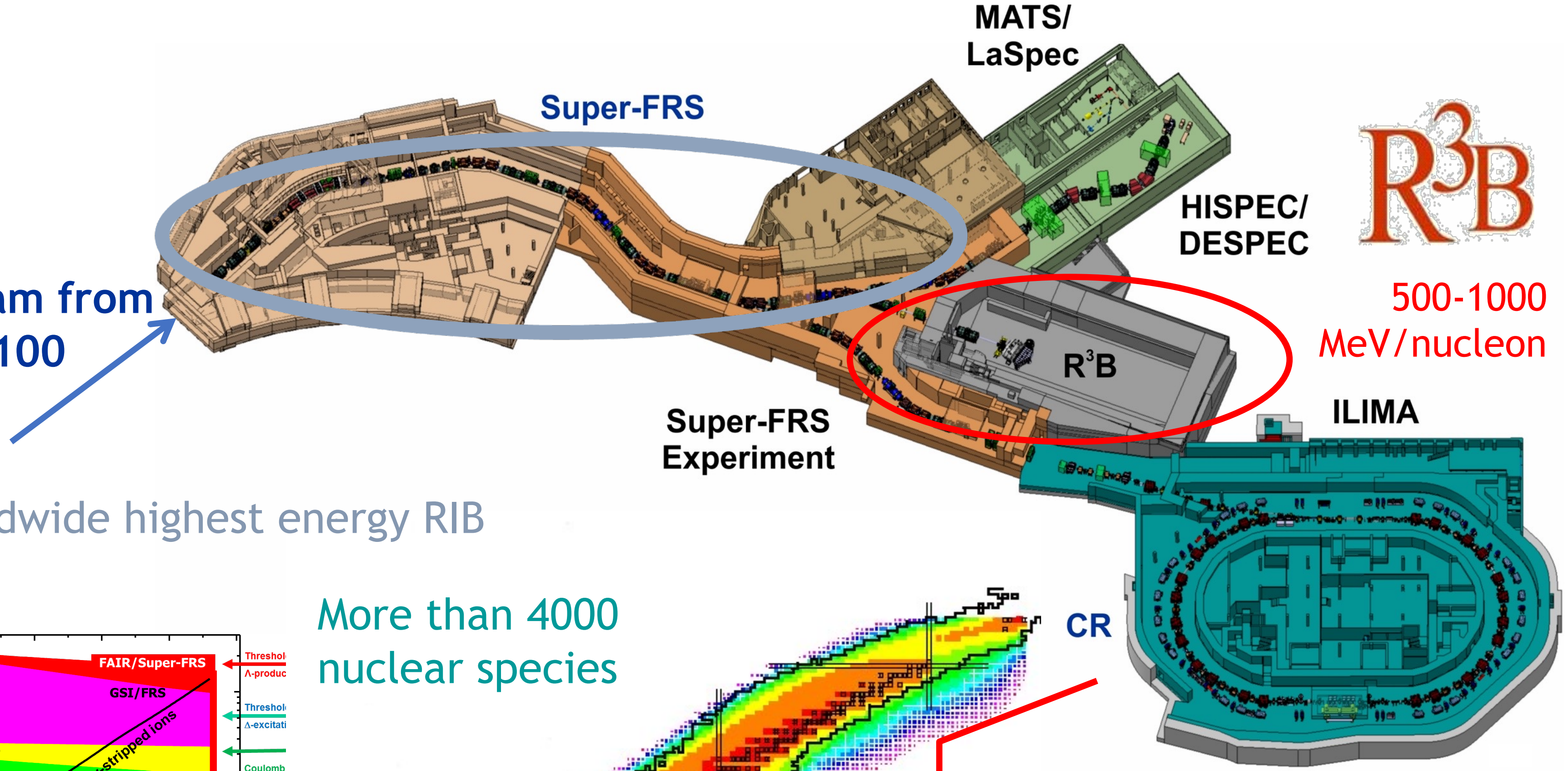
Design parameters U^{28+}		
	SIS18	SIS100
Energy	200 MeV/u	1.5 GeV/u
Ions per cycle	1.5×10^{11}	5×10^{11}
Repetition rate	2.7 Hz	0.3 Hz

Gain factors (compared with GSI):

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

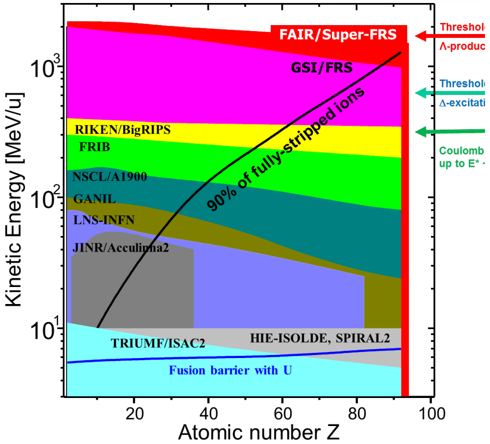
Reactions with Relativistic Rare Beams

Beam from SIS100

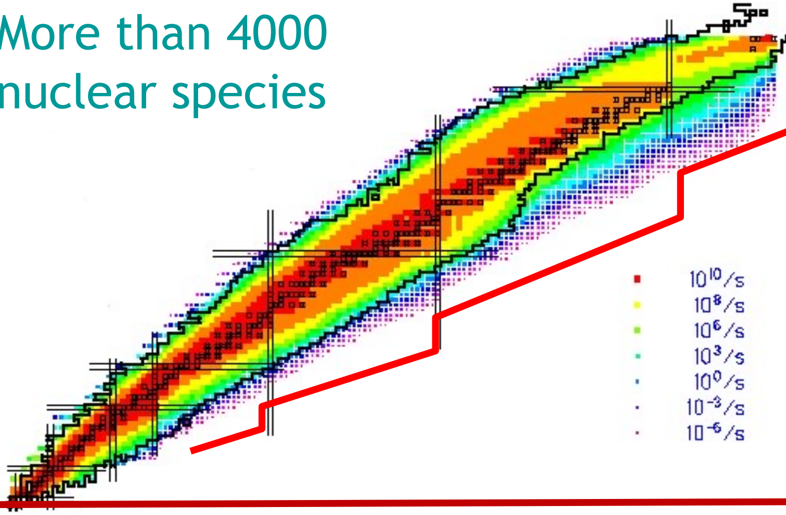


500-1000 MeV/nucleon

Worldwide highest energy RIB



More than 4000 nuclear species



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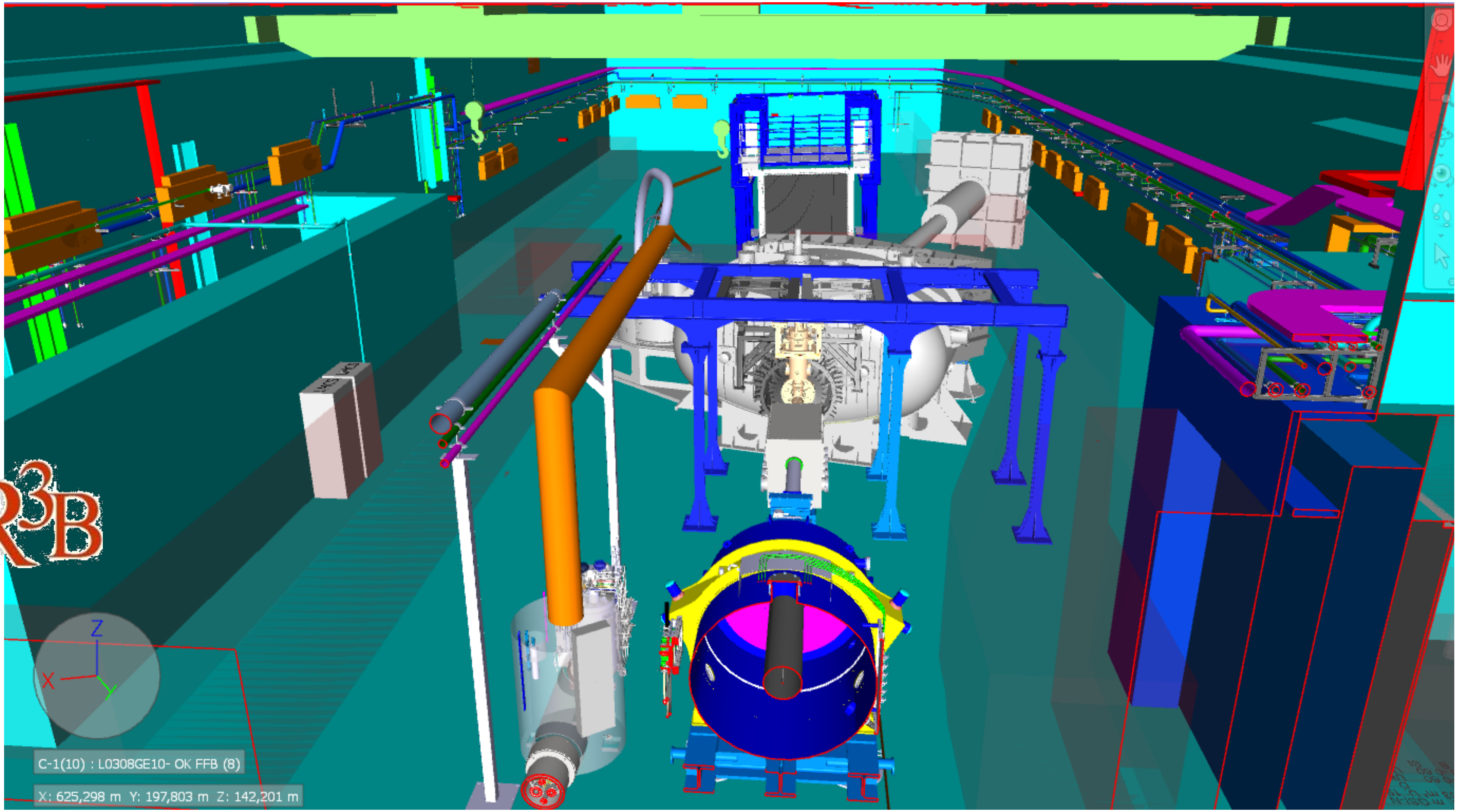
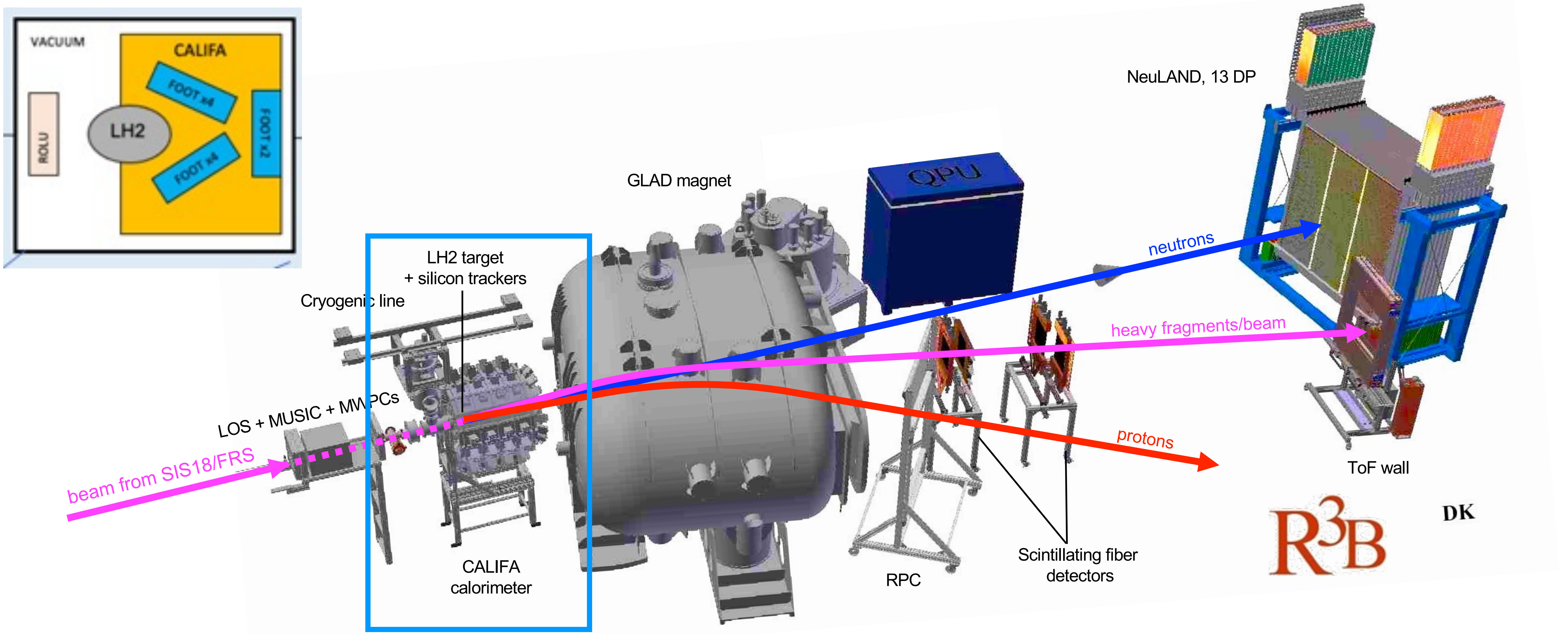
Reactions with Relativistic Rare Beams



Reactions with Relativistic Rare Beams

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

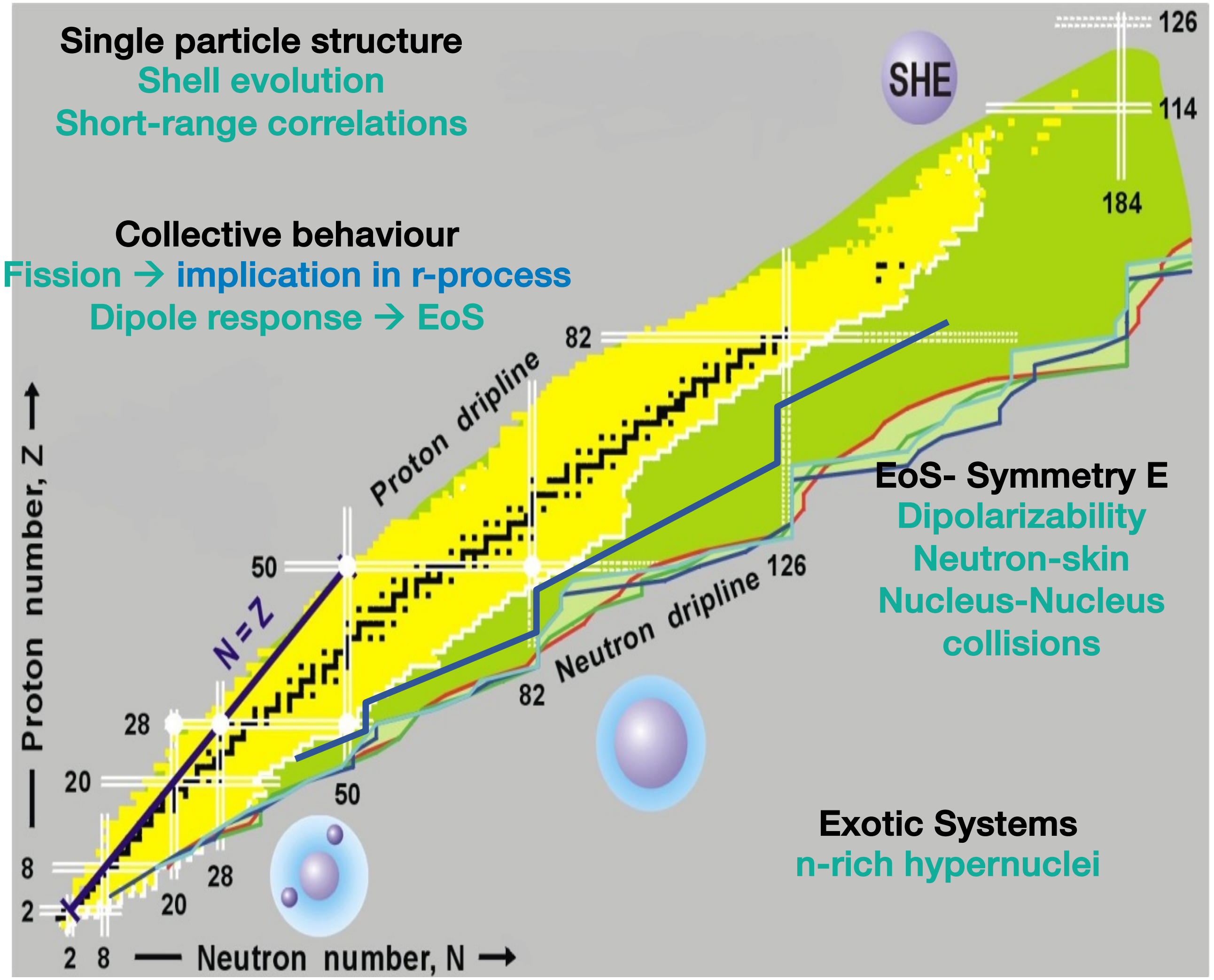
Optimised for the kinematically-complete measurement of reactions at high beam energies (up to 1 A GeV). R3B is unique due to the combination of high-energy beams, large acceptance, high resolution and large efficiency, including multi-neutron detection



Courtesy of Daniel Körper

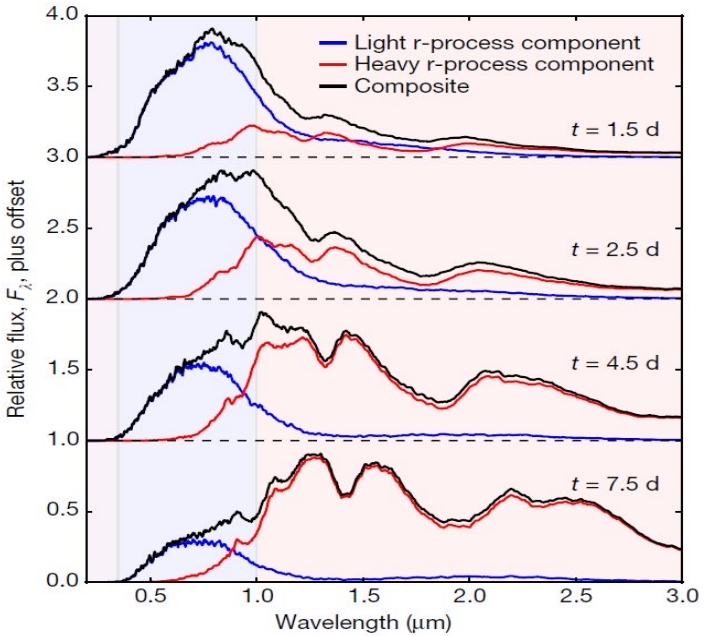
Reactions with Relativistic Rare Beams

Physics program R3B/FAIR



Neutron Stars Physics

Kilonova Physics



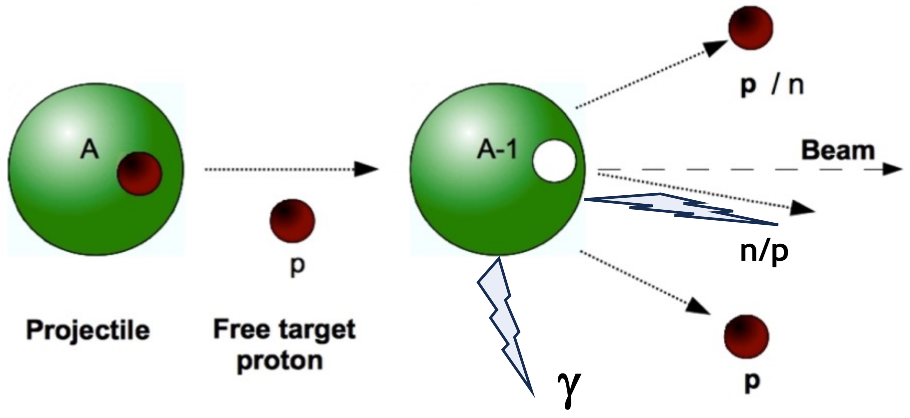
EM signals provided the first evidence for r-process nucleosynthesis.

Metzger & Martinez-Pinedo et al (2010)

Reactions with Relativistic Rare Beams

Quasi-free scattering of rare isotopes in Inverse kinematics

We have access to very exotic nuclei from the Super-FRS . .



Detection : Heavy fragments
light charged particles
neutrons
gamma-rays

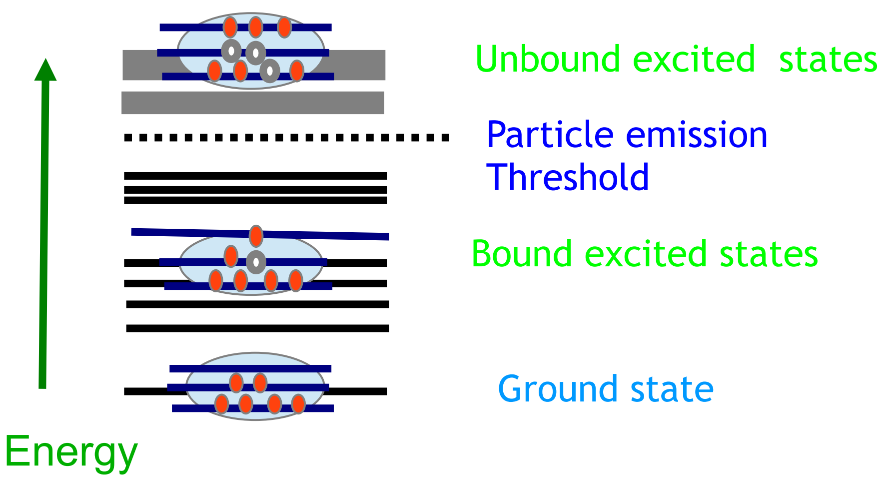
The QFS in inverse kinematics program
(p,2p) (p,pn) (p,pα)

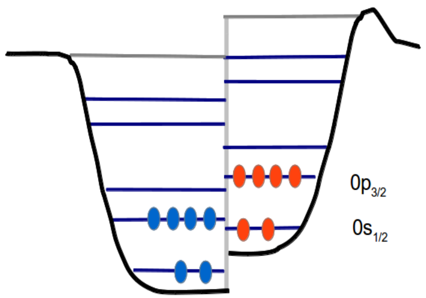
- Evolution of shell structure
- Cluster structure
- States beyond the neutron dripline
- Nucleon-Nucleon correlations (SRC)
- Reaction to induce fission

Complete kinematics

Reactions with Relativistic Rare Beams

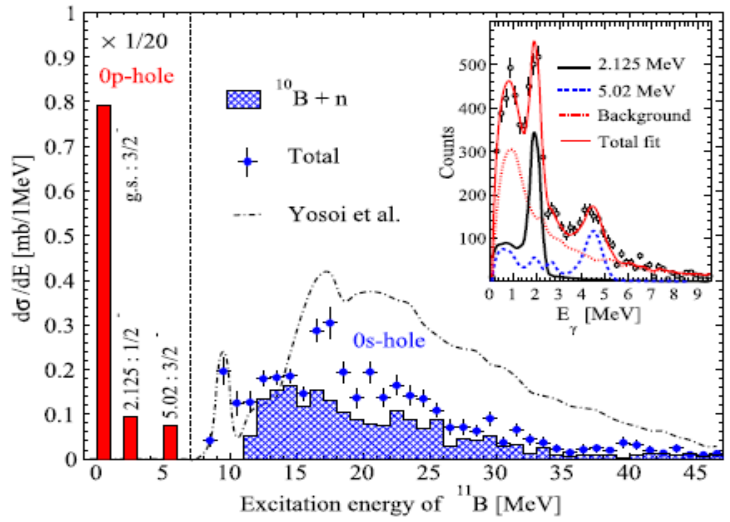
QFS of ^{12}C a powerful spectroscopy tool



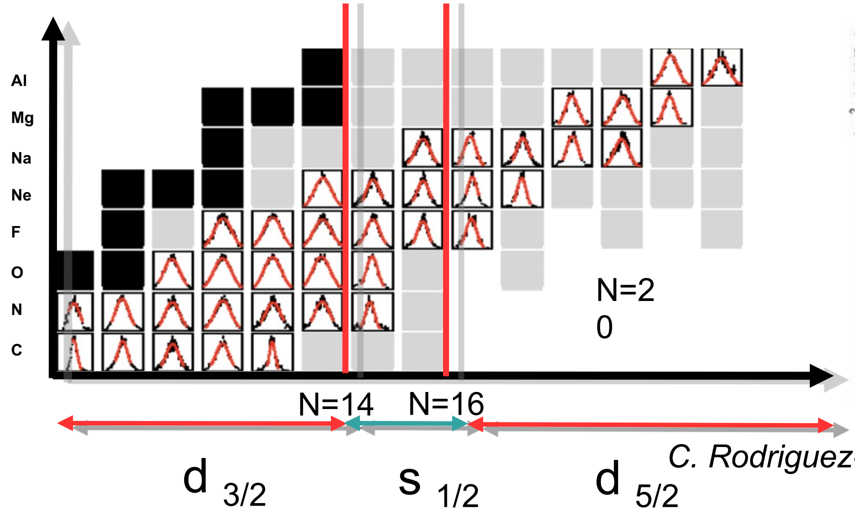


$^{12}C(p,2p)^{11}B$

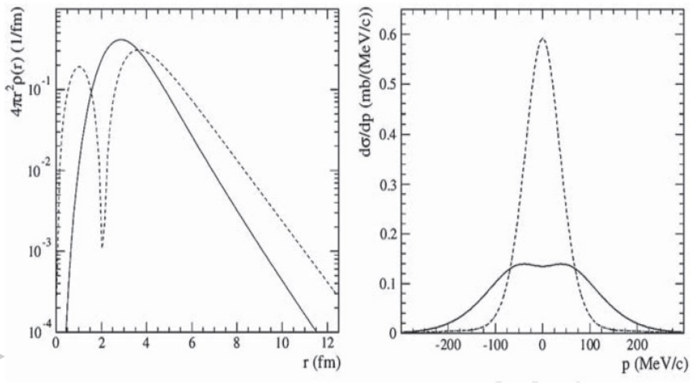
V. Panin PLB (2016)



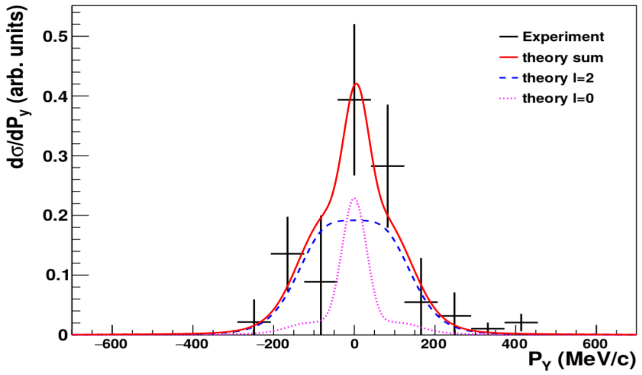
QFS on exotic nuclei to explore Shell evolution



C. Rodriguez-Tajes and D. Cortina



$^{23}O(p,2p)^{22}N$



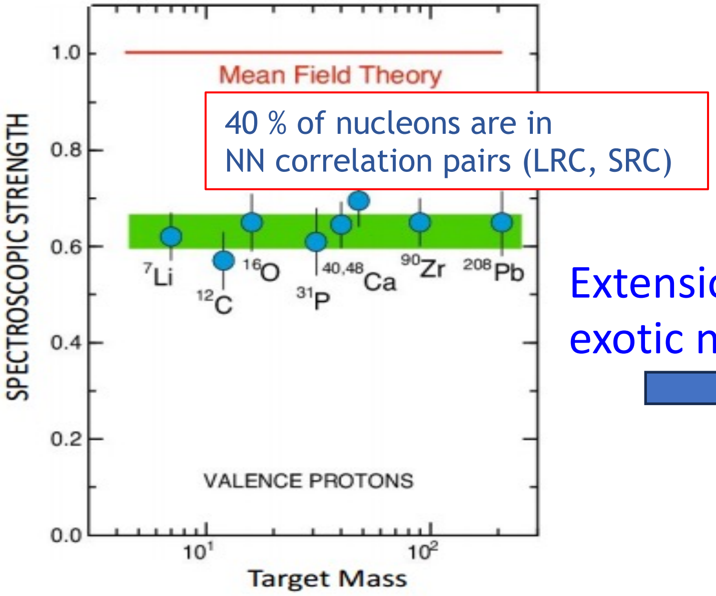
L. Attar PRLB (2018)

Reactions with Relativistic Rare Beams

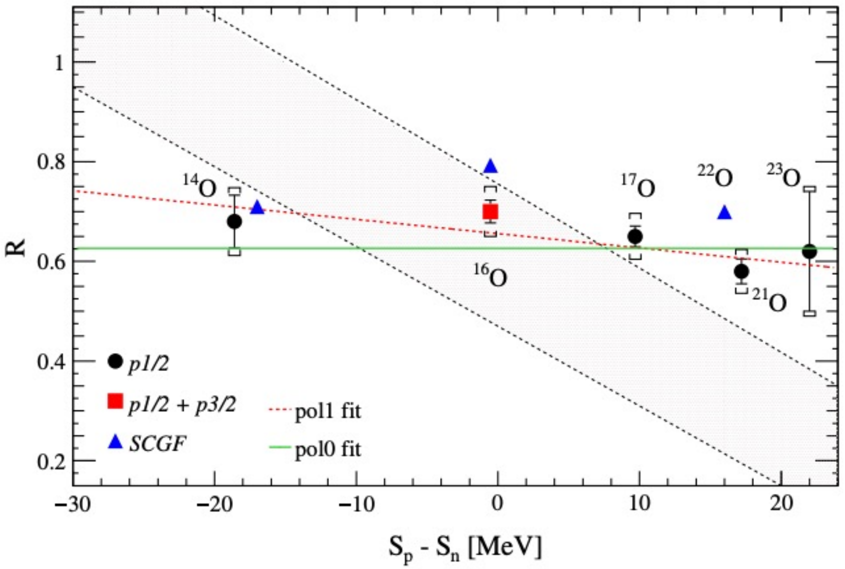
QFS on exotic nuclei to study the role of NN correlations

The most popular nuclear structure model is the shell model based on the assumption that the motion of each single nucleon is governed by an average potential due the presence of all the other A-1 particles (mean field).

The atomic nucleus is a strongly-correlated, bound, quantum many-body system formed by p and n.



Extension to exotic nuclei



L. Atar PRL (2018)
P. Díaz PRC (2018
M. Holl PLB (2019)

Reactions with Relativistic Rare Beams

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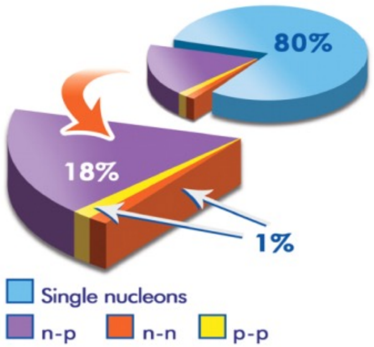
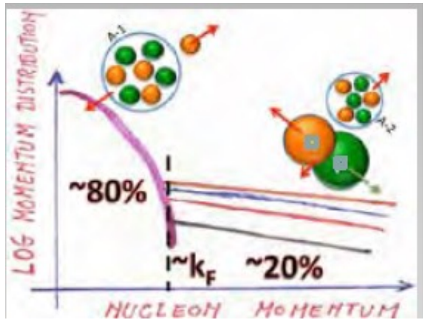




We have recently done the first study to caracterizze Short range correlations in exotic nuclei

Jefferson Lab results on ^{12}C showed that 20% nucleons form NN pairs strongly correlated

➢90% of them are np

R. Subedi et al., Science 320 (2008)

M. Duer Nature 560, 617-621 (2018)

Analysis on going

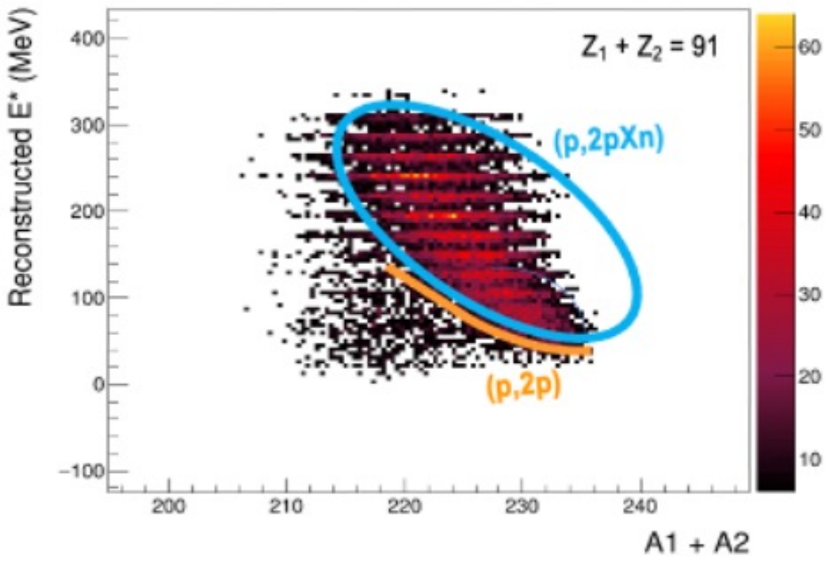
A. Lagni, M. Xarepe , E. Enz et al

Reactions with Relativistic Rare Beams

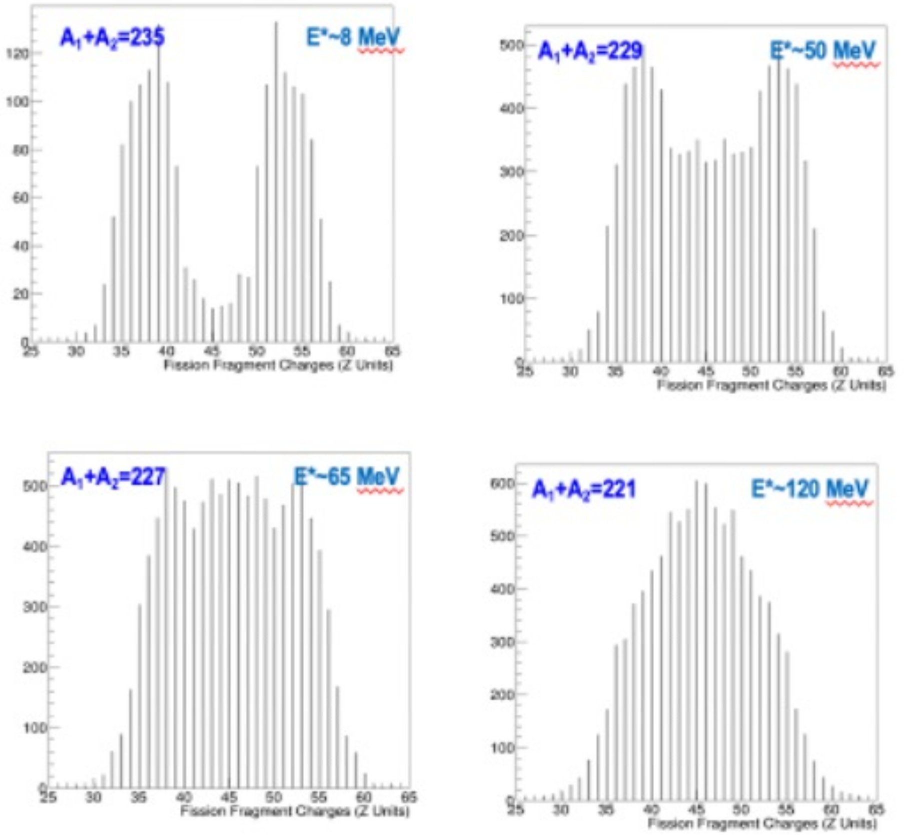
QFS to induce fission : Access to the excitation energy of the fissioning system

First evidence for QFS-induced fission

G. Garcia , A. Graña et al. Preliminary results



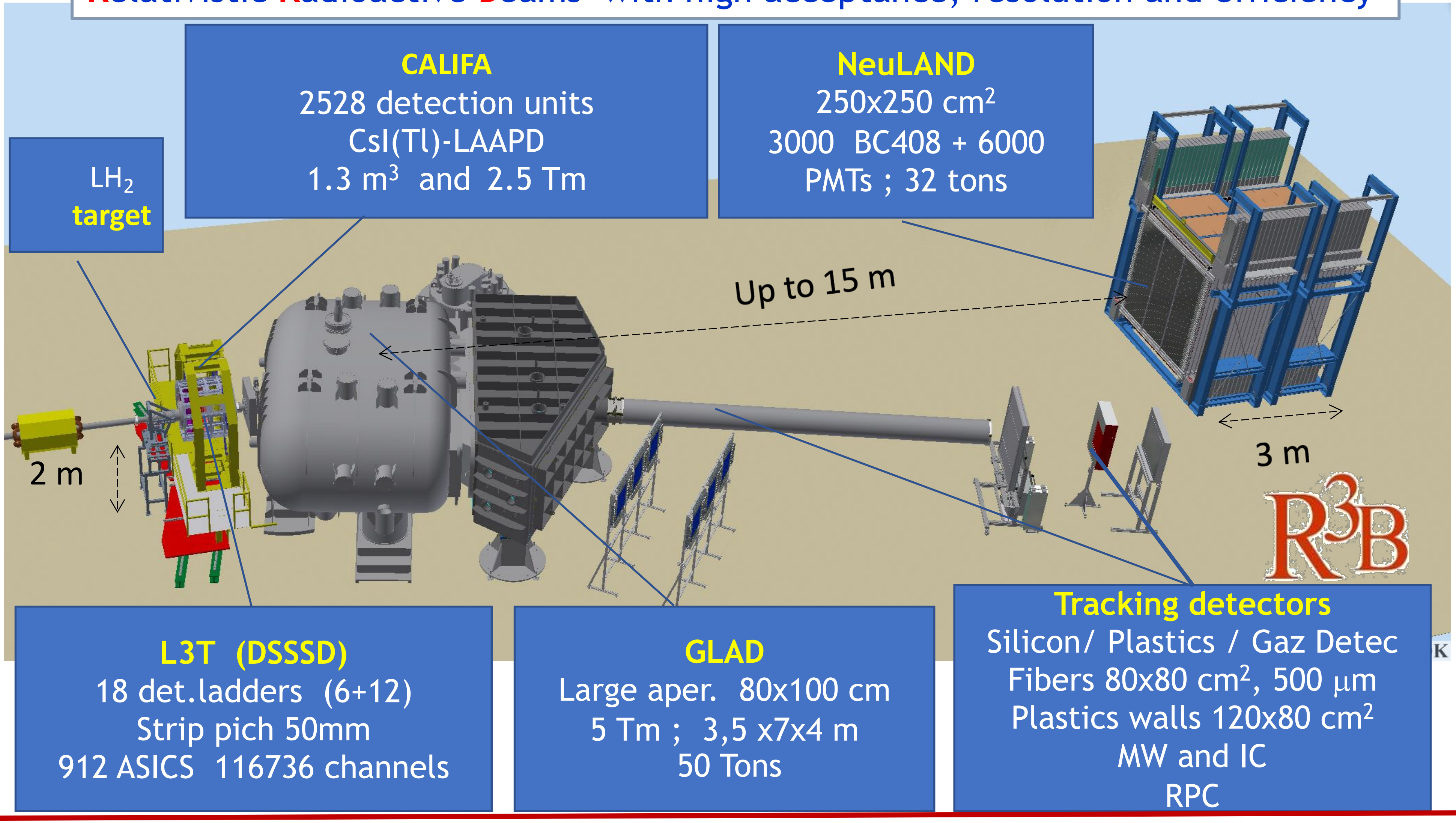
$^{238}U(p,2p)$ induced fission



Analysis on going

Reactions with Relativistic Rare Beams

Complete kinematics, fixed target experiment to study Reactions with Relativistic Radioactive Beams with high acceptance, resolution and efficiency



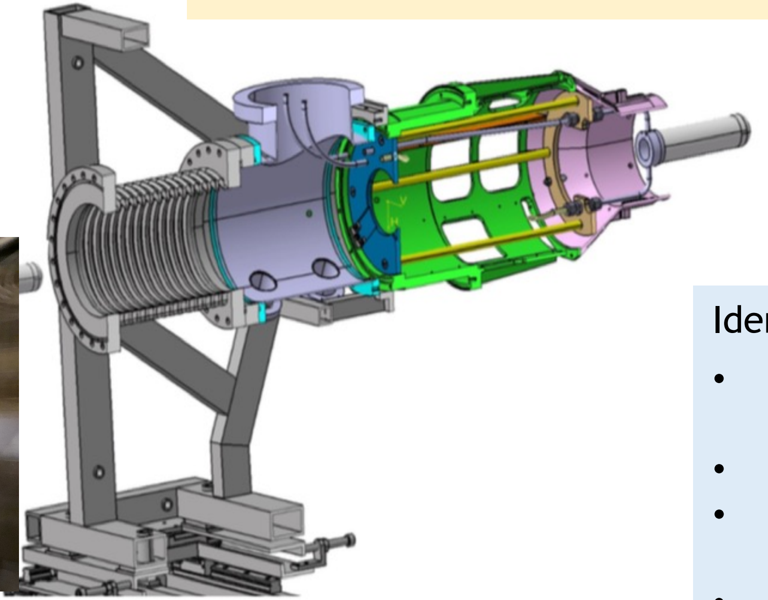
D.Cortina

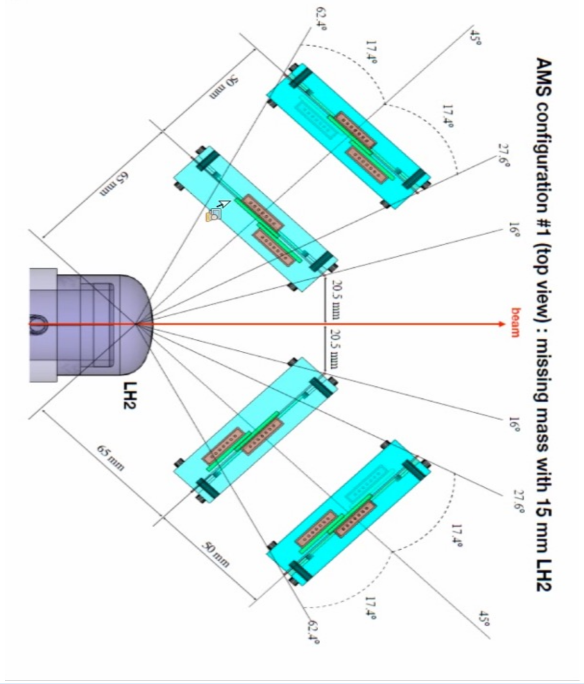
LH_2 target and p tracker

The target cell is made of Mylar

The target cell diameter is 42 mm,. Three target length of 15, 50 and 150 mm.

- The cryogenic system operates in a closed loop.
- The target is connected to a 852 l storage tank.
- The tank is filled with 800 l of hydrogen at room temperature.
- After liquefaction the hydrogen is at 20.3 K and 1041 mbar.

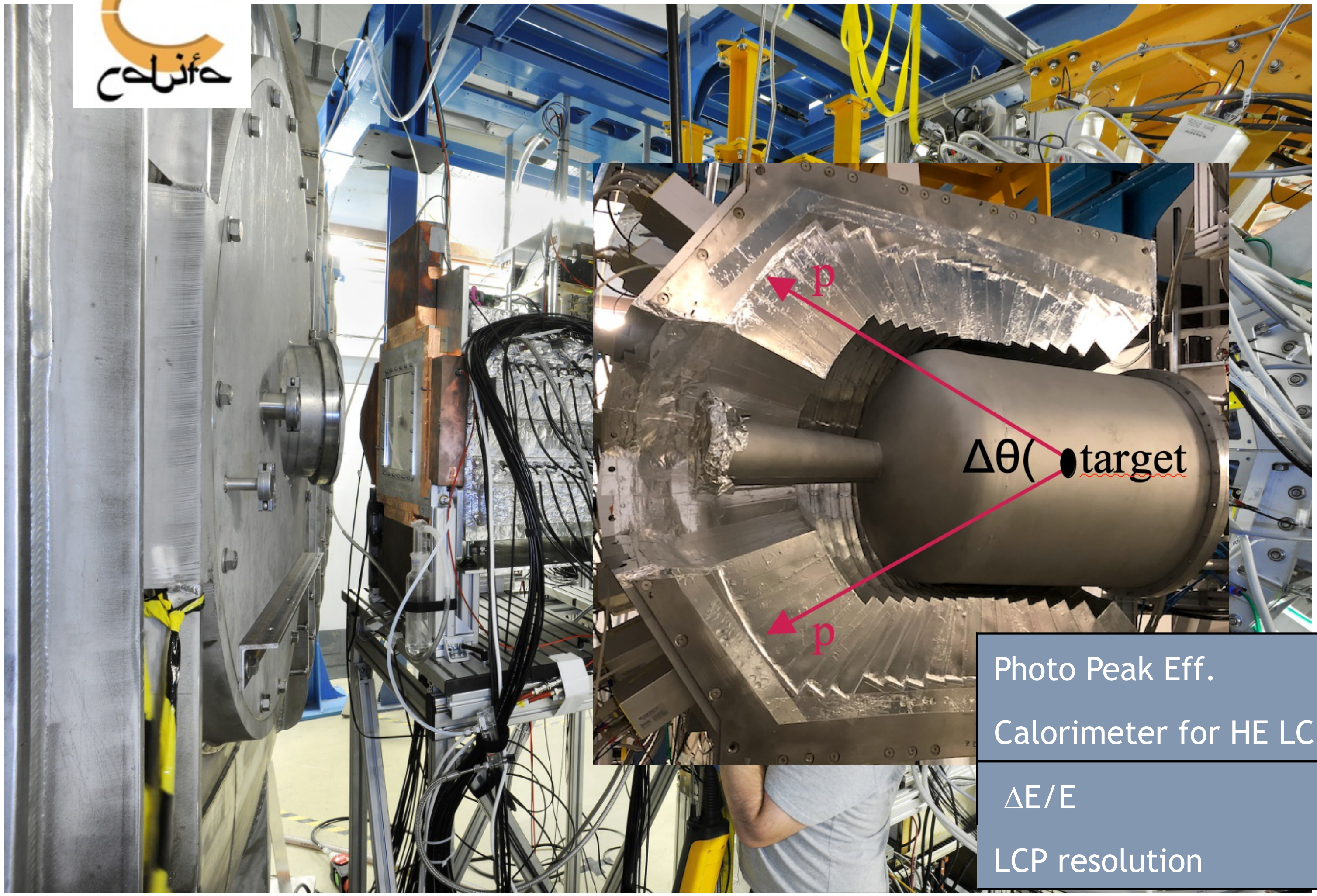




Identify and track recoils emmitted at large angles

- High angular resolution (better than 1 mrad) → very high segmentation
- Low noise level → detection of MIP
- Multi-layer sensors 50-100 mm for 1st layer → minimize multiple scattering or shadow g rays
- Low threshold 25 KeV
- Multi-hit capability

CALIFA : calorimeter for in flight particles and gamma rays



- Highly segmented CsI (Tl) + LAAPD
- Thick detection volumen
- Inner radius 50cm

  Barrel: Crystal length 15-22 cm

  1952 crystals = 2 Ton

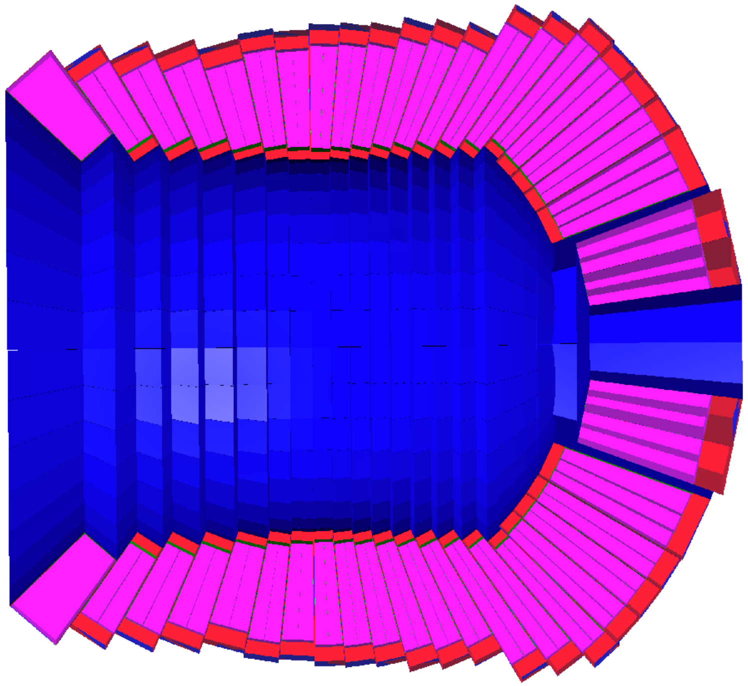
  EndCap: Crystal length 20-22 cm

  592 crystals = 1 Ton
- Externtal structure 3.5 x 4 m
- Detector volume 1.3 m3

Photo Peak Eff.	40% (up to Eγ=15 MeV projectile frame)
Calorimeter for HE LCP	200-700 MeV in lab system
ΔE/E	~5-6% (FWHM at Eg=1 MeV) , ~ 3% forward
LCP resolution	~2% (stopped particles), ~ 5% (punch through)

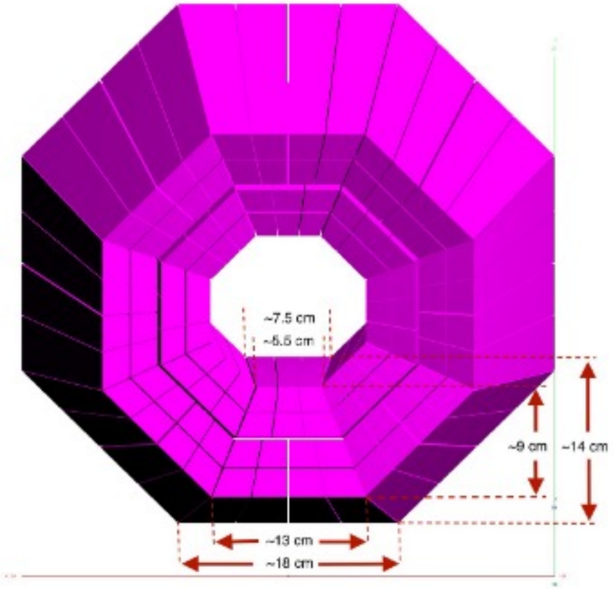
CALIFA : calorimeter for in flight particles and gamma rays

CEPA- CsI (Tl)



8 sector in total

14 crystals each – 14 geometries

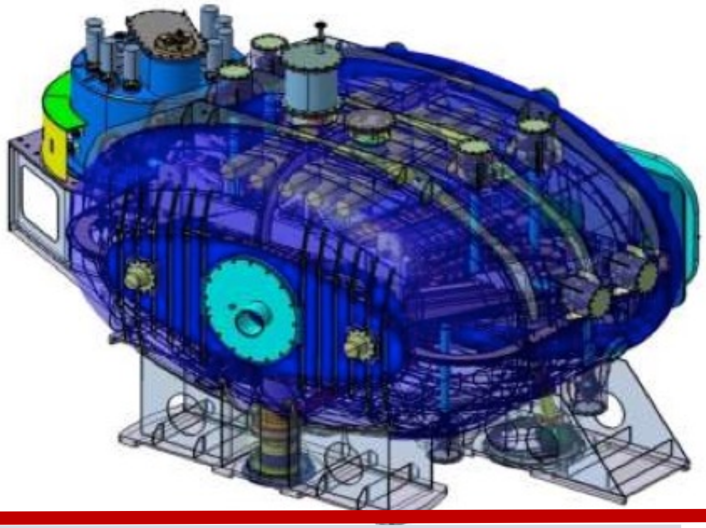


Will be installed in 2 weeks at FAIR for 2024 campaign

GLAD - Large-acceptance superconductingdipole magnet

Magnet parameters: Weight: 50 t

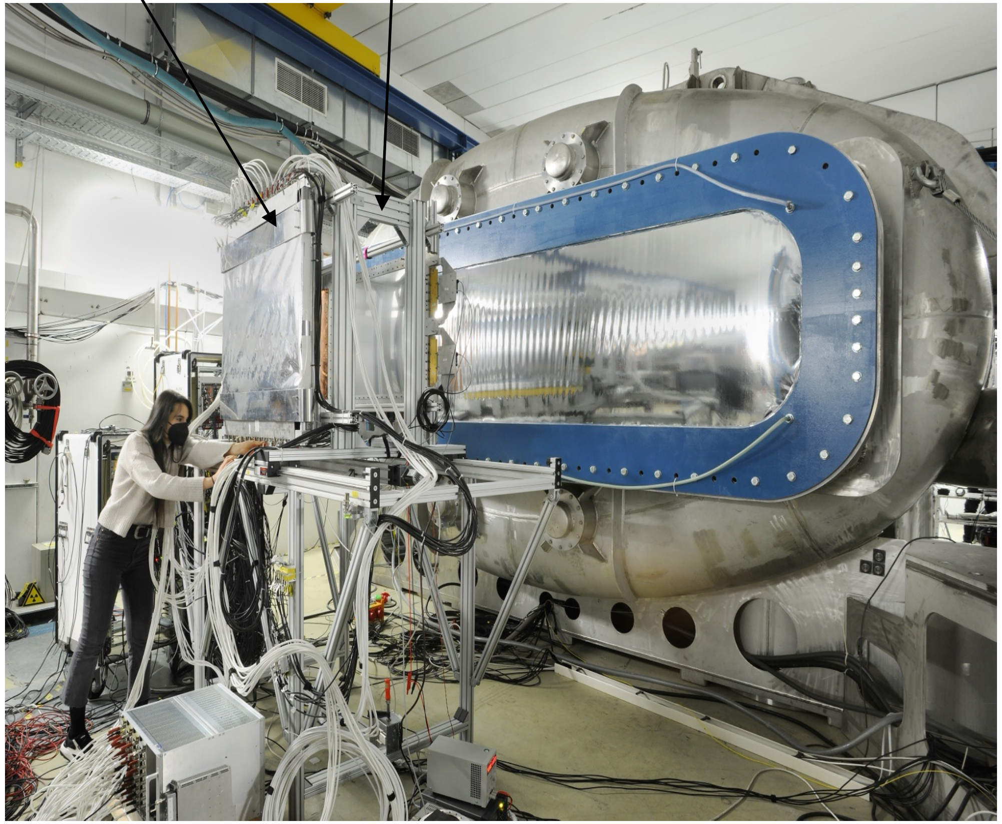
- Large vertical gap ± 80 mrad
- High integrated field of 4.8 Tm
- Fringe field at the target position less than 20 mT
- Operational temperature 4.6 K
- The overall size of the conical cryostat: 3.5 m long, 3.8 m high and 7 m wide.



Tracking system

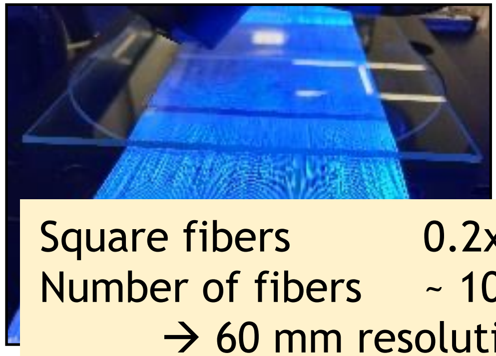
Plastic wall

Multiwire chambers



Different depending on the experimental needs

Plastic Fibers

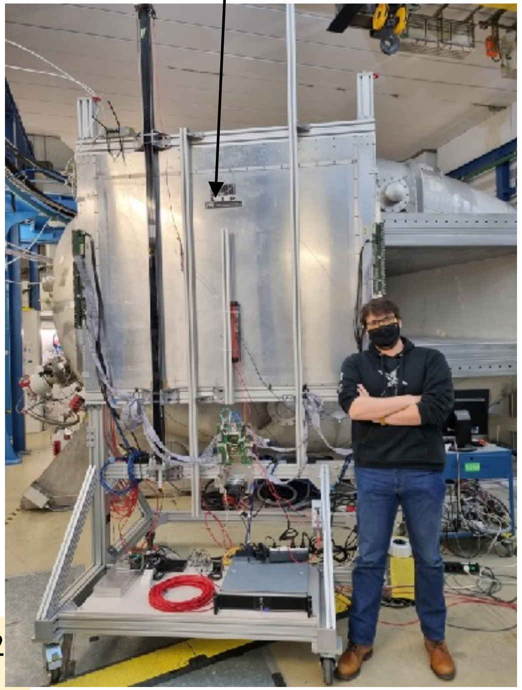


Square fibers 0.2x0.2 mm^2

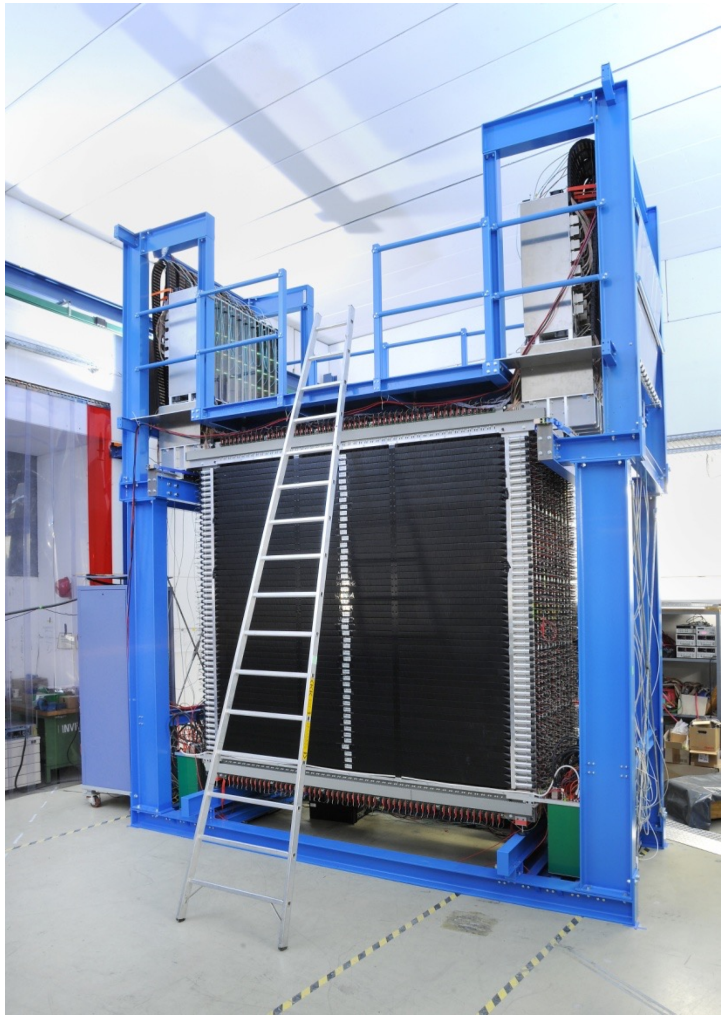
Number of fibers ~ 10^4 fibers

→ 60 mm resolution

Resistive Plate Chambers



NeuLAND - High-resolution neutron ToF spectrometer



NeuLAND detector parameters:

- full active detector using RP/BC408
- face size 2.50x2.50 m^2
- active depth 3m (30 double-planes)
- 3000 scintillator bars
- 6000 PM / readout channels (both ends)
- 32 tons

NeuLAND design goals:

- >90% efficiency for 0.2-1.0 GeV neutrons
- Multi-hit capability for up to 5n
- invariant-mass resolution:

  NeuLAND to target distance 35 m

  $\Delta E < 20$ keV at 300 keV

Muchas gracias por vuestra atención