Opening a new Era in Exotic Nuclear Physics: FAIR

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Lisboa, LIP Seminar

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Outline

- Motivation:
  - **Exotic** nuclei
  - Places in **nature** where we **find** them
- **FAIR: F**acility for **A**ntiproton and **I**on **R**esearch
  - Experimental setup (**LAND/R³B**)
  - Results on **particle-exclusive** and **particle-inclusive** **neutron knock-out** on a **proton target**
  - Results on measurement of **high-energy photons** with **CALIFA @ CTN-Lisbon**
- Towards **Phase-0 @ FAIR**…. next year!

Exotic

Definition:

(Cambridge Dictionary)

English:
unusual and exciting because of coming (or seeming to come) from far away, especially a tropical country

American:
unusual and specially interesting because of coming from a country that is far away

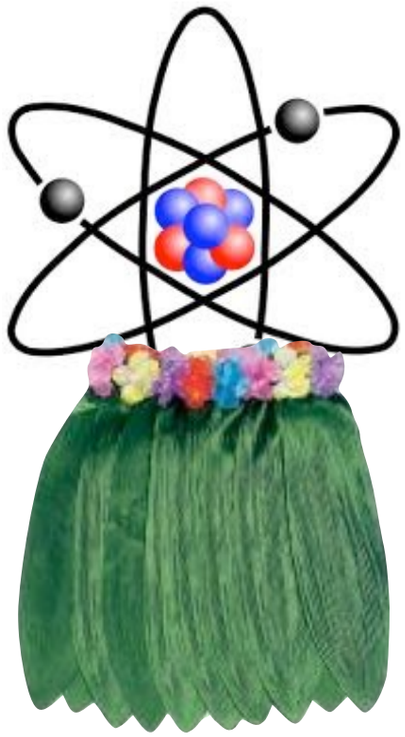


Table of Isotopes

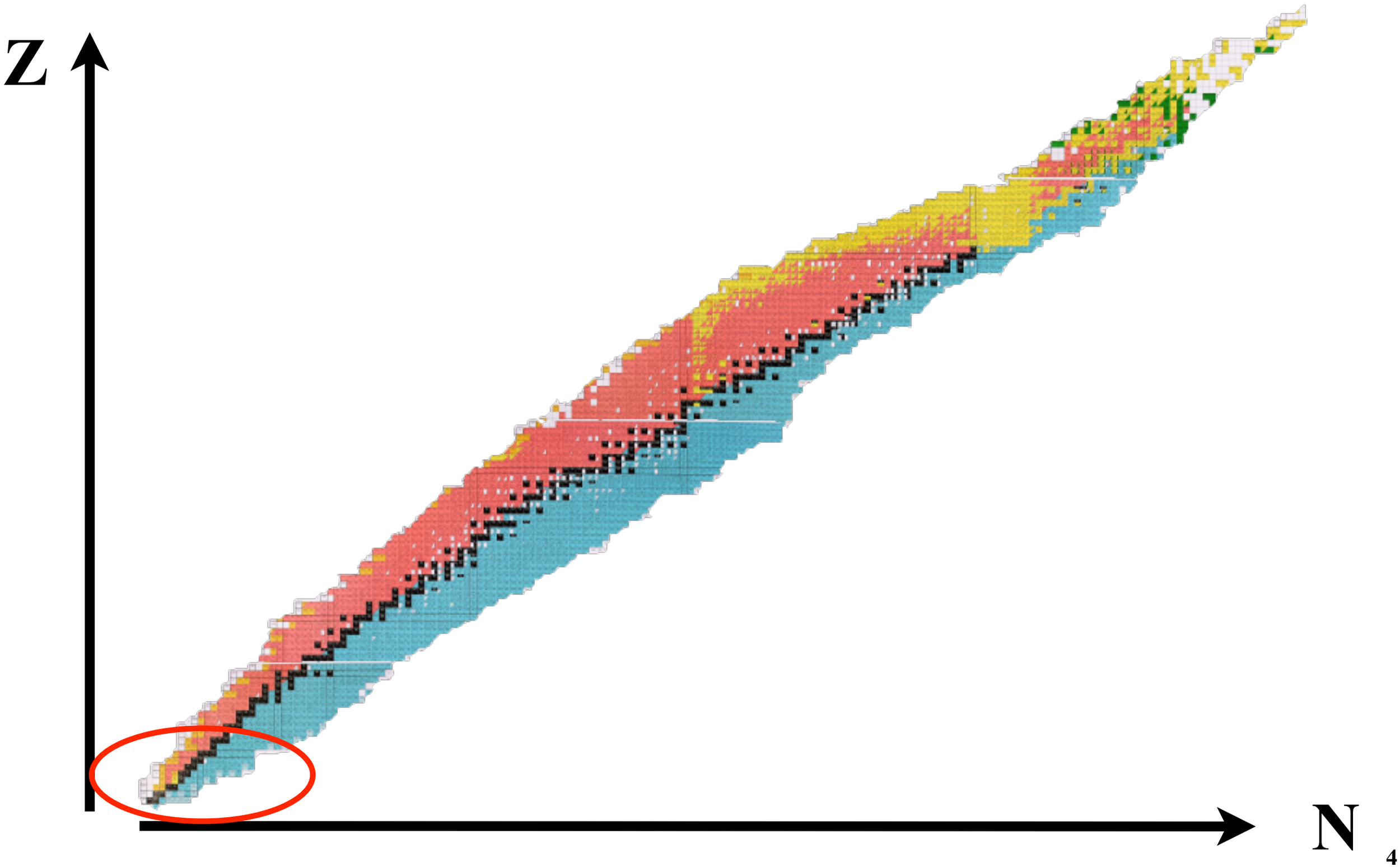


Table of Isotopes

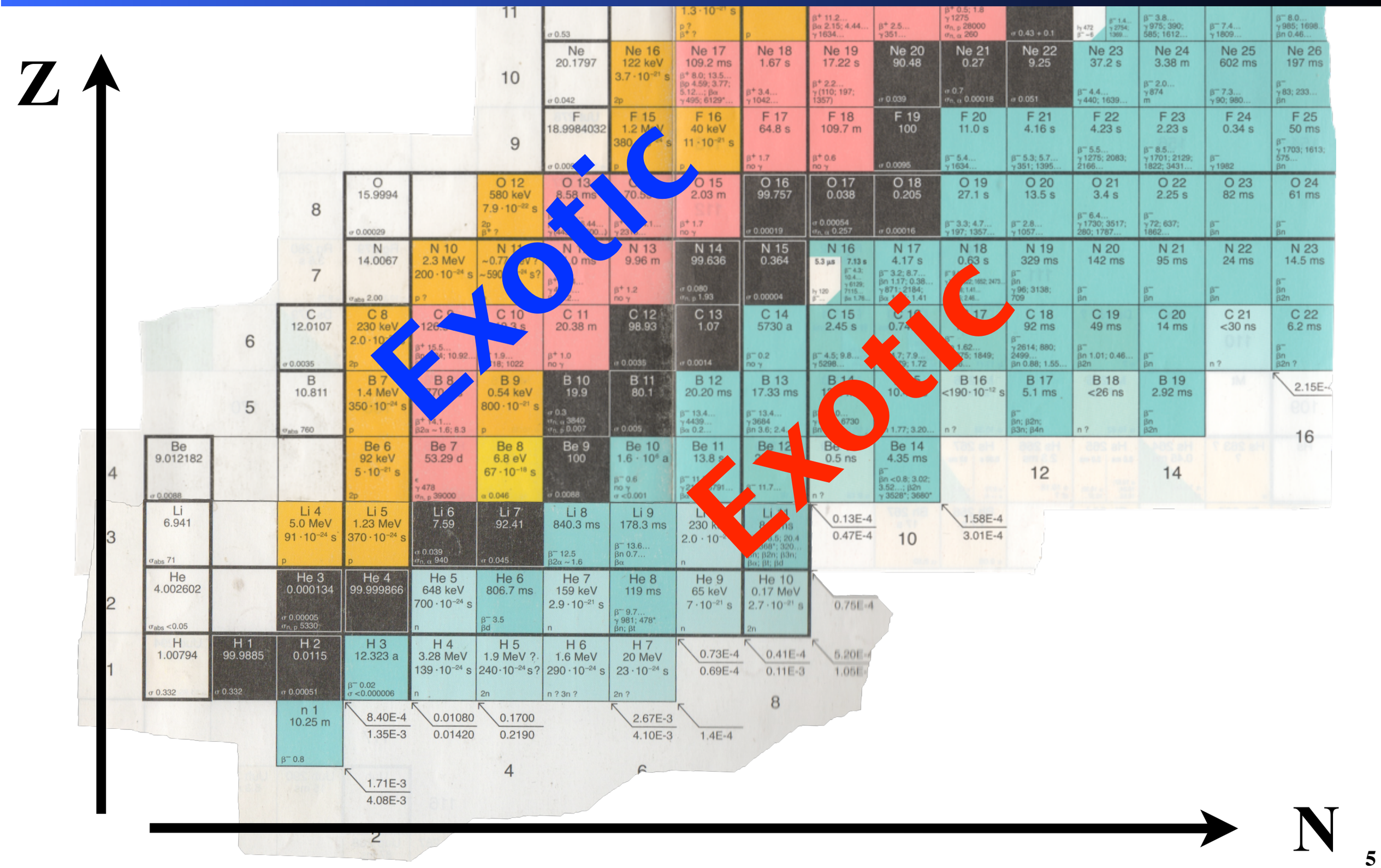
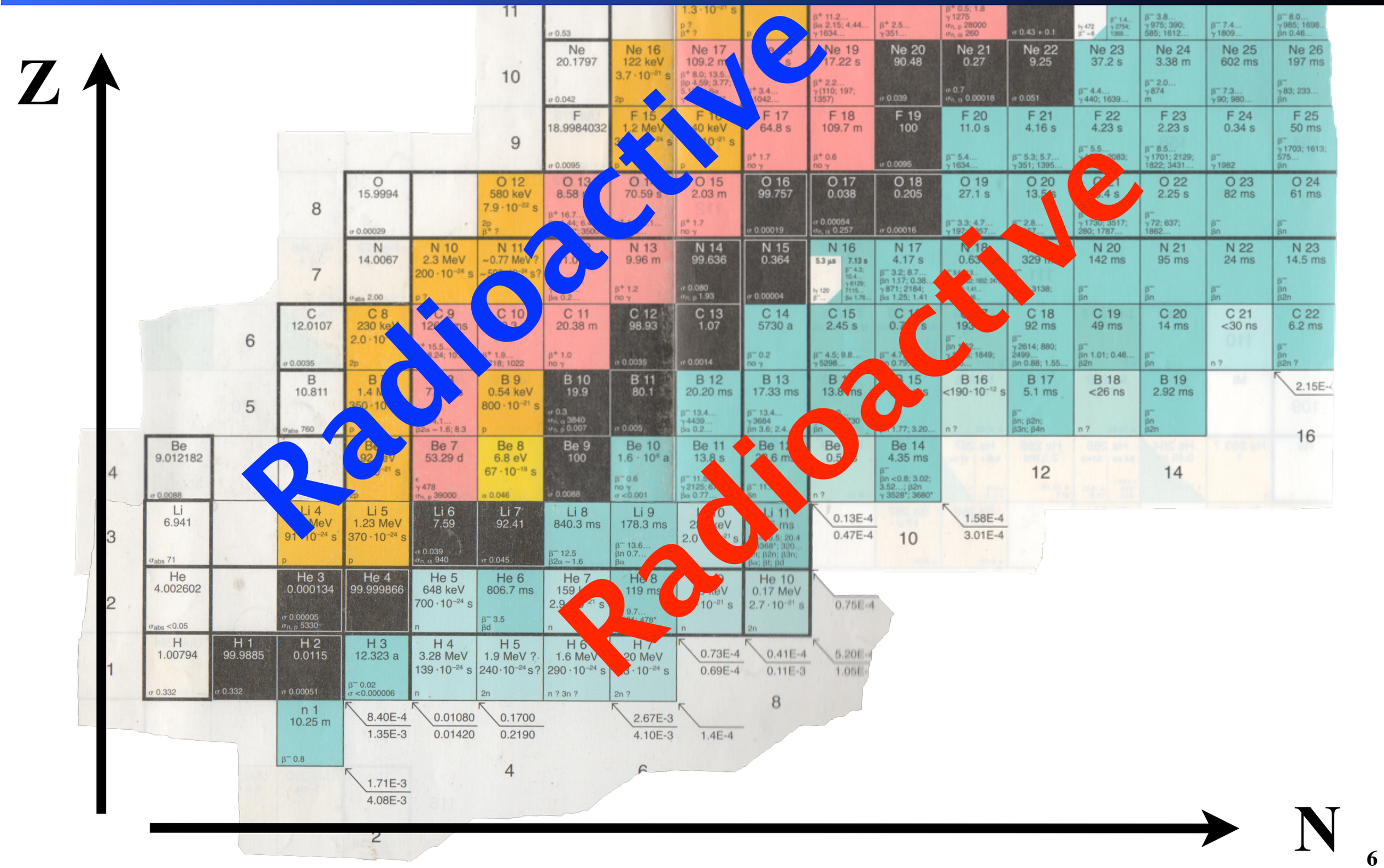


Table of Isotopes



Exotic Nuclei in Nature

- Do they exist?
  - Isotopes with half-live > Solar System:

^{235}U, ^{238}U, ^{232}Th, ^{40}K, ^{36}Cl

Pictures from L. Peralta's Lab

Exotic Nuclei in Nature

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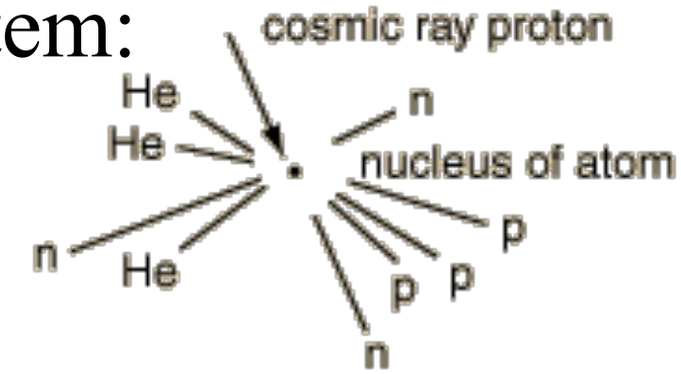
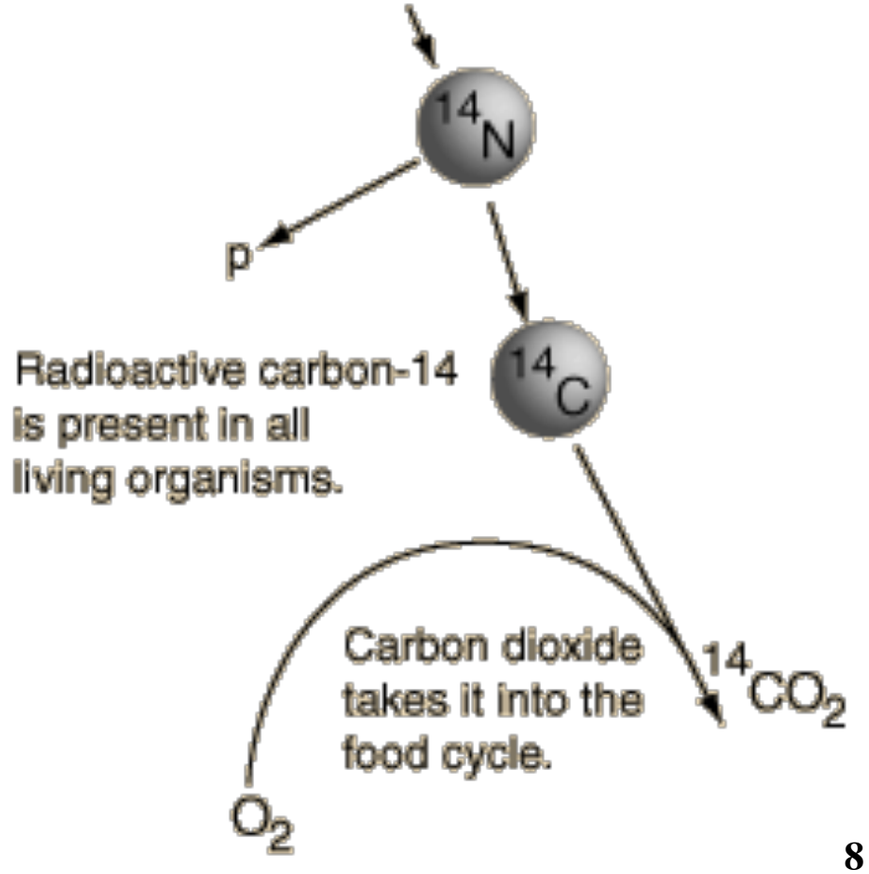


  - Isotopes continously produced on our planet:

^{14}C



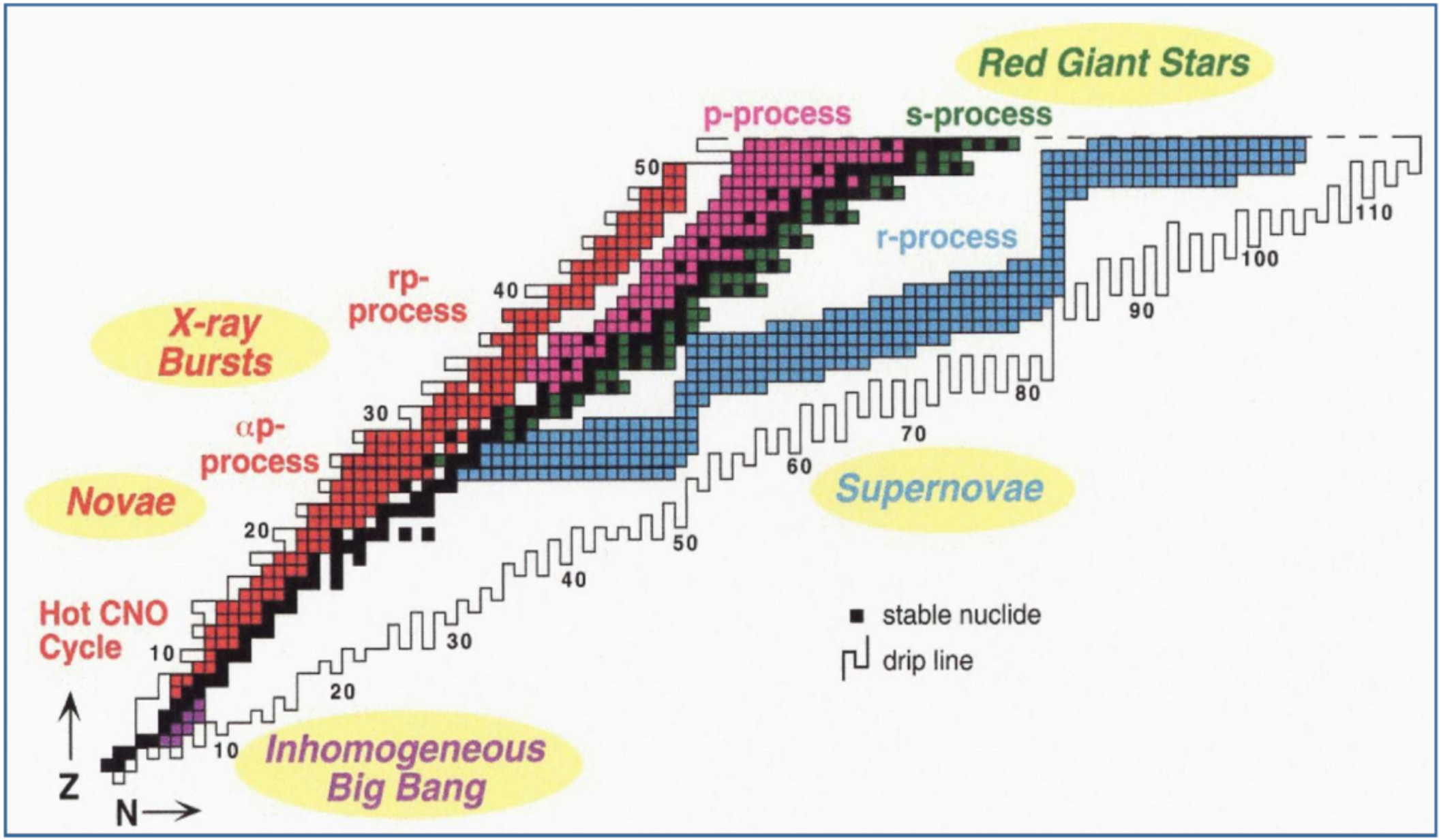
Interest in Exotic Nuclei

- Applications:
  - Radiopharmaceuticals (^{123}I, ^{131}I, ^{99m}Tc, ^{18}F)
  - Gammagraphy (^{60}Co, ^{137}Cs)
  - Dating (^{14}C, ^{87}Rb)

- Basic Research:
  - Nuclear Interaction Properties
  - Origin of the Elements in the Universe

Exotic Nuclei in the Universe

Overview of main astrophysical processes



Adopted from Adriana Banu, JMU

… and Neutron Star Collisions

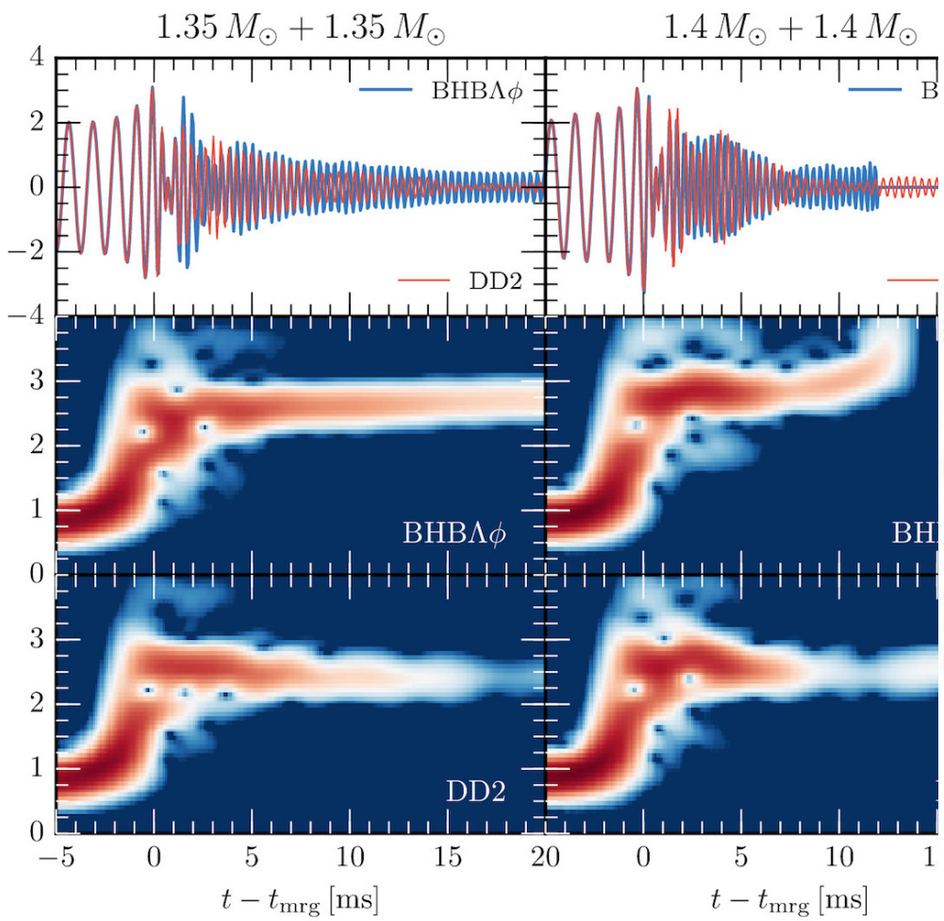
… and Neutron Star Collisions

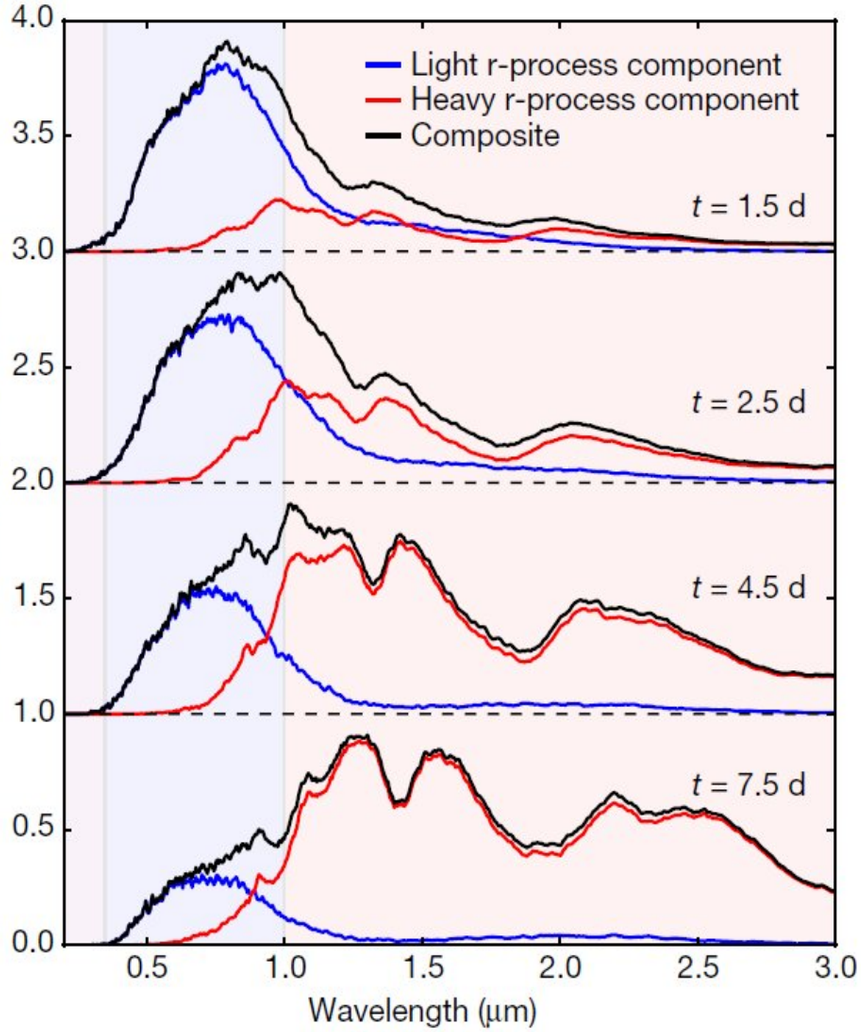
LETTER

doi:10.1038/nature24453

Origin of the heavy elements in binary neutron-star mergers from a gravitational-wave event

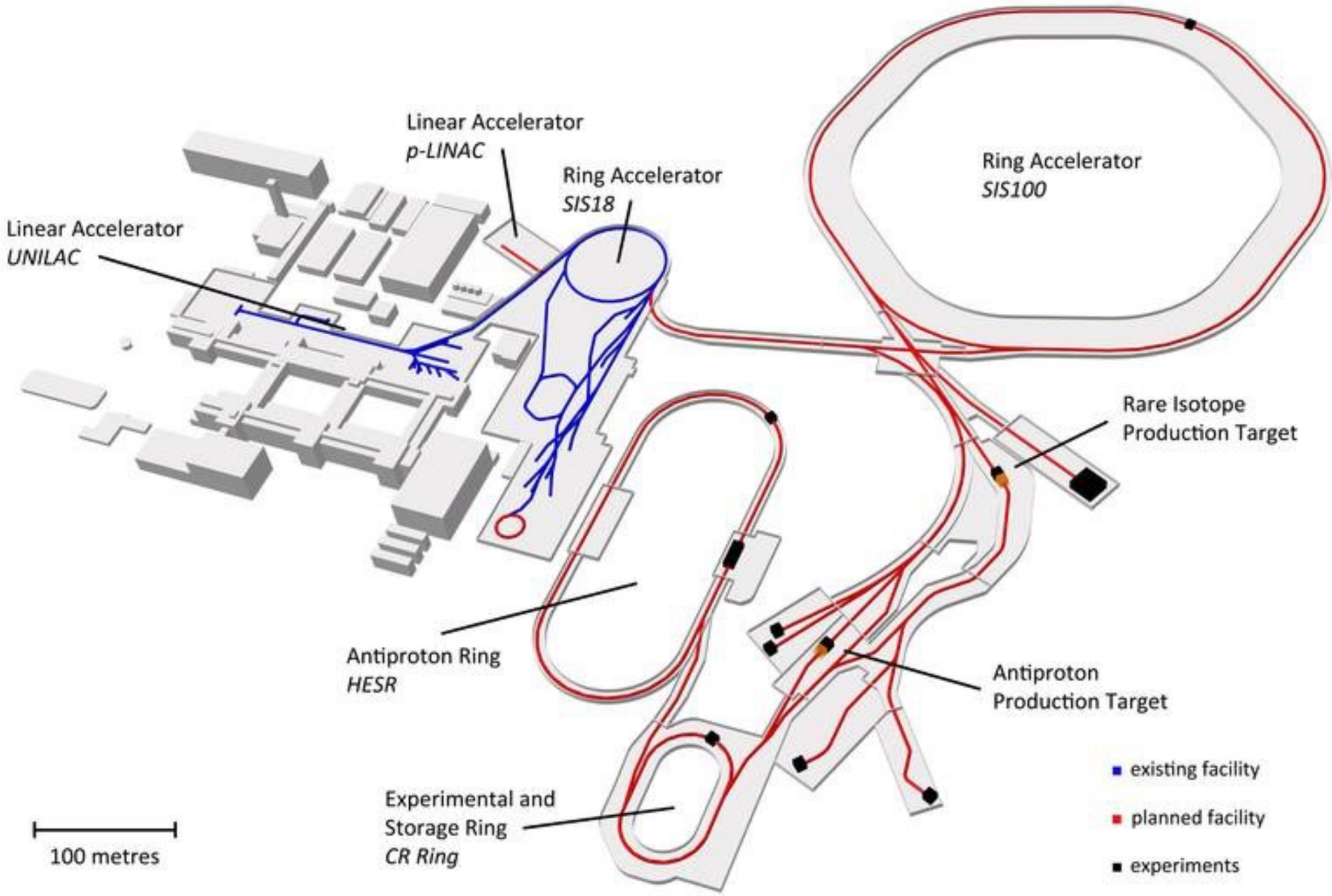
Daniel Kasen[1,2], Brian Metzger[3], Jennifer Barnes[3], Eliot Quataert[1] & Enrico Ramirez-Ruiz[4,5]

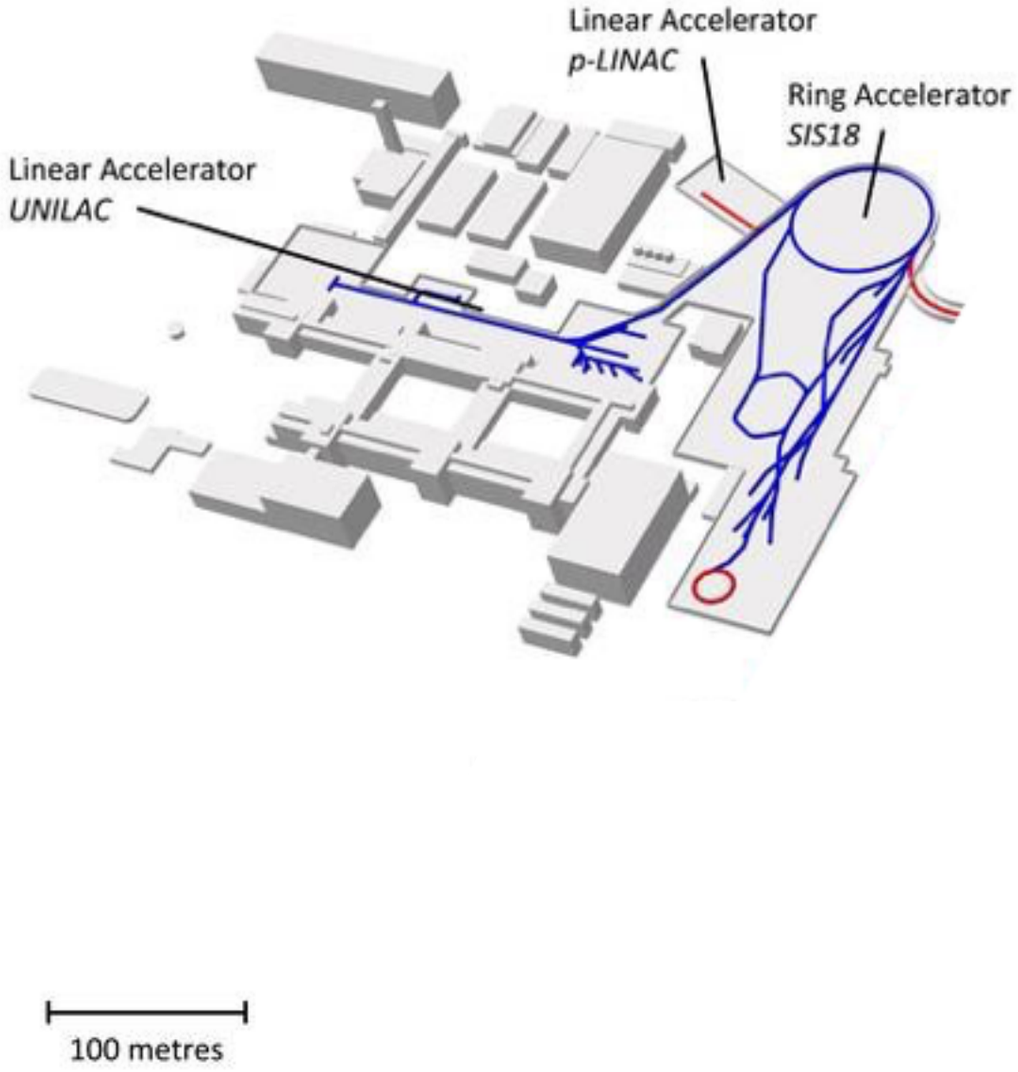




Discovery of the electromagnetic counterpart to the GW170817
→ Provides the first evidence for r-process nucleosynthesis.

FAIR


Linear Accelerator
p-LINAC
Ring Accelerator
SIS18
Linear Accelerator
UNILAC
Ring Accelerator
SIS100
Rare Isotope
Production Target
Antiproton Ring
HESR
Antiproton
Production Target
existing facility
planned facility
experiments
Experimental and
Storage Ring
CR Ring
100 metres


Linear Accelerator
p-LINAC
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Linear Accelerator
UNILAC
100 metres

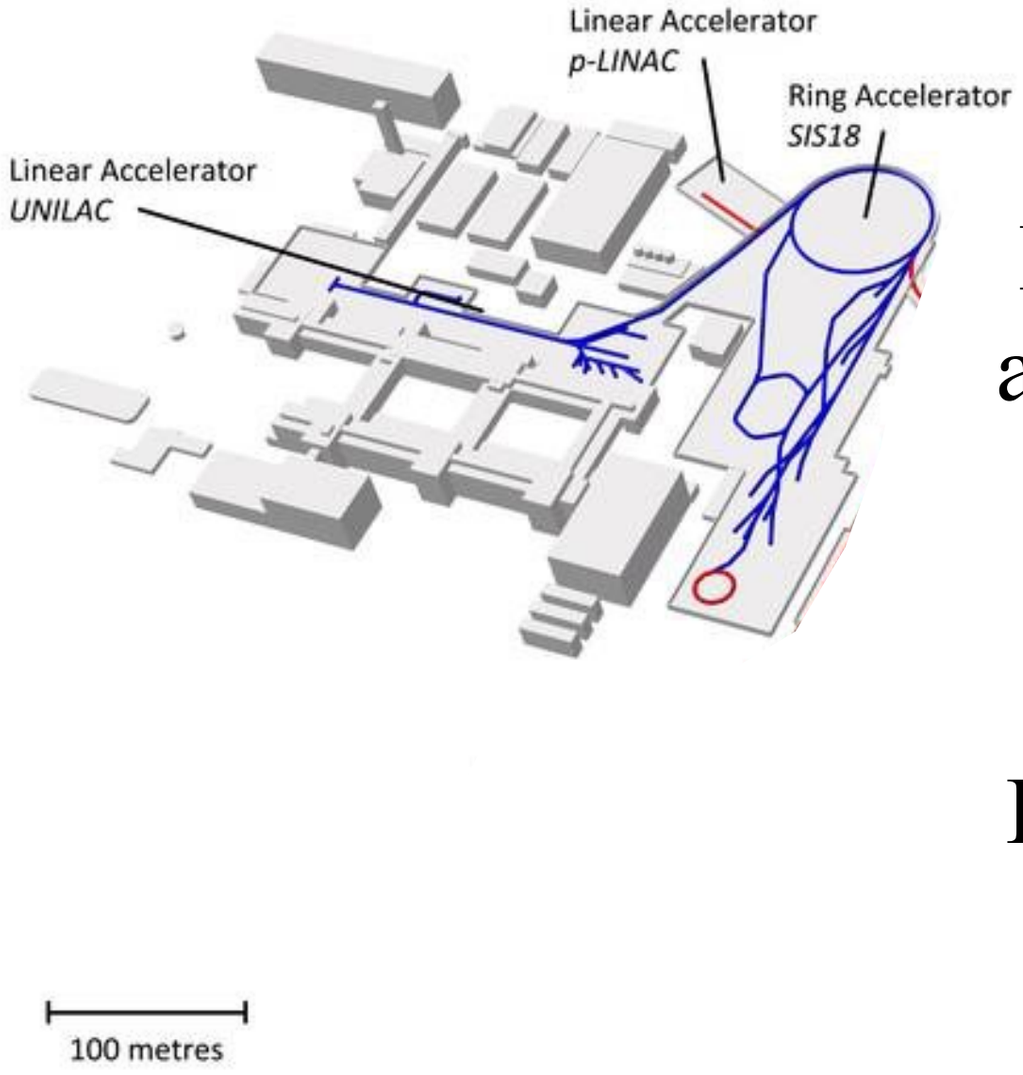
GSI

Helmholtzzentrum für Schwerionenforschung

Located in Darmstadt (Hessen)
Founded in 1969

Employs about 1400 people

- Best known results are:
  - → Discovery of **six** new **chemical elements** (from $_{107}$Bh till $_{112}$Cn)
  - → **Tumor treatment** developments using **Ion Beams**



1990:

Commissioning of SIS18 and ESR

2003:

Federal Ministry of Education and Research gives **green light** to FAIR

2010:

FAIR is **founded** by 9 partners

2017:

FAIR starts **civil construction**

FAIR

The Universe in the Laboratory

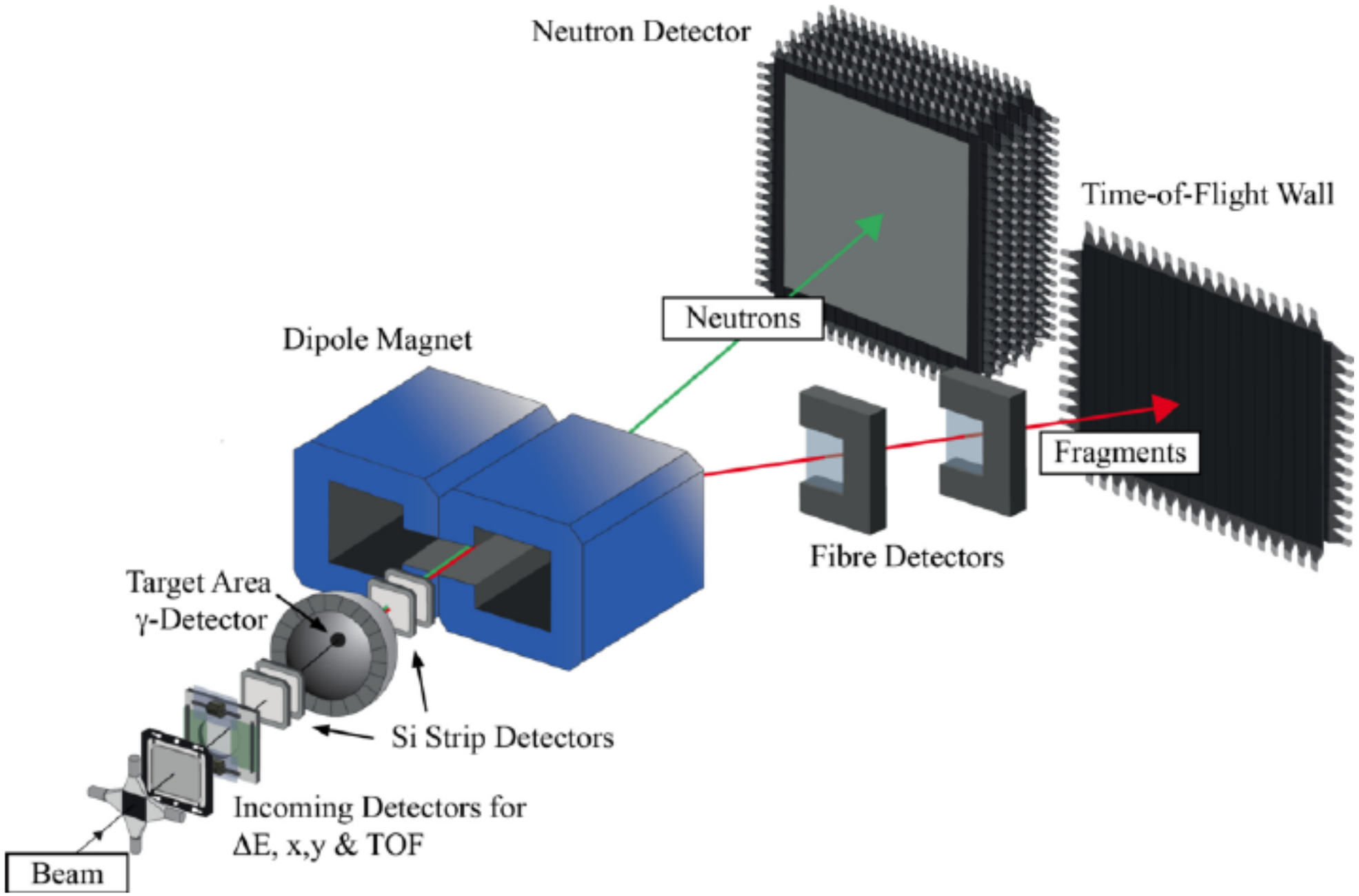
Research at the world-wide unique
international particle accelerator facility

Facility for Antiproton and Ion Research,
Darmstadt, Germany

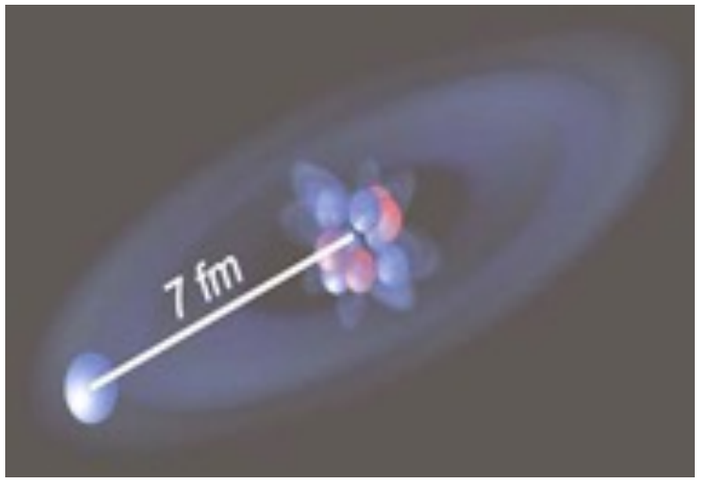
https://fair-center.eu

Pillars

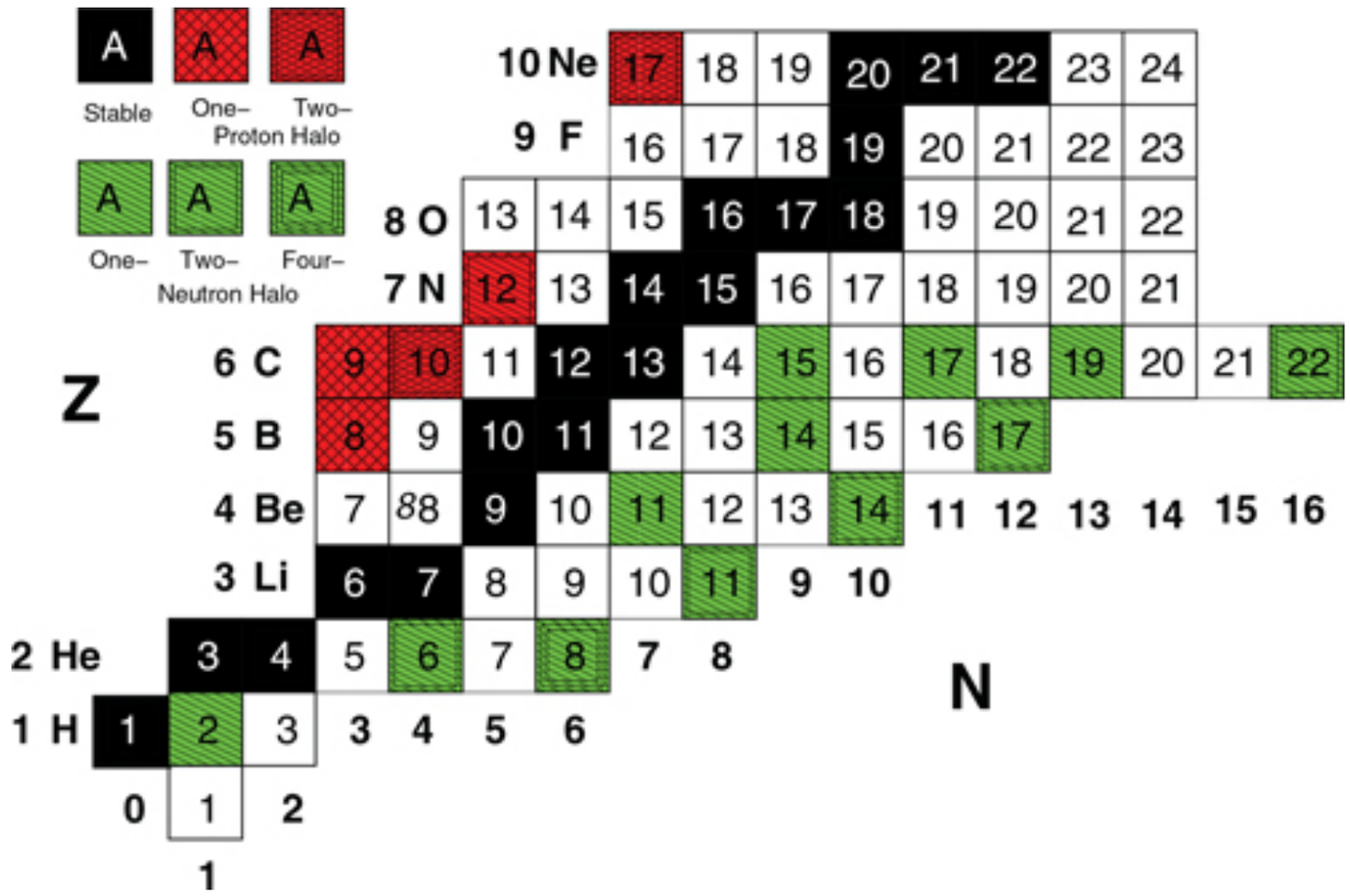
LAND/R³B


Neutron Detector
Time-of-Flight Wall
Neutrons
Dipole Magnet
Fragments
Fibre Detectors
Target Area
γ-Detector
Si Strip Detectors
Incoming Detectors for
ΔE, x,y & TOF
Beam

Halo nuclei



^{11}Be



- **Cluster** structure + **halo** particle(s)
  - **Extended** mass distribution
- Low **separation energy** (< 1 MeV)
  - Low angular momentum state (**s-wave**)

Halo nuclei: ^{11}Be & ^{15}C

	S_n (MeV)	g.s. (J^π)	g.s. conf.
^{11}Be	0.5	$1/2^+$	$\alpha[^{10}\text{Be}(0+) \otimes 1\nu\,(2s_{1/2})] \oplus \beta[^{10}\text{Be}(2+) \otimes 1\nu\,(1d_{5/2})]$
^{15}C	1.2	$1/2^+$	$^{14}\text{C}(0+) \otimes 1\nu\,(2s_{1/2})$

^{11}Be

T. Aumann *et al.*, Phys. Rev. Lett. **84**, 35(2000)

J. A. Tostevin *et al.*, Phys. Rev. C **66**, 024607 (2002)

N. Fukuda *et al.*, Phys. Rev. C **70**, 054606 (2003)

^{15}C

J. A. Tostevin *et al.*, Phys. Rev. C **66**, 024607 (2002)

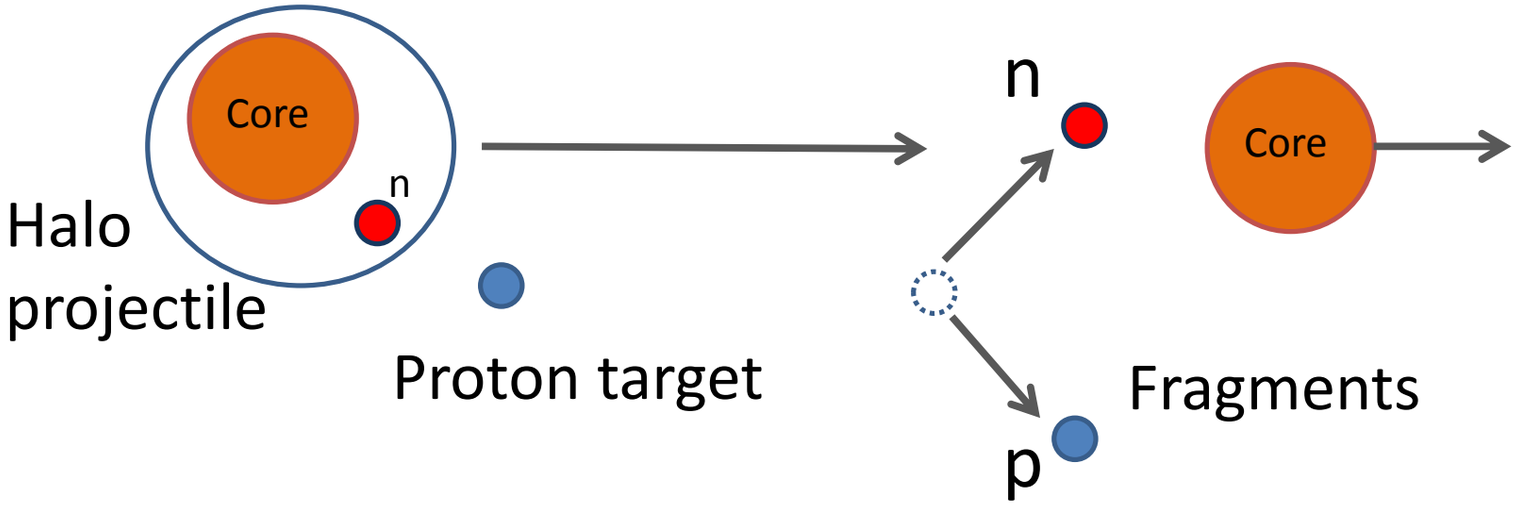
U. Datta Pramanik *et al.*, Phys. Lett. B **551**, 63 (2003)

T. Nakamura *et al.*, Phys. Rev. C **79**, 035805 (2009)

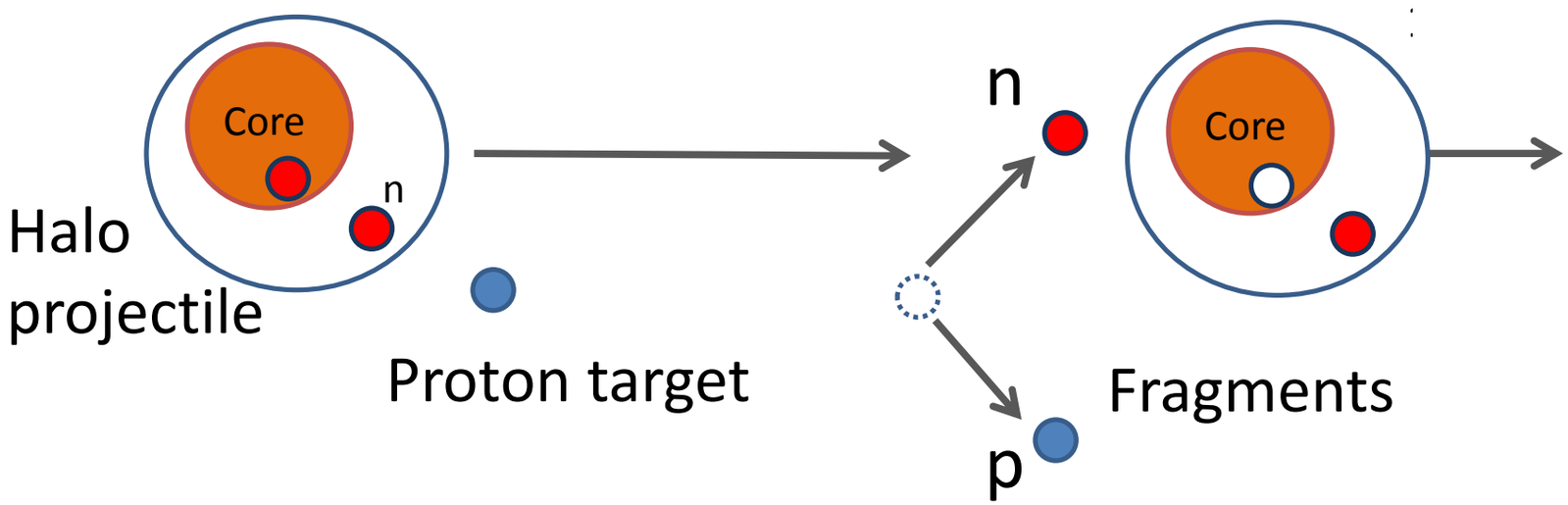
Suitable cases for the verification of the **reaction mechanism** studying its **break-up** on a **proton** target at **relativistic energies**

Nucleon knock-out contributions

Valence knock-out

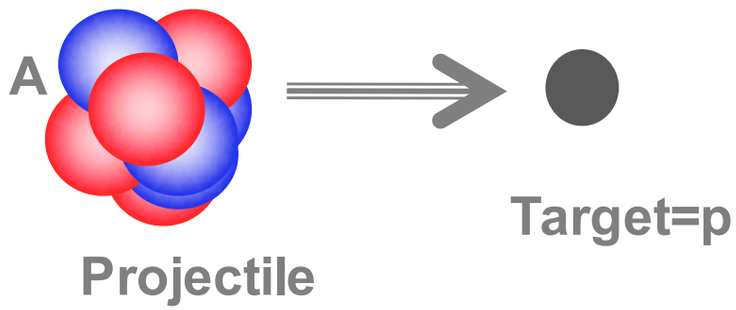


Inner shell knock-out



1

Reaction theory



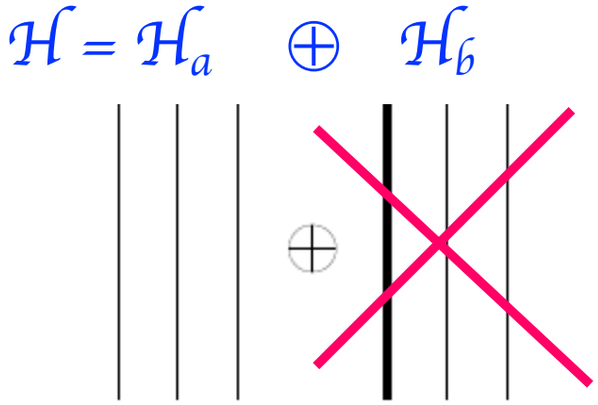
A+1 many body problem

Projectile = Core(Heavy Fragment) + N

Three body problem

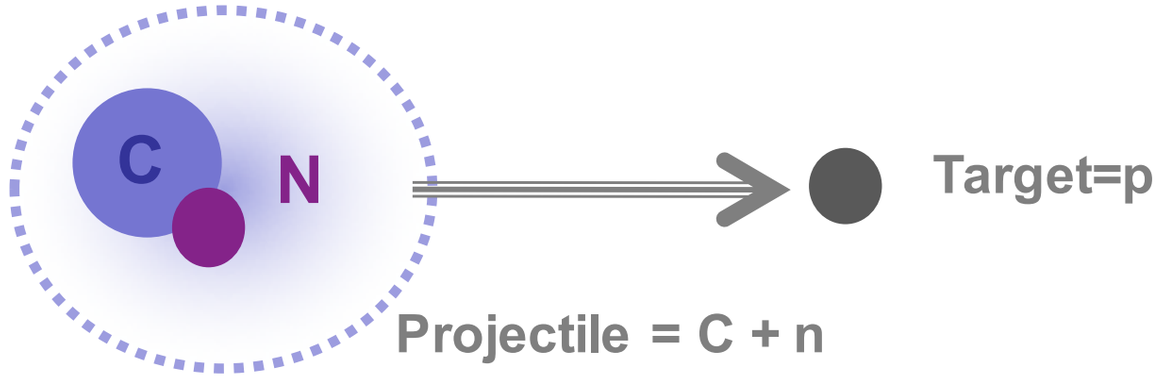
Space Truncation

- **Projectile** well described as **C** + **N**
- **Core** assumed to be **inert** during the collision process
  (possible to account on core excitation admixtures on the wave function)
- **Excited states** above threshold generally
  not included



Reaction theory: Faddeev/AGS

- **Non-relativistic**
- **Truncated Hilbert space**



- Each particle is treated **on an equal footing** to the others
- Takes into account **all open channels** simultaneously

- Formulated in terms of the **transition amplitude** for each **interacting pair**

$$t_\gamma = v_\gamma + v_\gamma \; G_0 \; t_\gamma$$

Pair transition operators

$$G_0 = (E + i0 - H_0)^{-1}$$

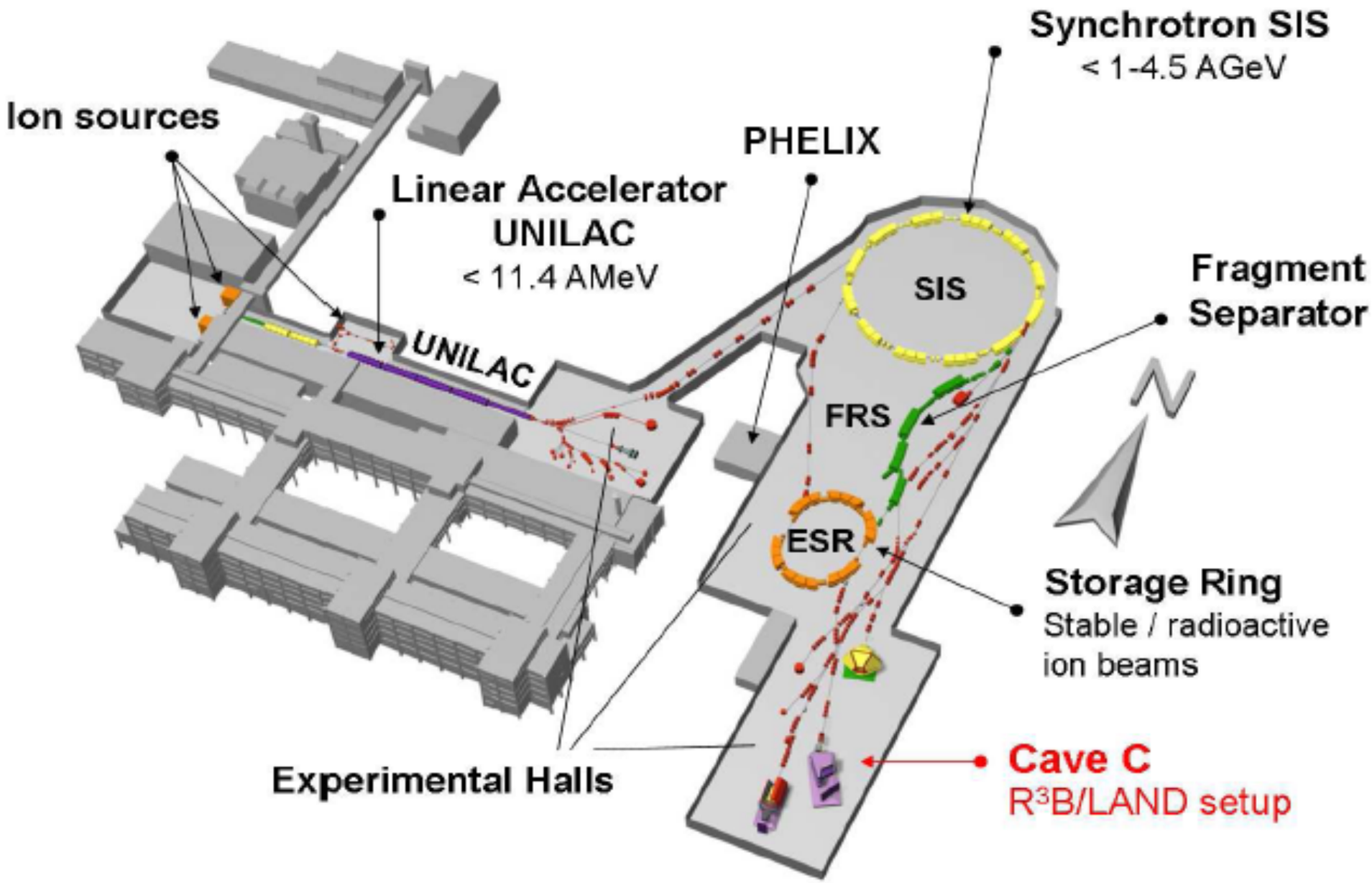
Free propagator

Tool for investigating:

★ **Single particle** properties

★ **Spectroscopic factors**

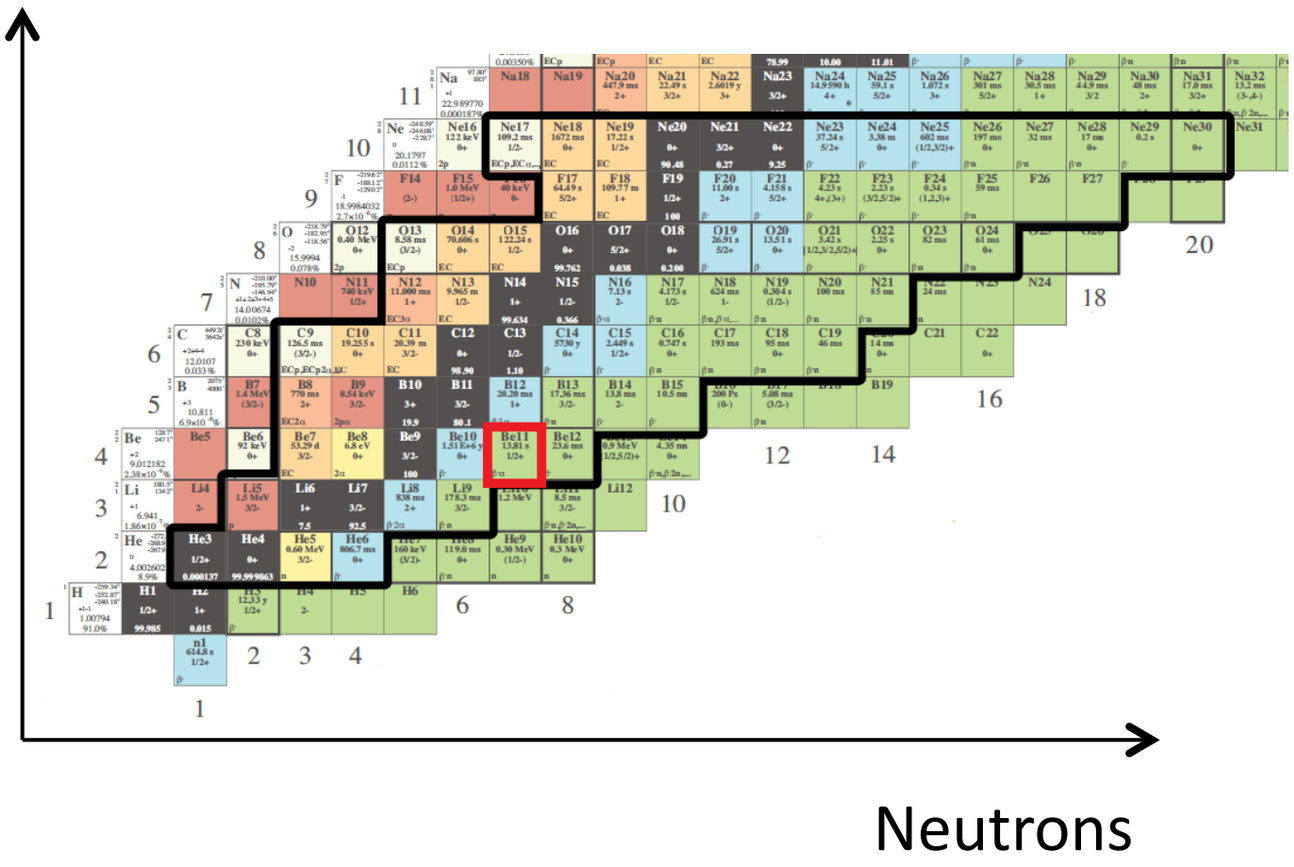
Experiment S393 at Cave C



S393 experiment at LAND/R³B

GSI Experiment **S393**

"Neutron-rich Nuclei at and Beyond the Dripline in the Range Z=4 to Z=10 Studied in Kinematically Complete Measurements of Direct Reactions at Relativistic Energies"



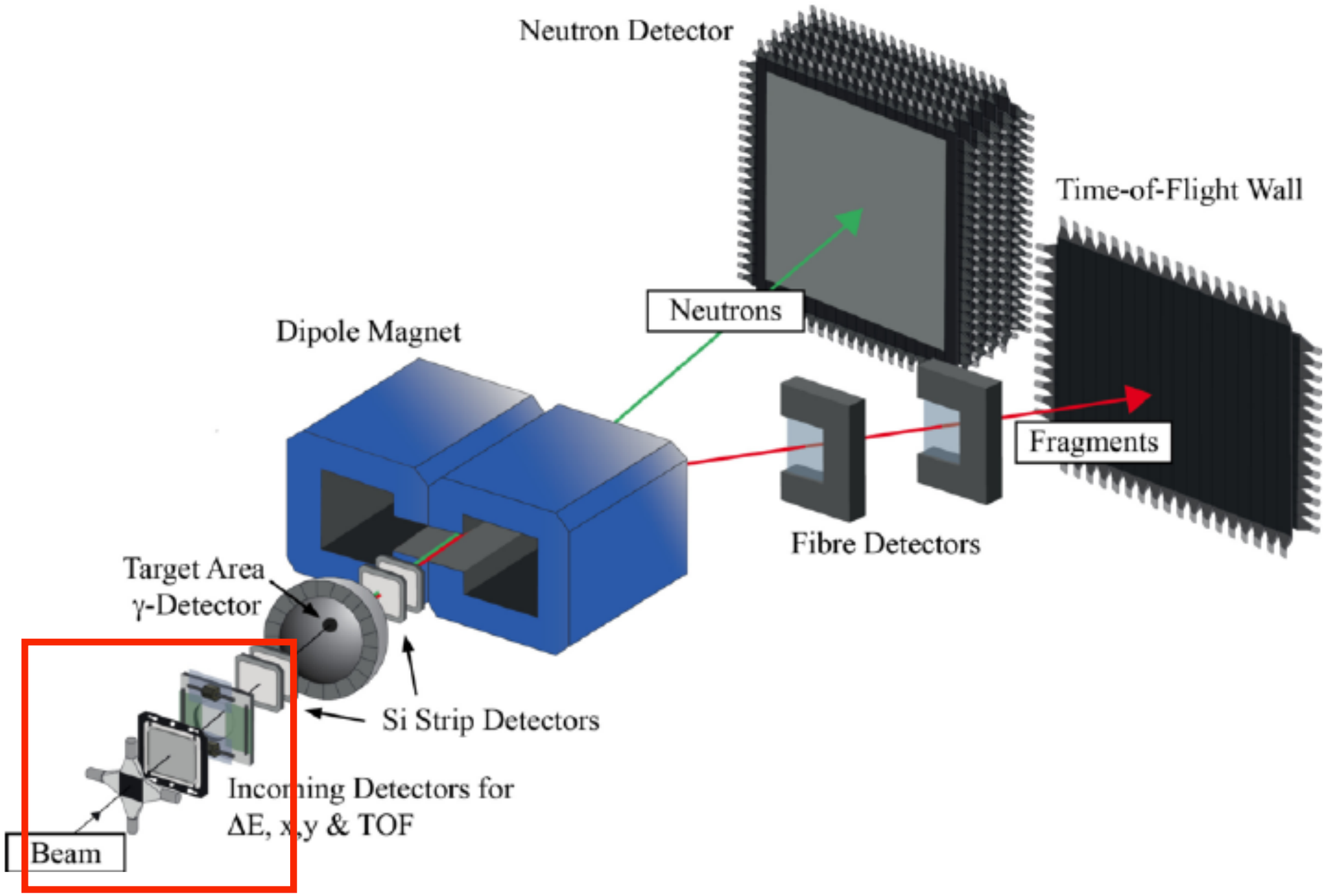
- Primary beam: **^{40}Ar** (600 MeV/u)

- Primary target: Be: 4 g/cm^2

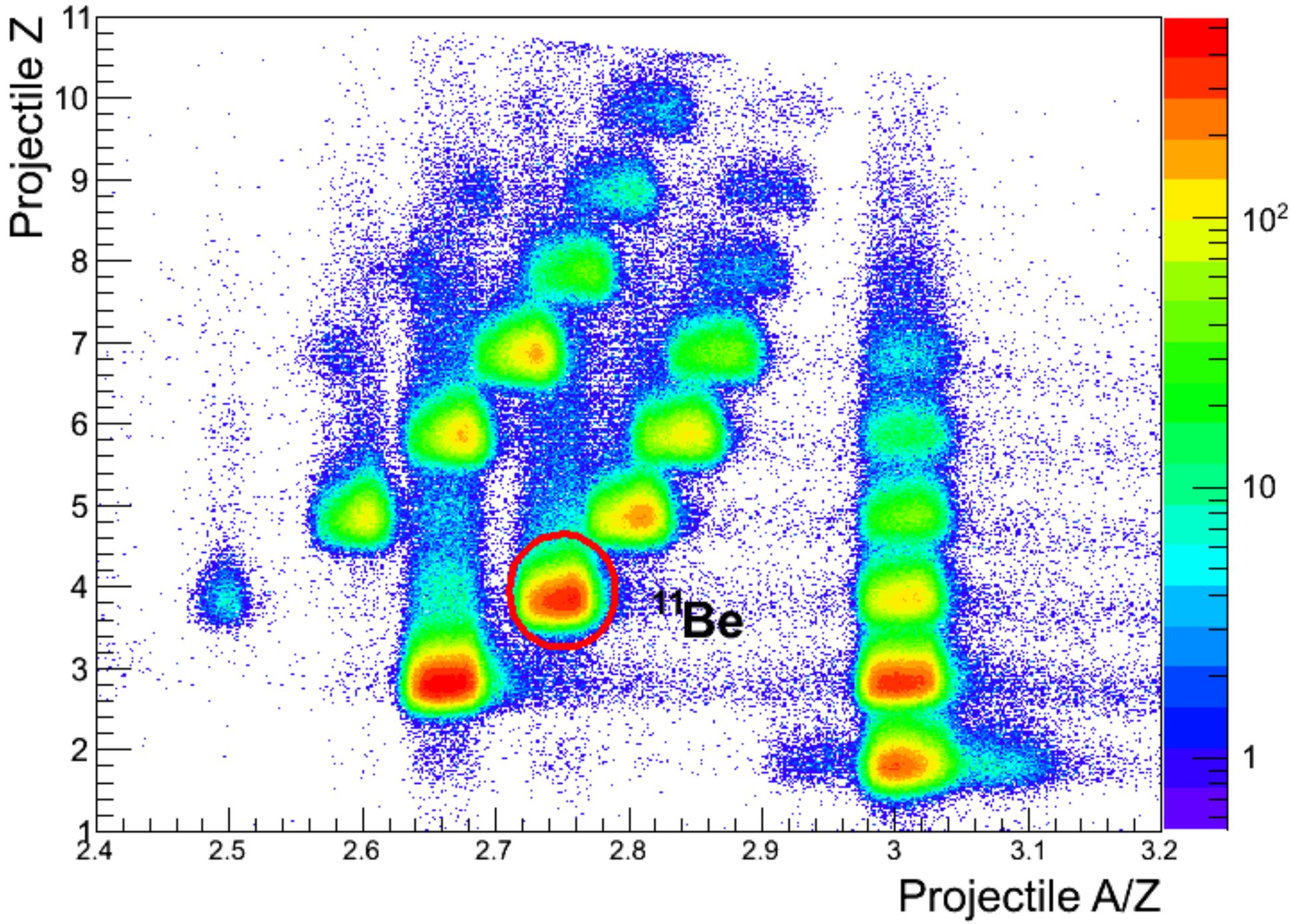
- Secondary **cocktail beam** @ (500 MeV/u)
  6 different **settings**:
  $4 < Z < 10$
  $1{,}5 < A/Z < 3$

- Several secondary targets for different reactions:
  * Pb target (coulomb excitation)
  * **CH_2**
  * C

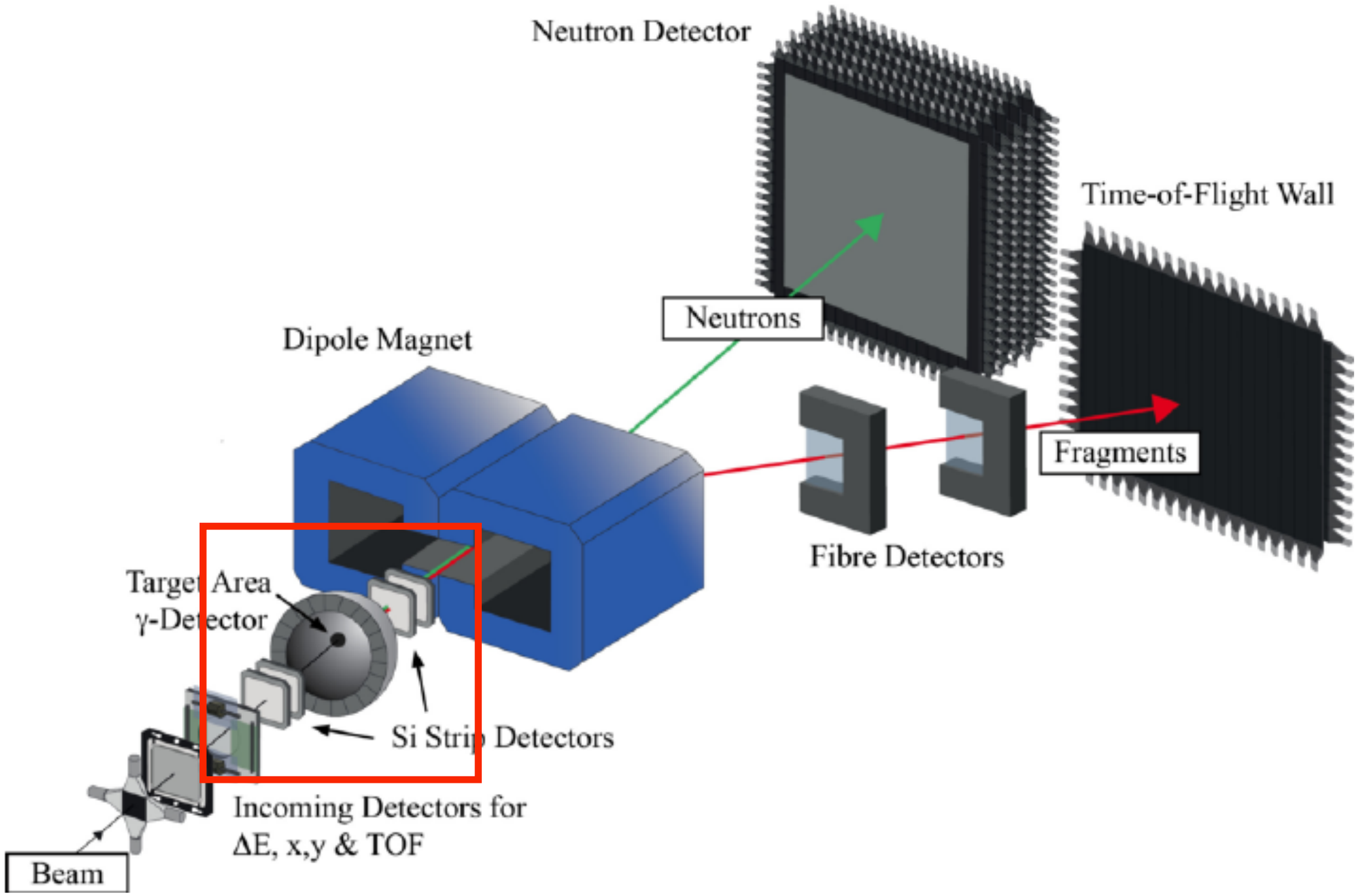
LAND/R³B setup



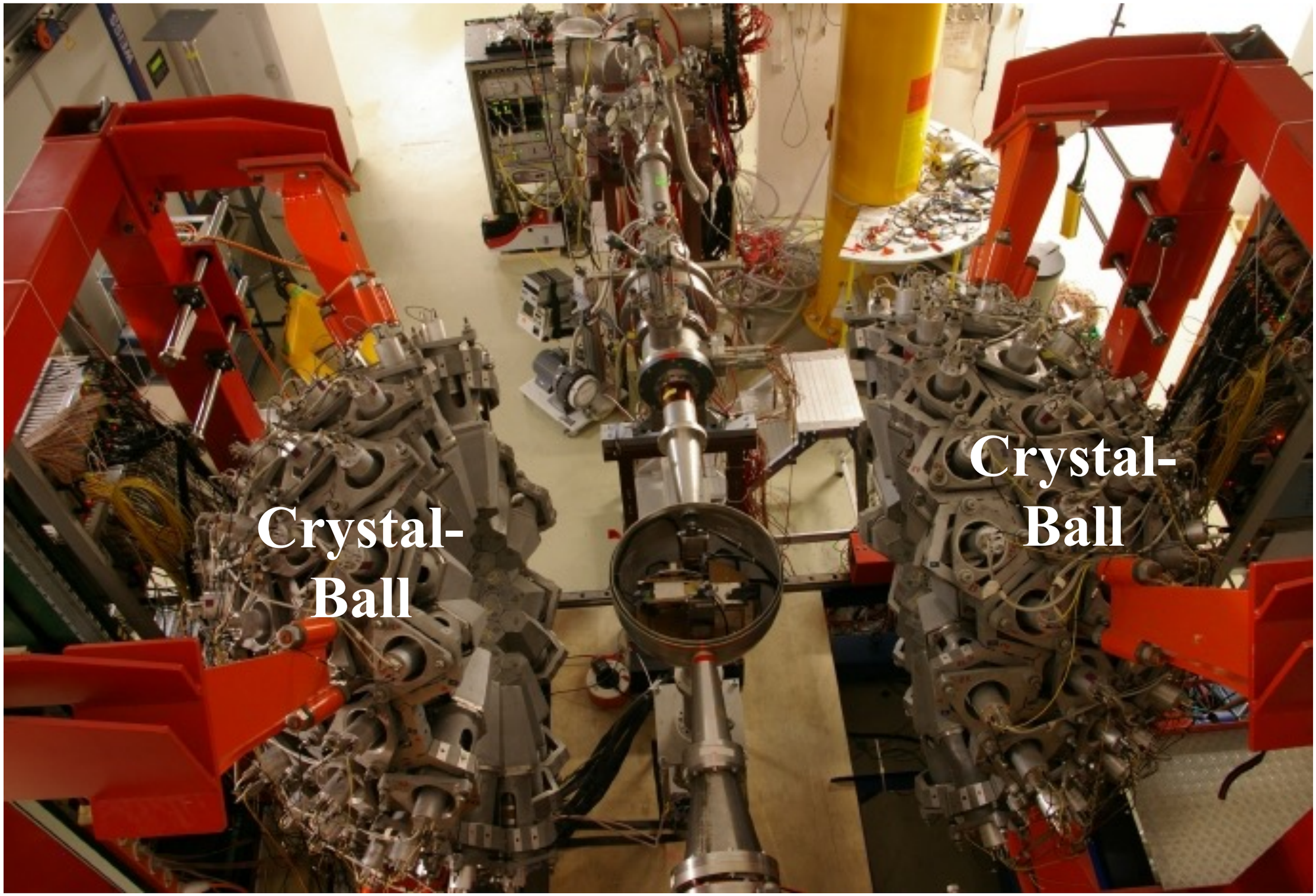
Incoming Beam Identification



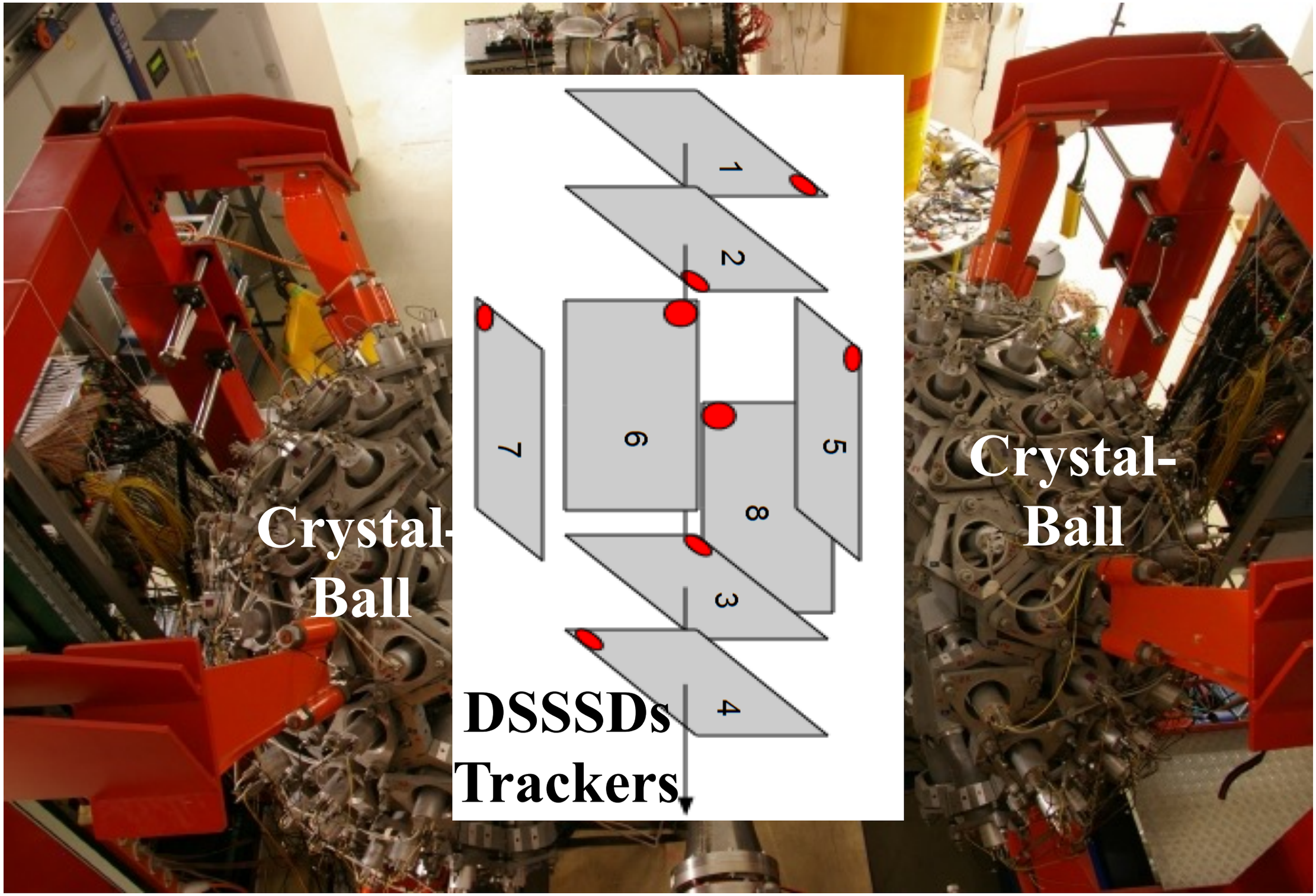
LAND/R³B setup

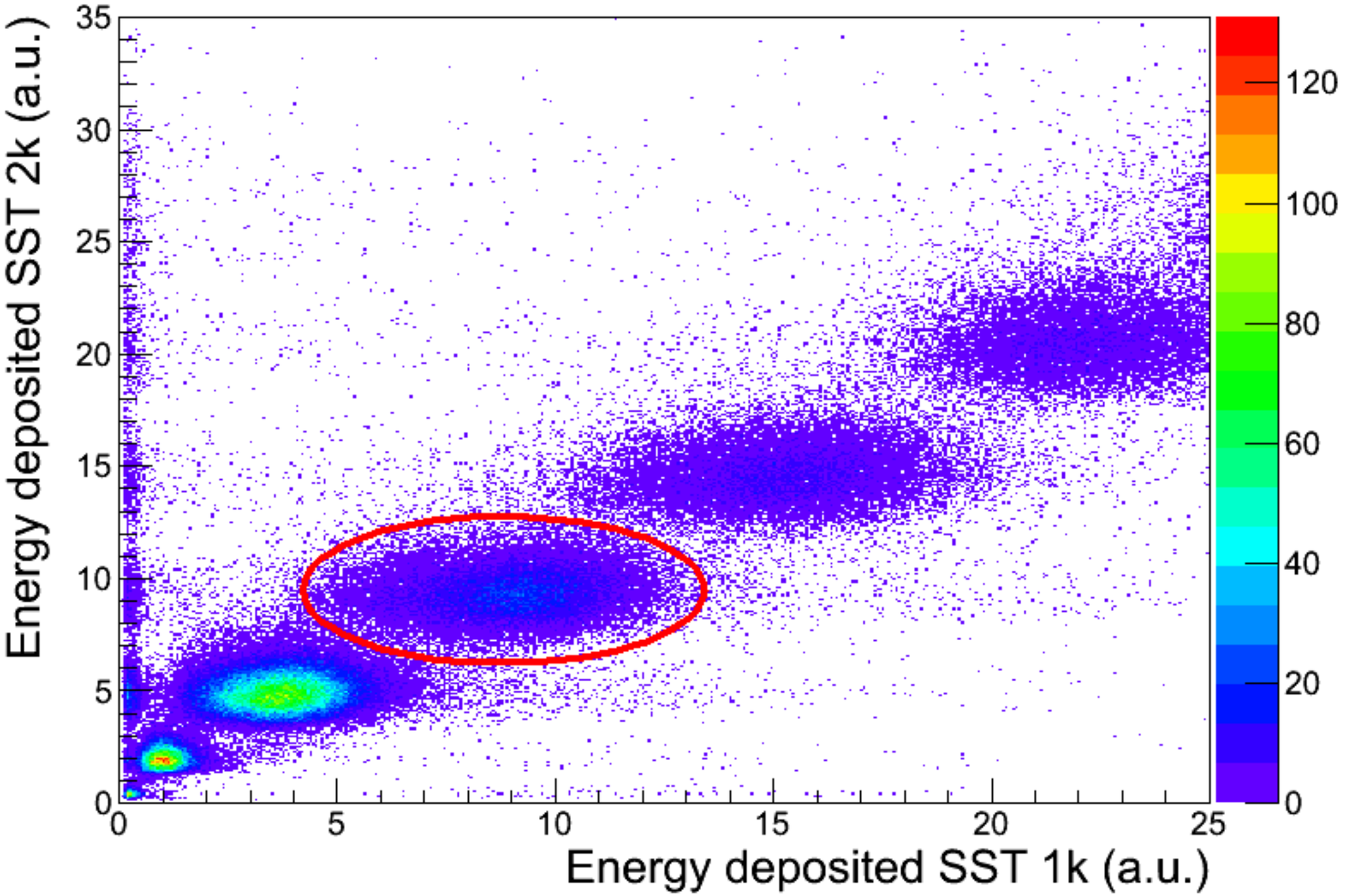


Target detectors

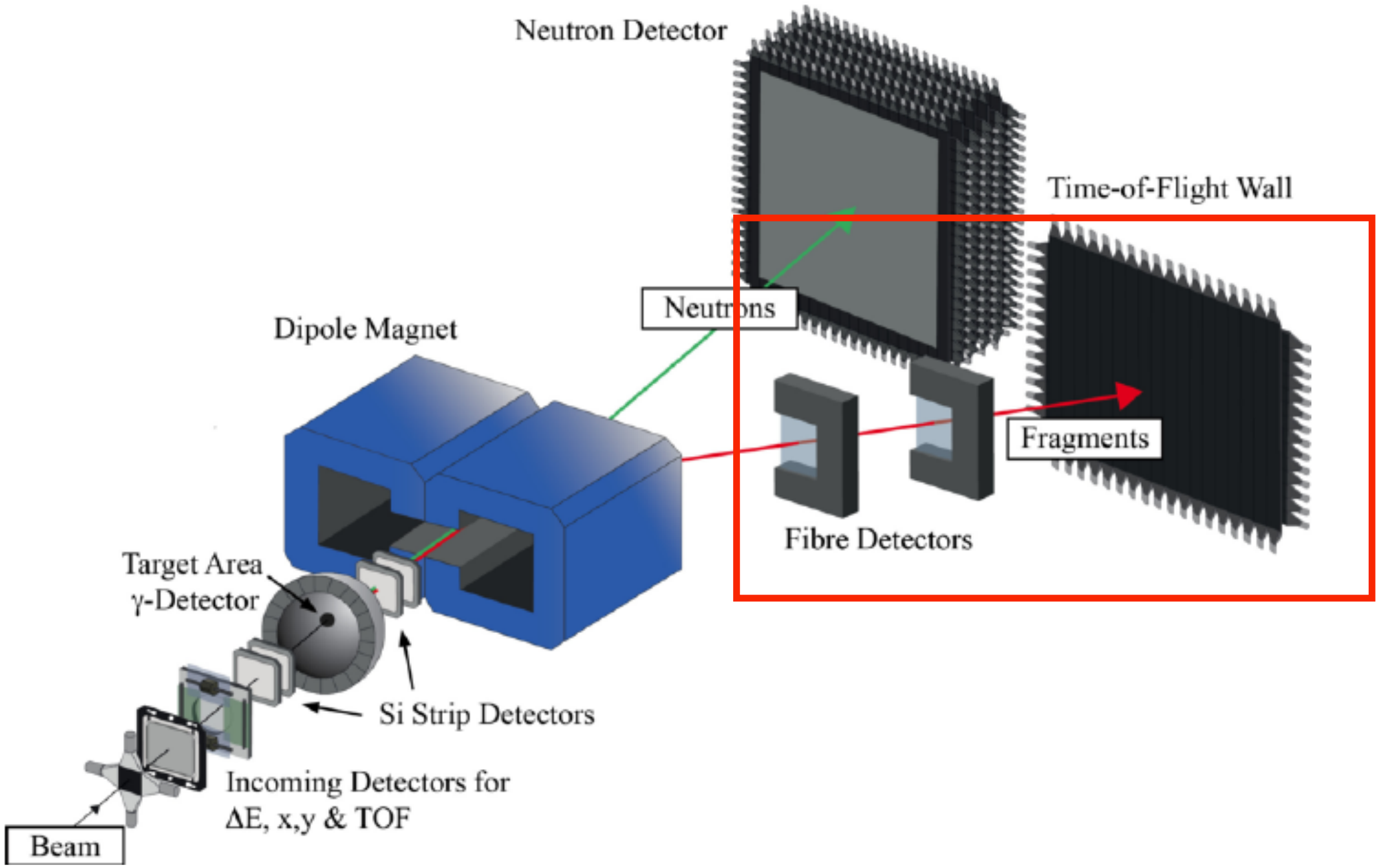


Target detectors

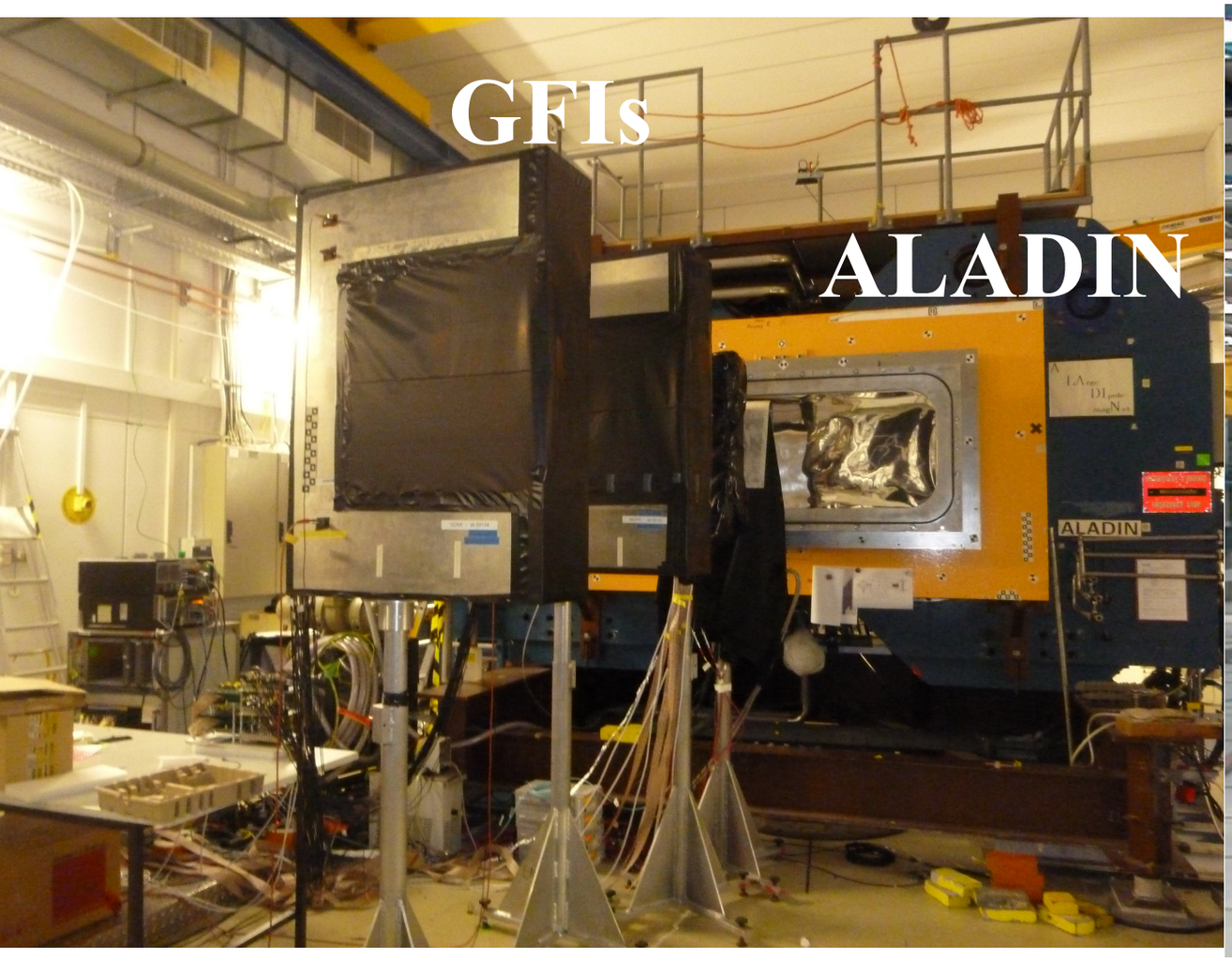



Energy deposited SST 2k (a.u.)
Energy deposited SST 1k (a.u.)
0
5
10
15
20
25
30
35
120
100
80
60
40
20
0

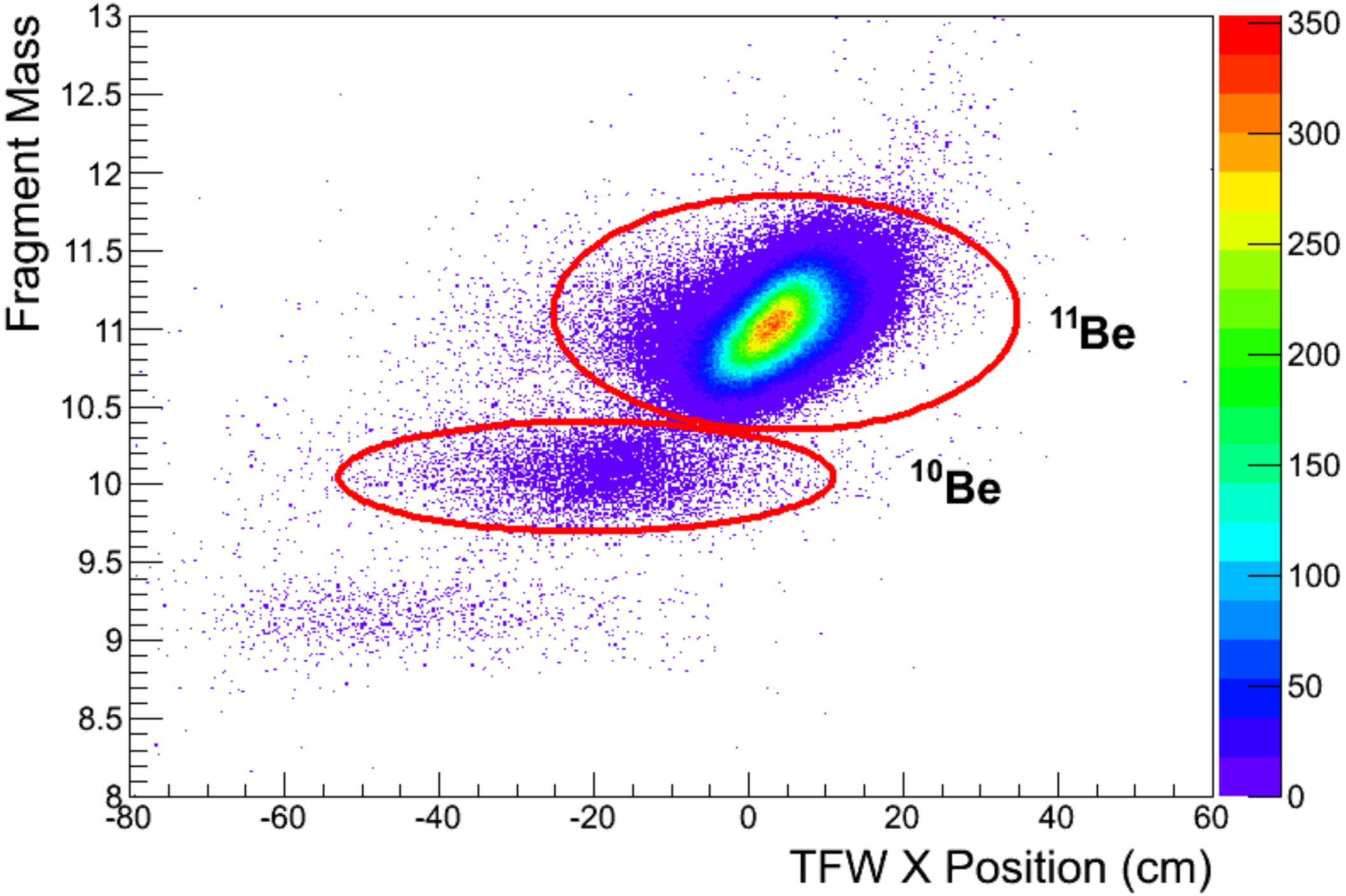
LAND/R³B setup



Heavy Fragment branch

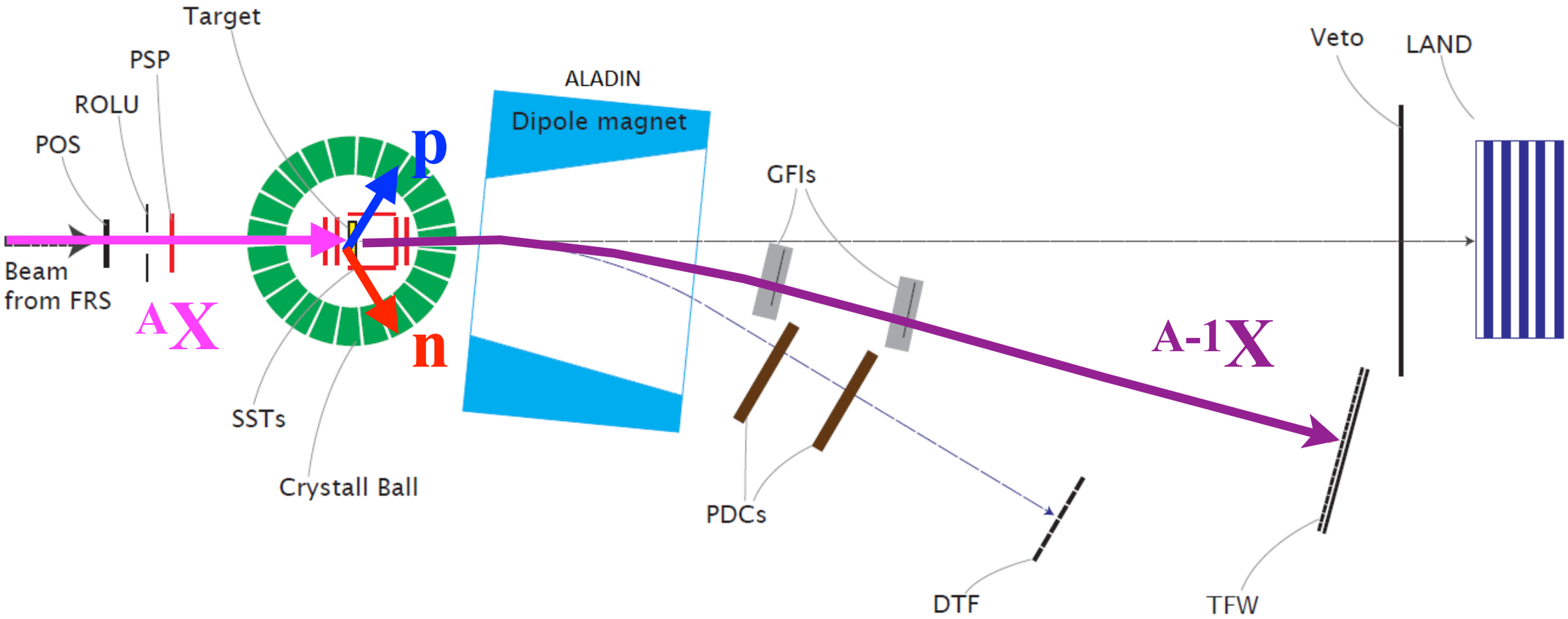


Heavy fragment identification



LAND / R³B Setup

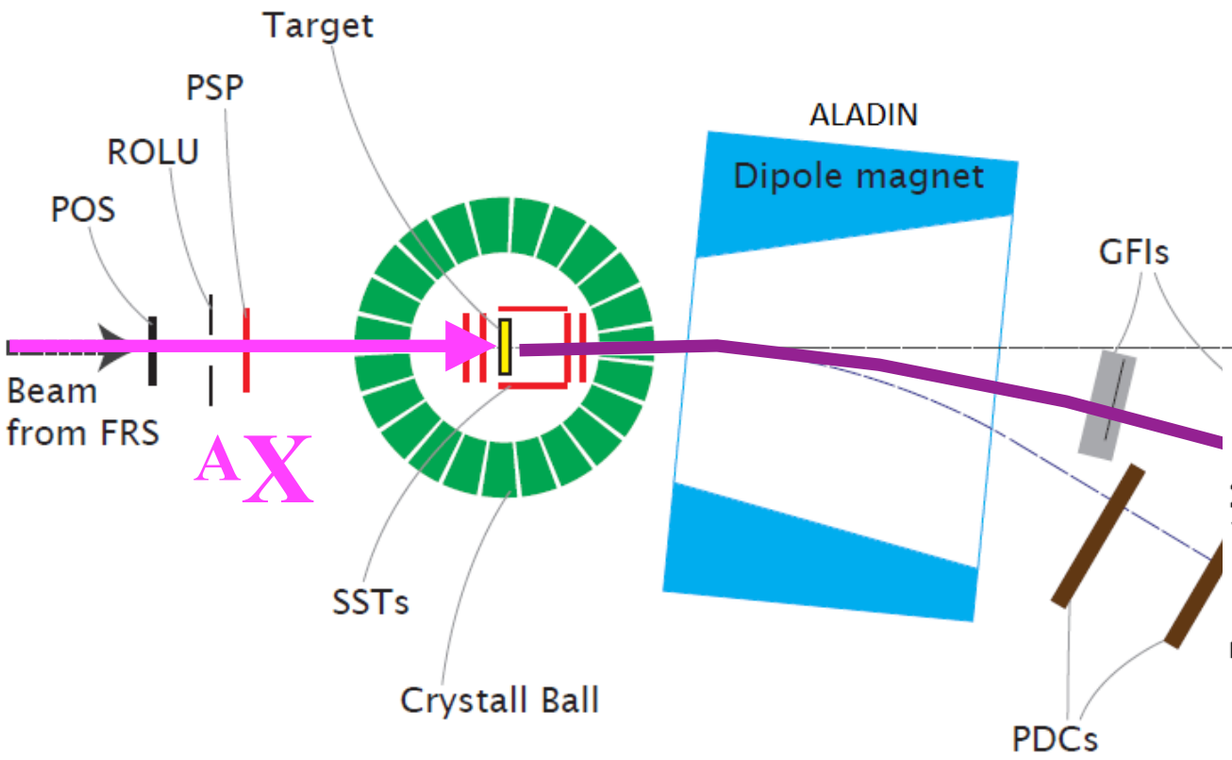
Reaction: $^{A}X(p,pn)^{A-1}X$

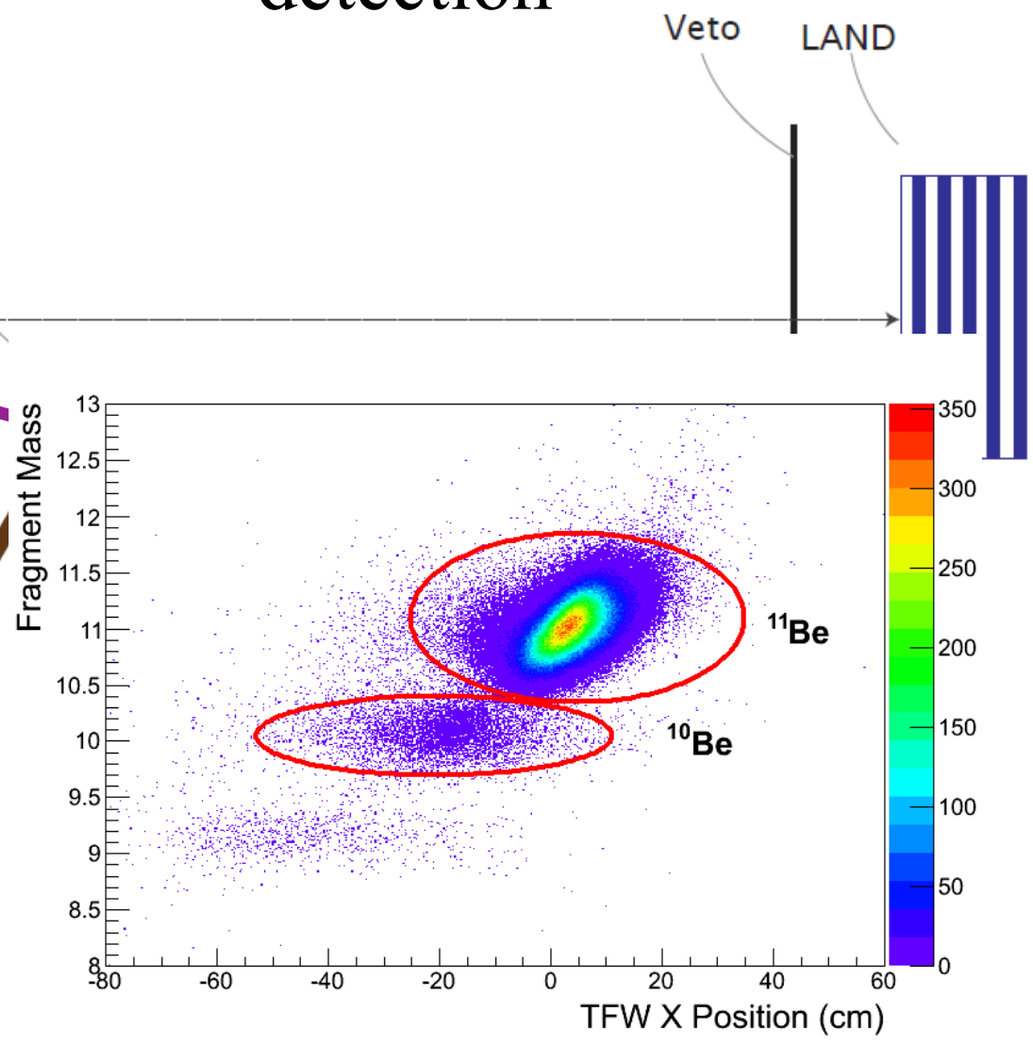


LAND / R³B Setup

Particle Inclusive knock-out reaction

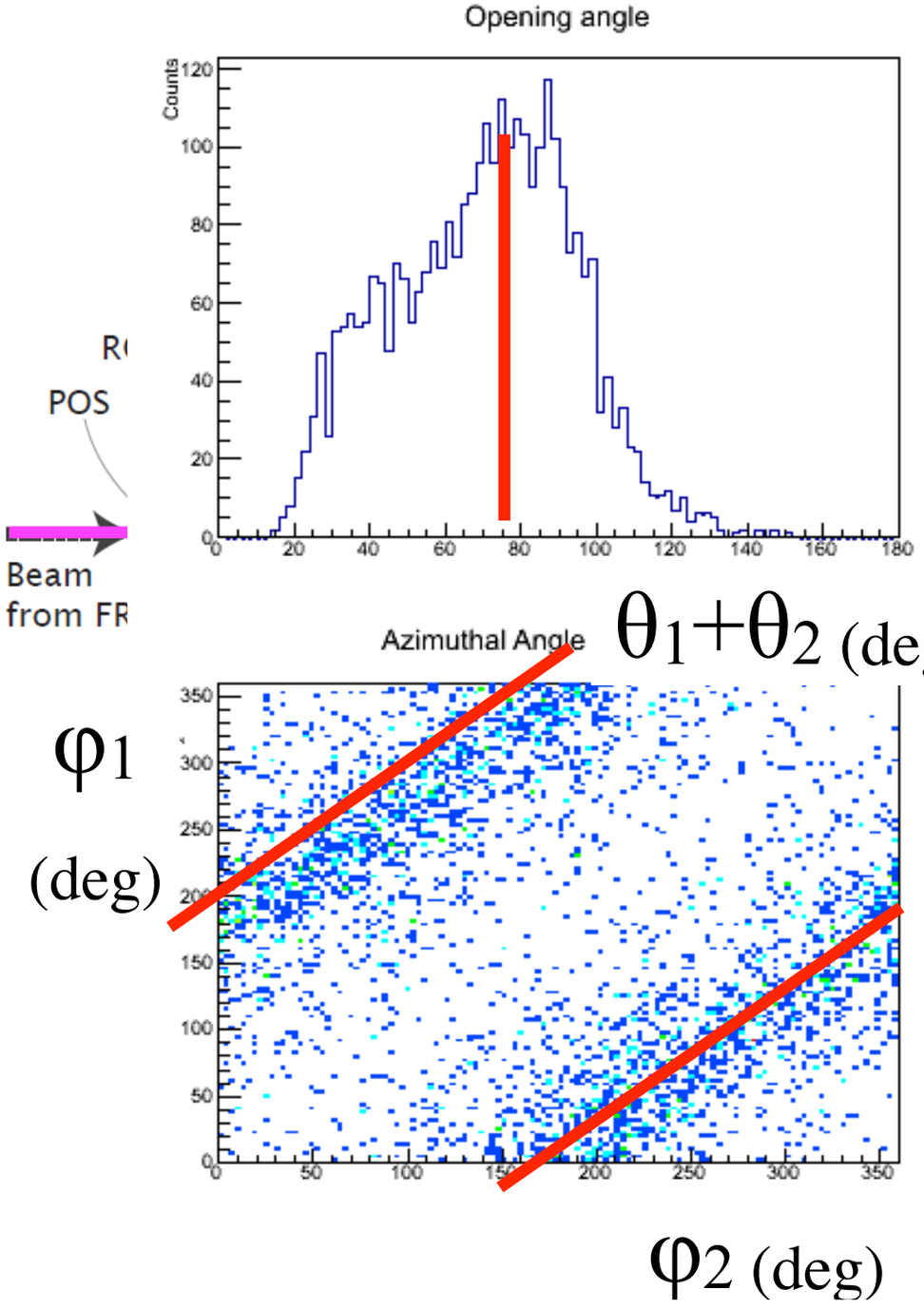
Only **heavy fragment** detection



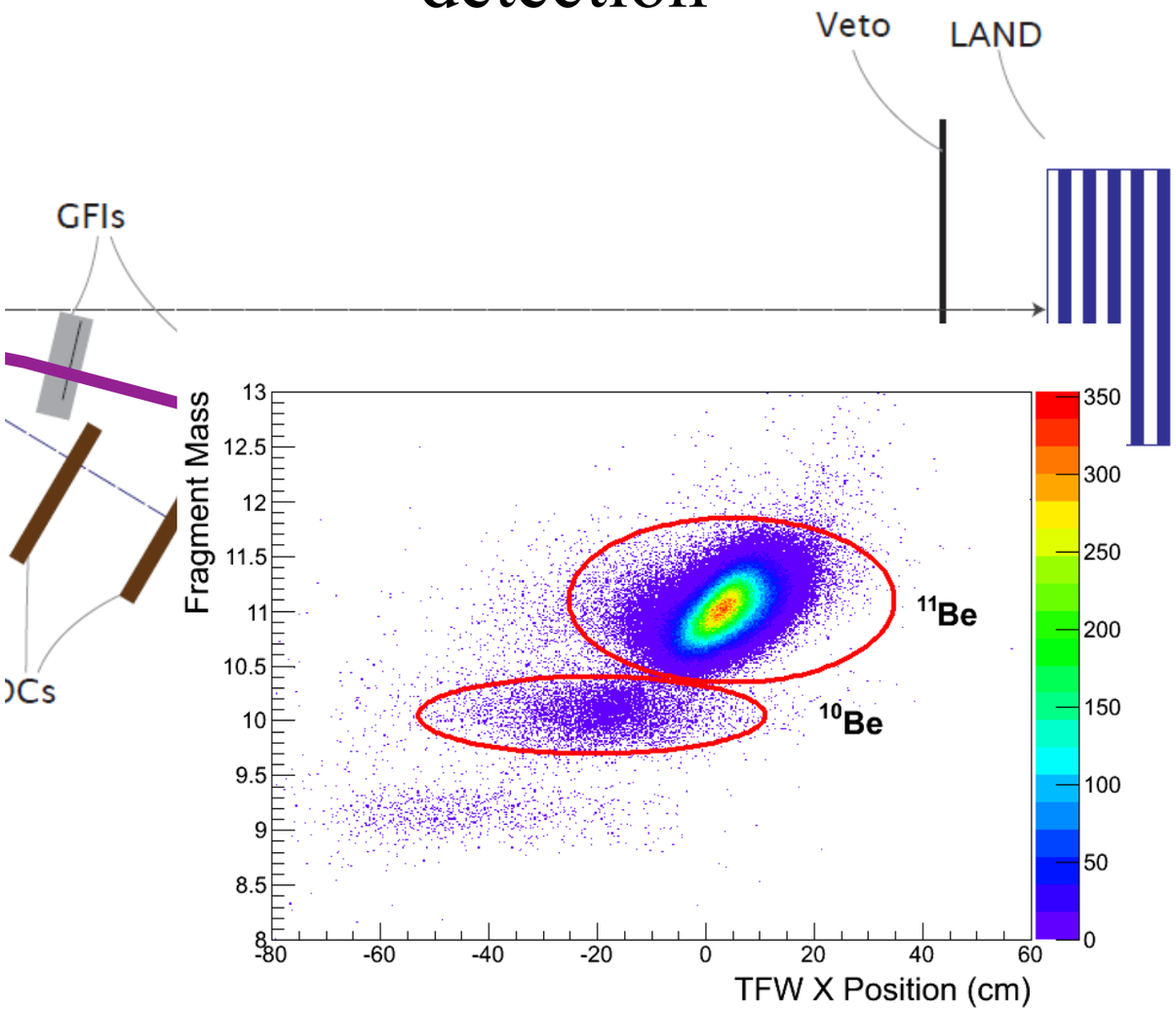


LAND / R³B Setup

Particle Exclusive knock-out reaction



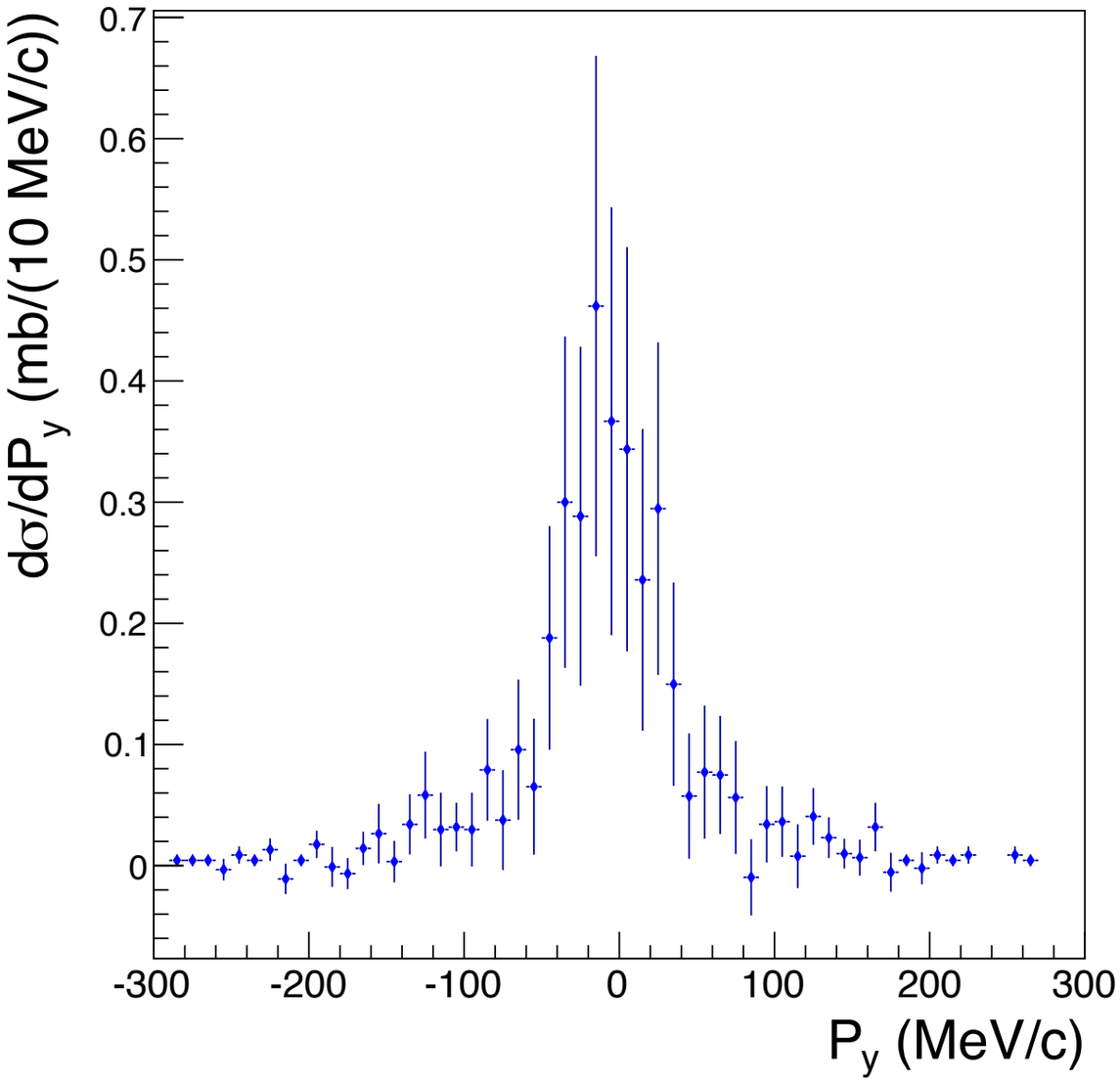
Heavy fragment + **p** + **n**
detection



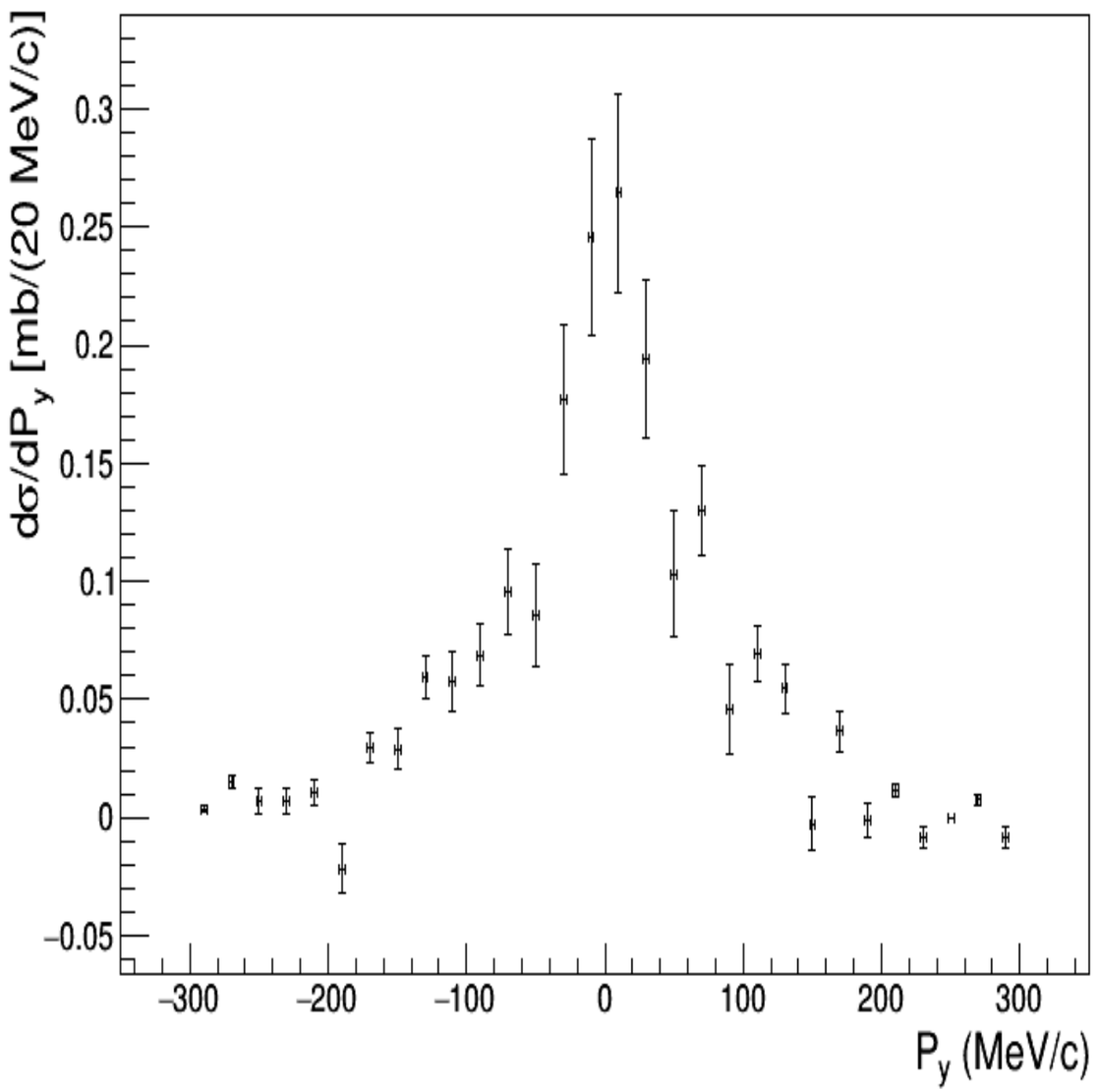
Momentum distributions

Particle Exclusive knock-out reaction

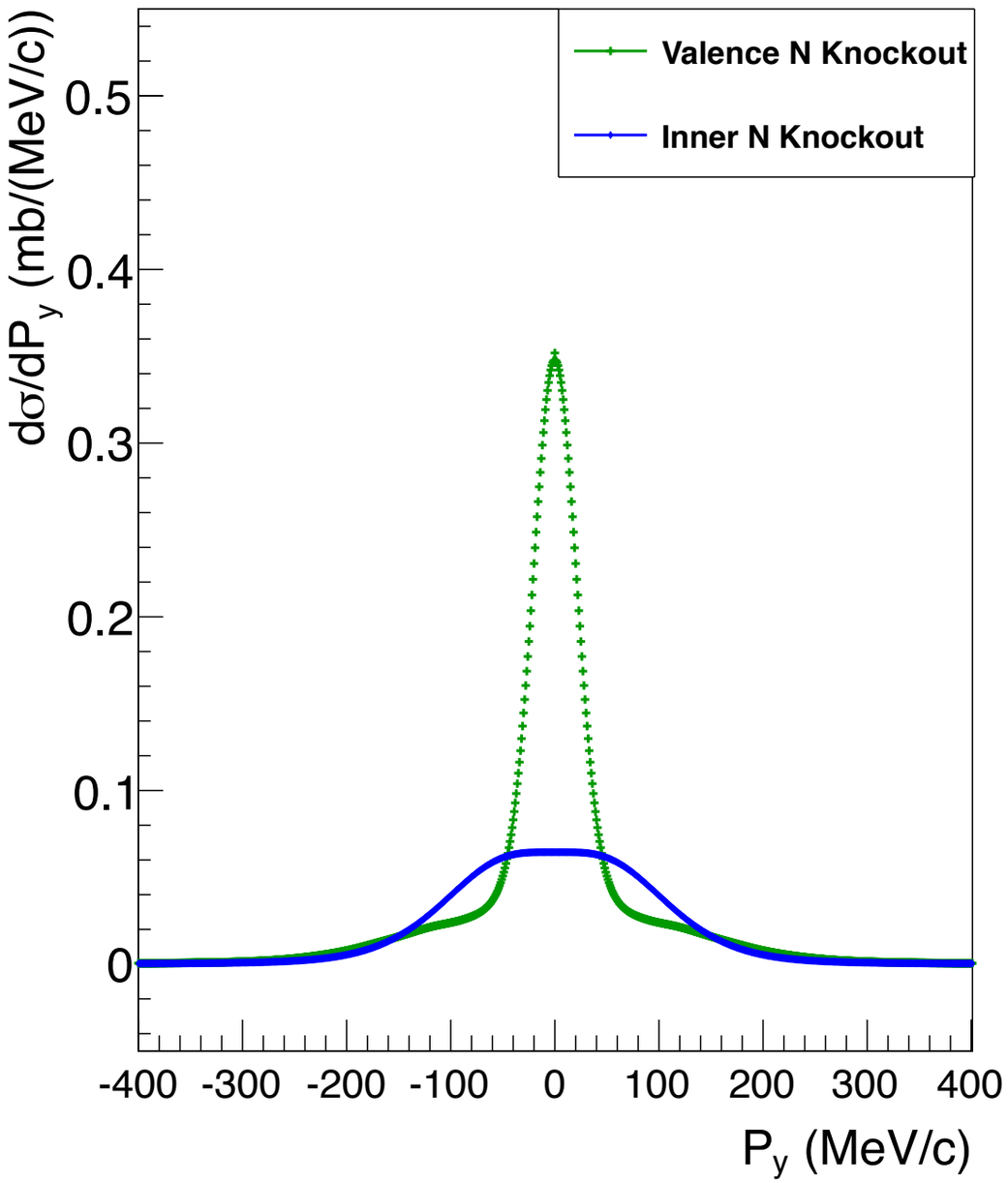
^{11}Be



^{15}C



Momentum distributions



Faddeev/AGS calculations for single particle **valence** and **inner core** neutrons

Allows the evaluation of different knock-out contributions

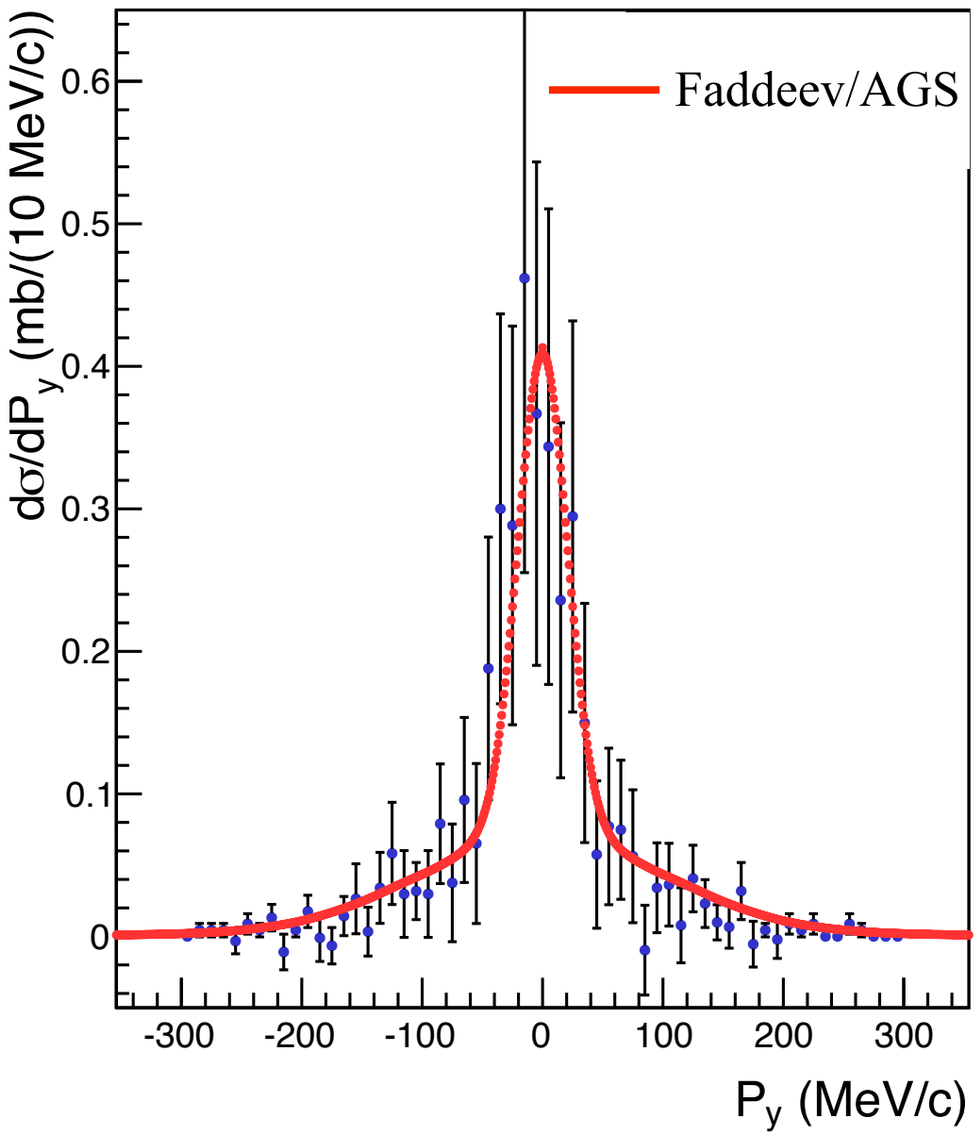
$$\sigma_{total} = a\ \sigma_{valence} + b\ \sigma_{inner}$$

The different **weights** are obtained via minimization of the reduced χ^2 function.

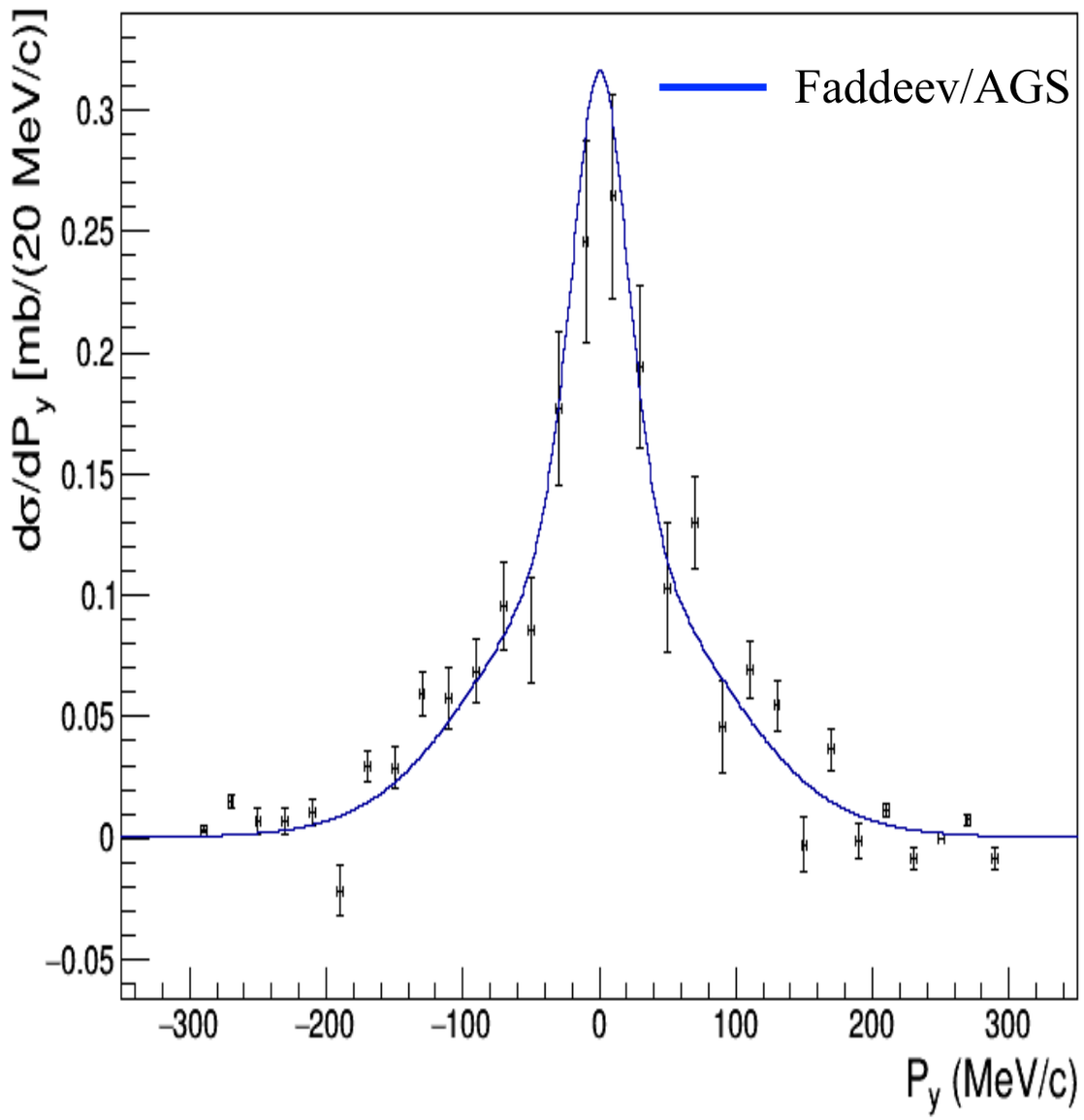
Momentum distributions

Particle Exclusive knock-out reaction

^{11}Be



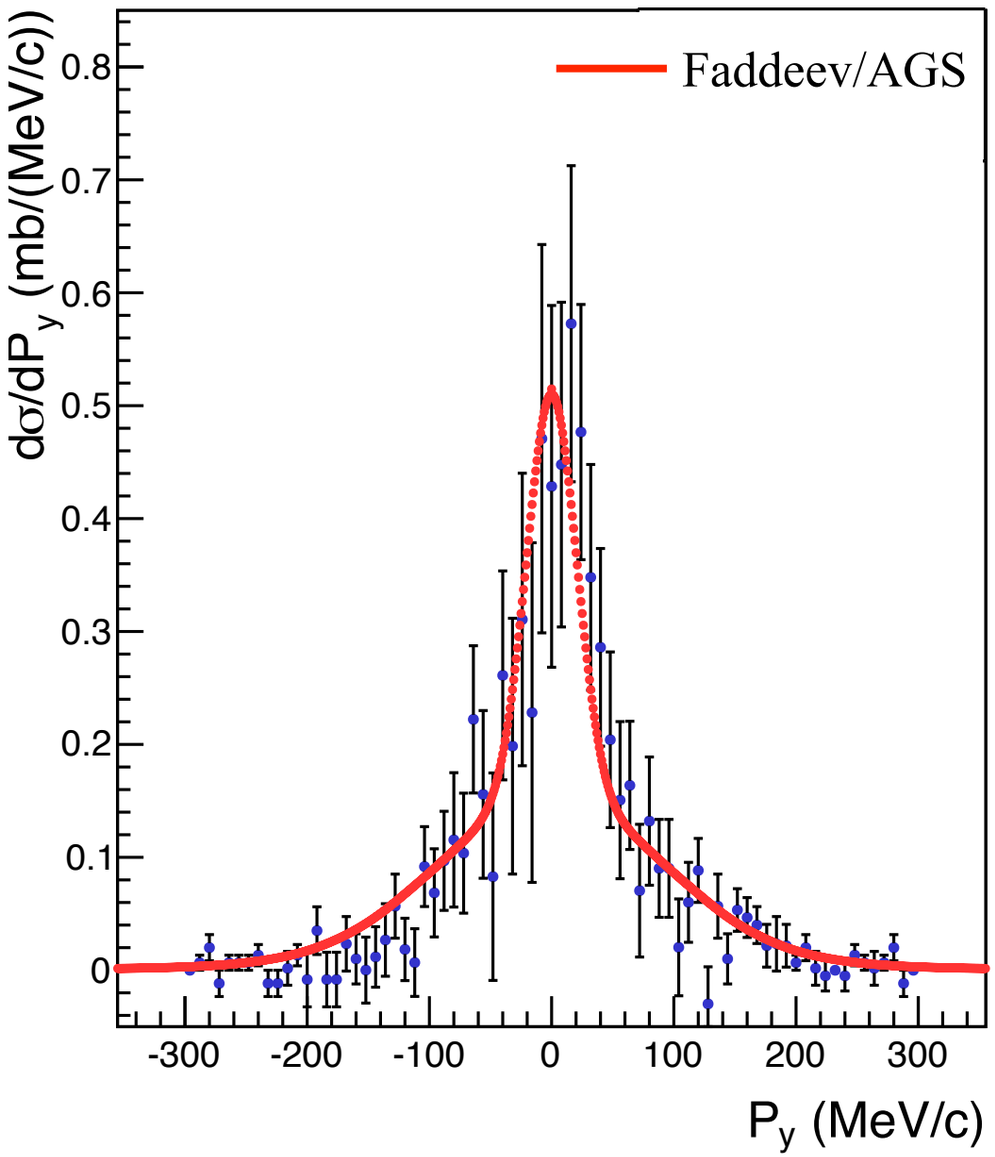
^{15}C



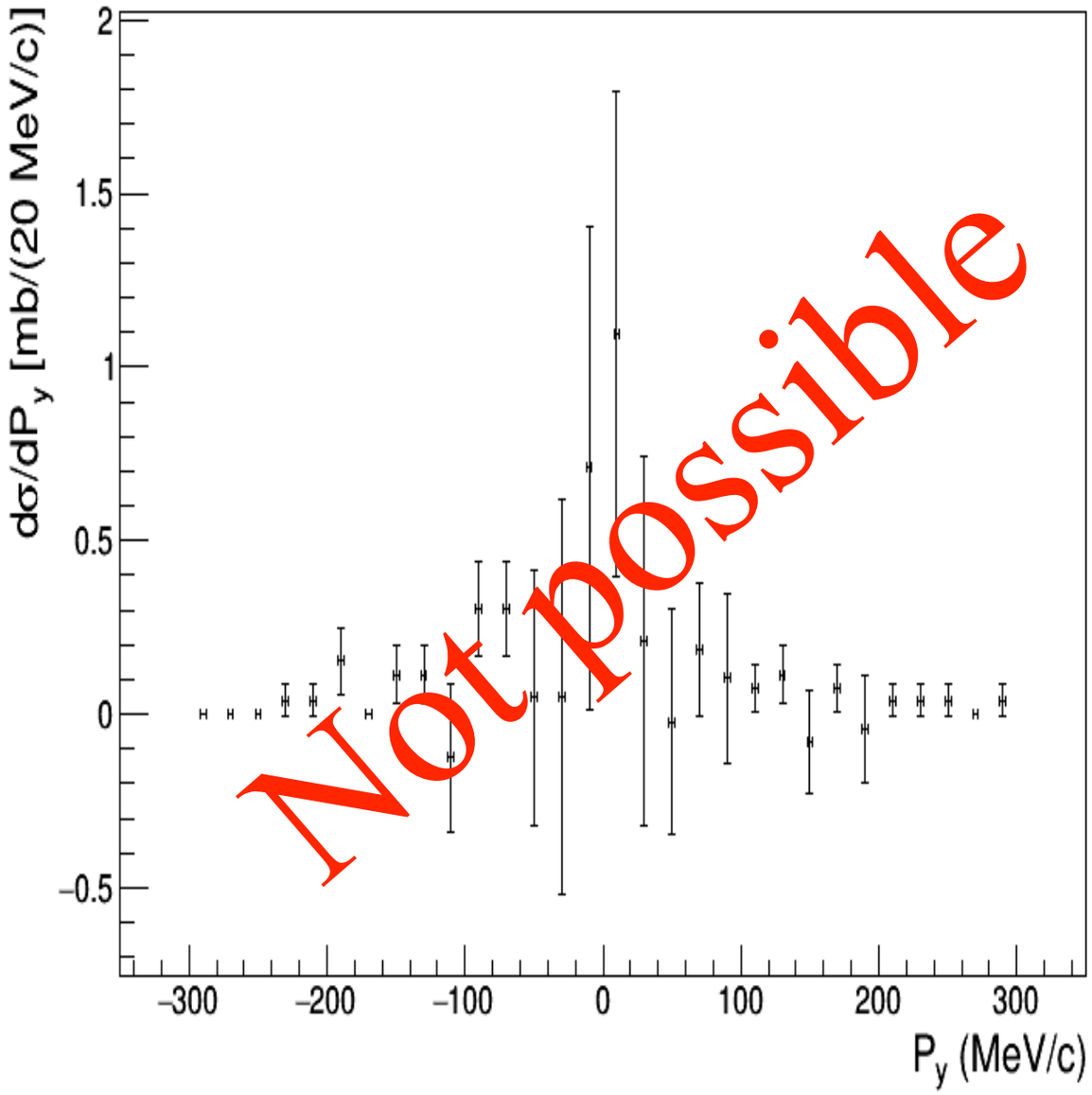
Momentum distributions

Particle Inclusive knock-out reaction

^{11}Be



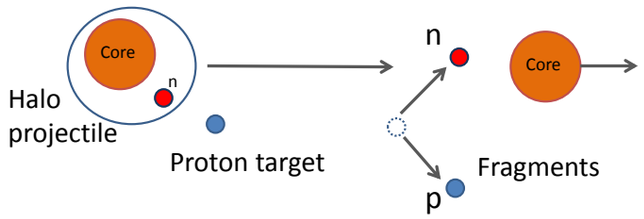
^{15}C



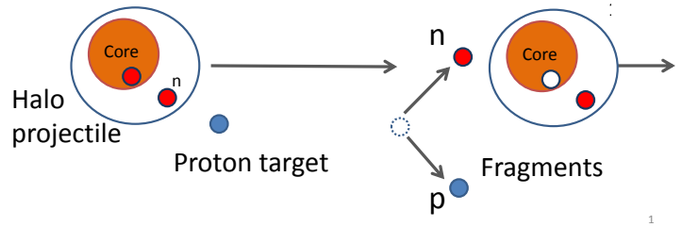
Knock-out cross sections

	Particle Inclusive		Particle Exclusive	
	^{11}Be	^{15}C	^{11}Be	^{15}C
Total Exp	52 ± 5 mb	72 ± 19 mb	37 ± 15 mb	35 ± 14 mb
Total Theo	55 mb	70 mb	36 mb	35 mb
a $\sigma_{valence}$	32 mb	—	29 mb	17 mb
b σ_{inner}	23 mb	—	7 mb	18 mb

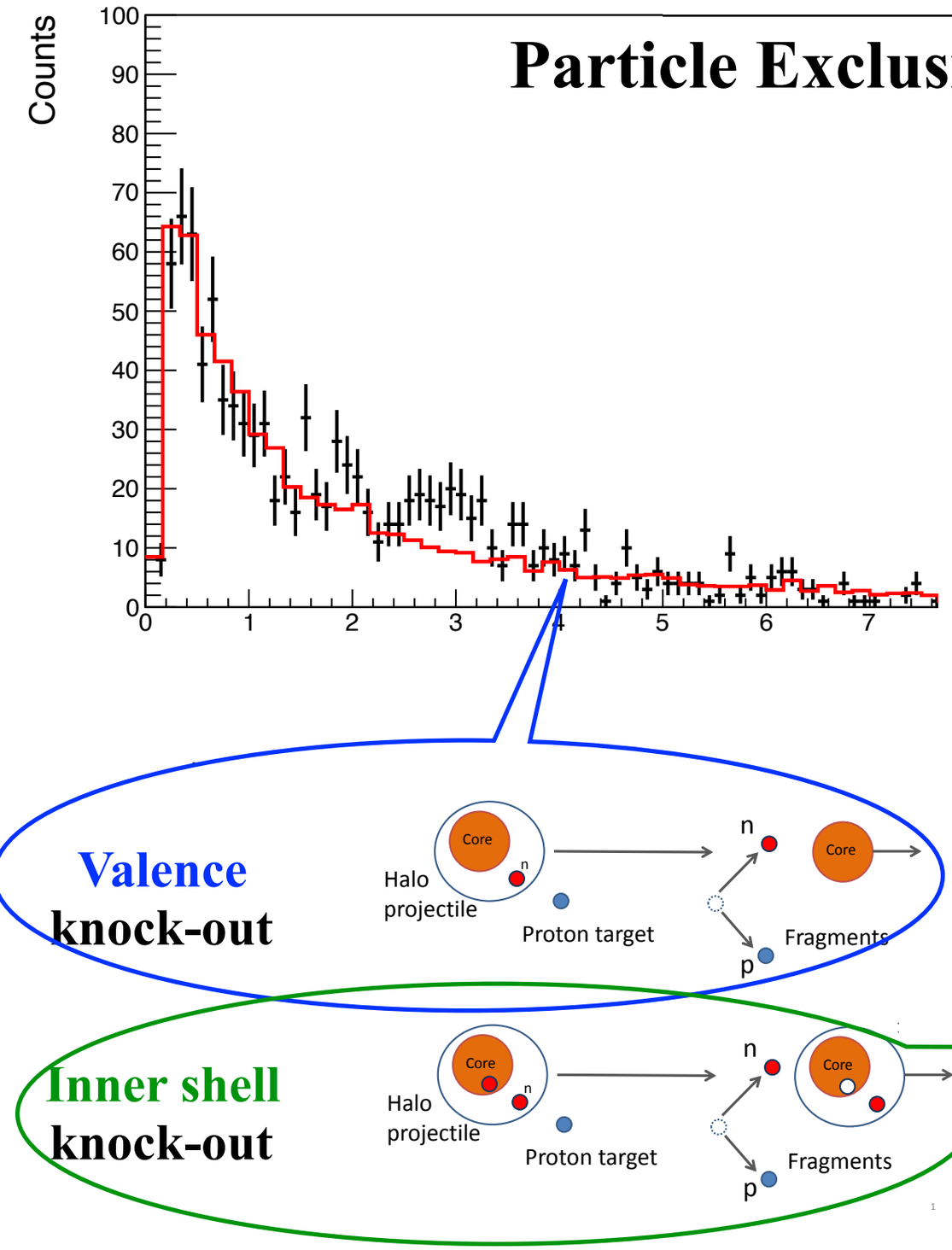
Valence knock-out



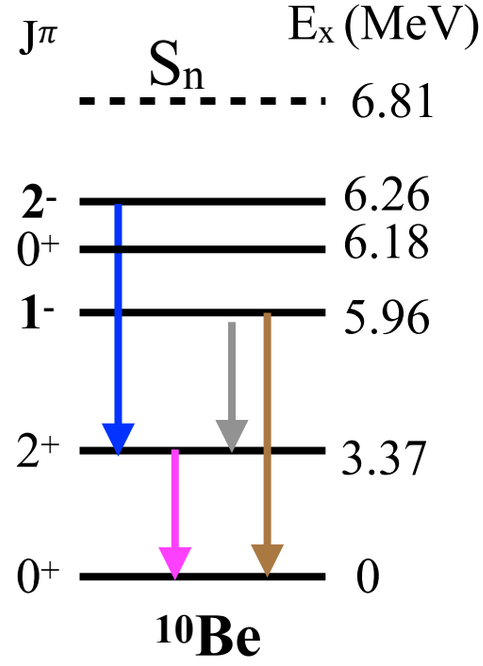
Inner shell knock-out

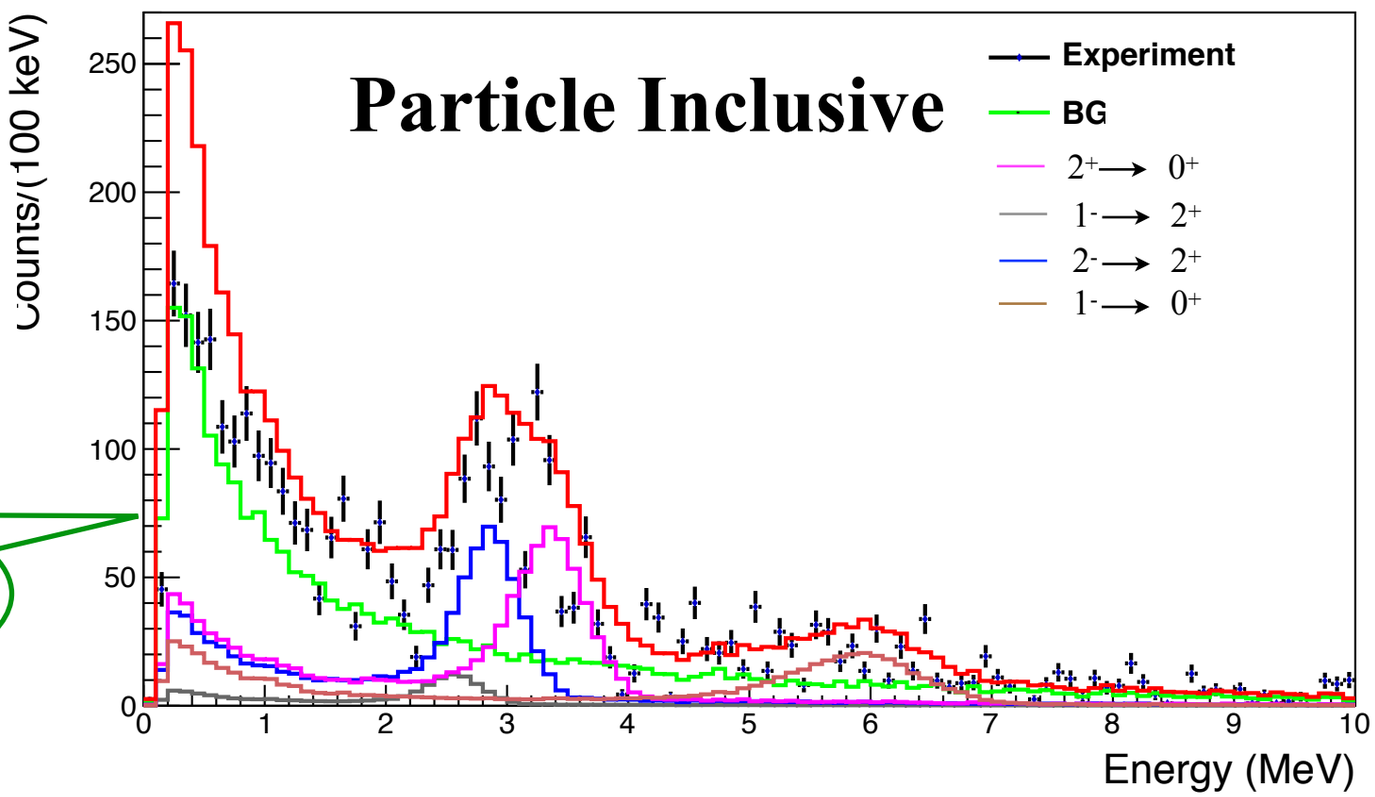


Photon spectrum with X-Ball

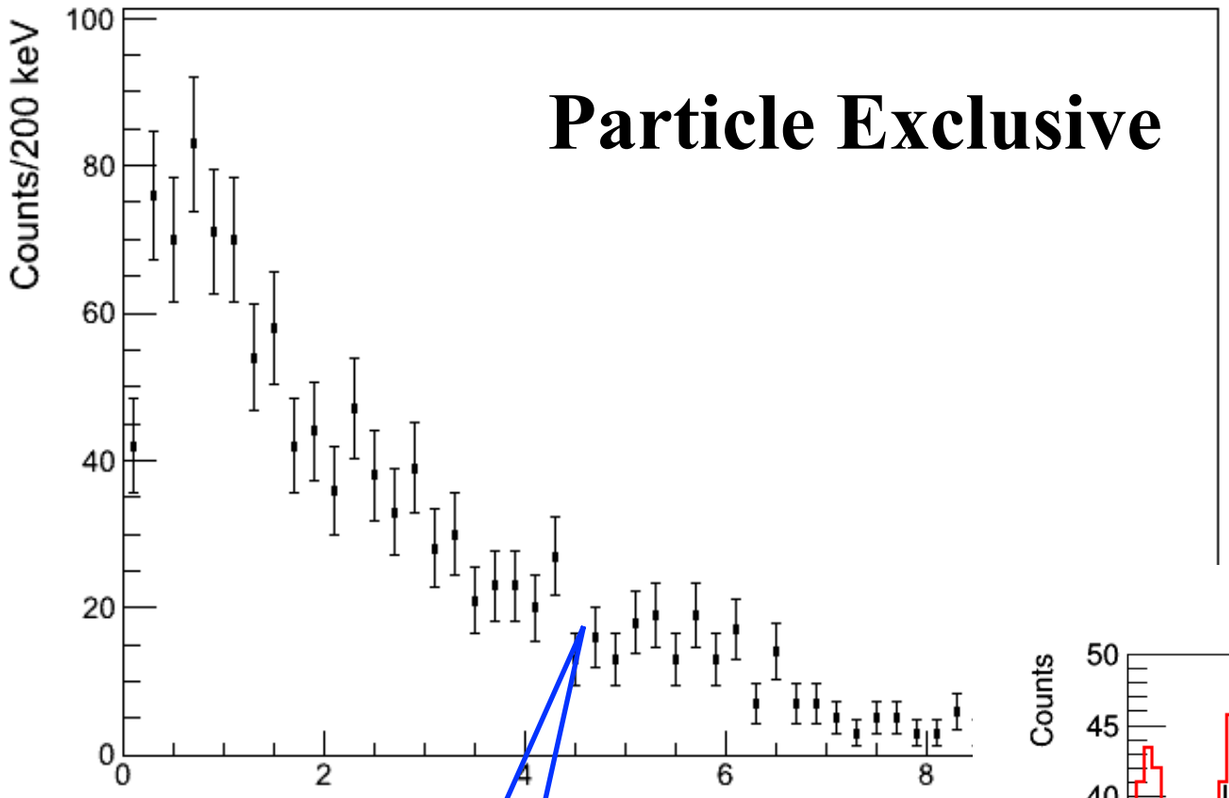


$^{11}Be(p,pn)^{10}Be$

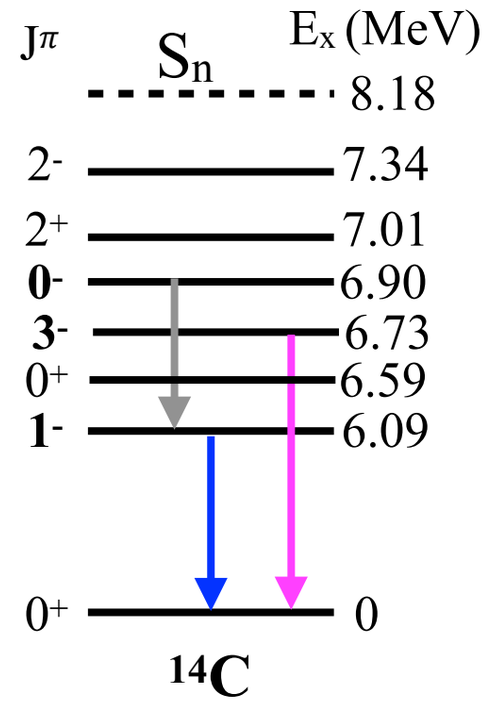




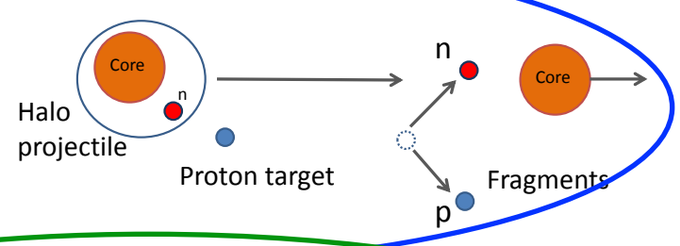
Photon spectrum with X-Ball



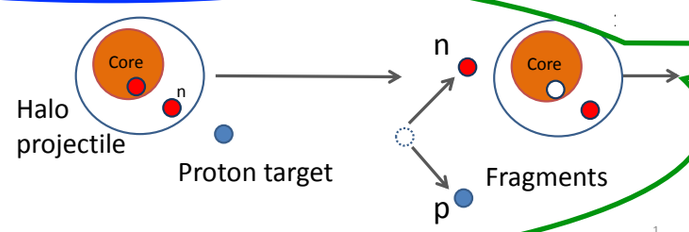
$^{15}C(p,pn)^{14}C$

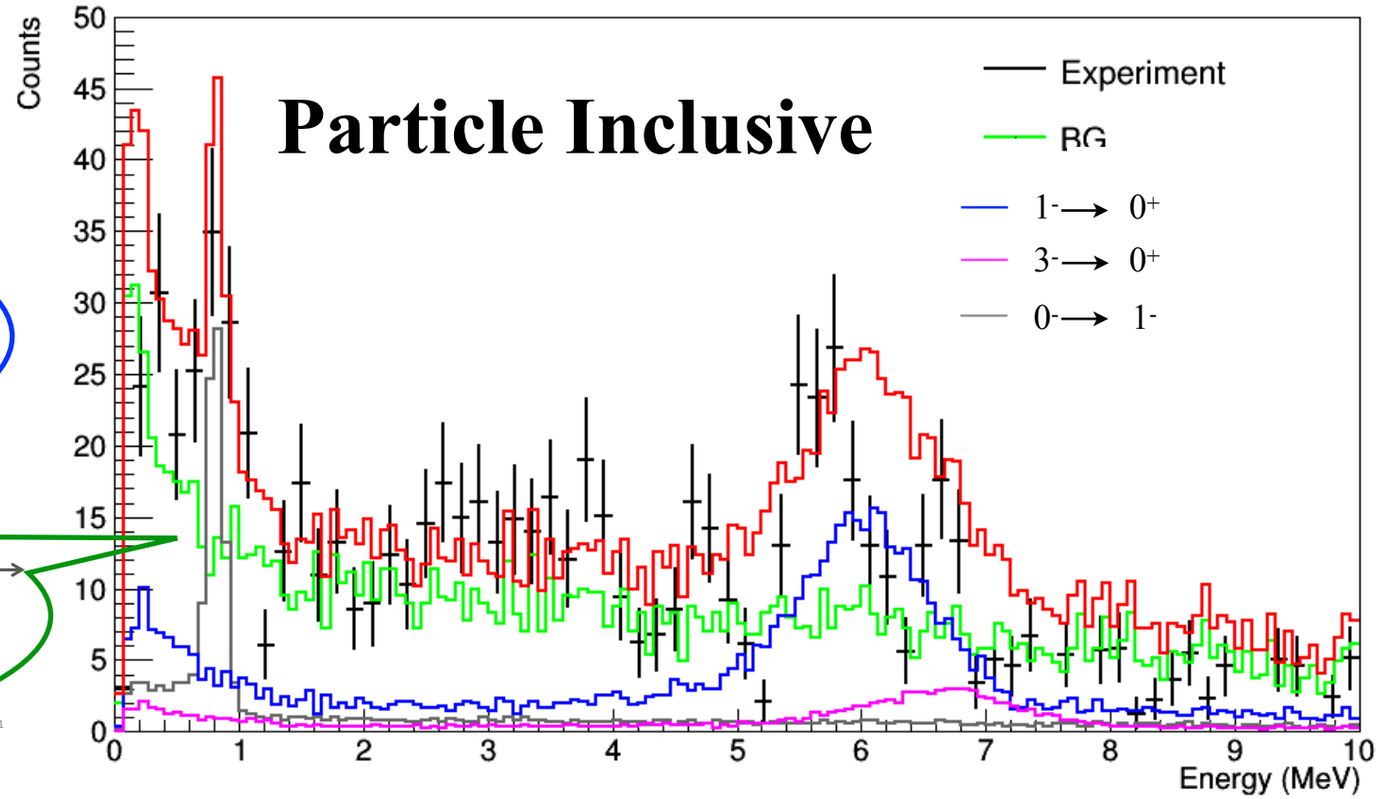


Valence knock-out

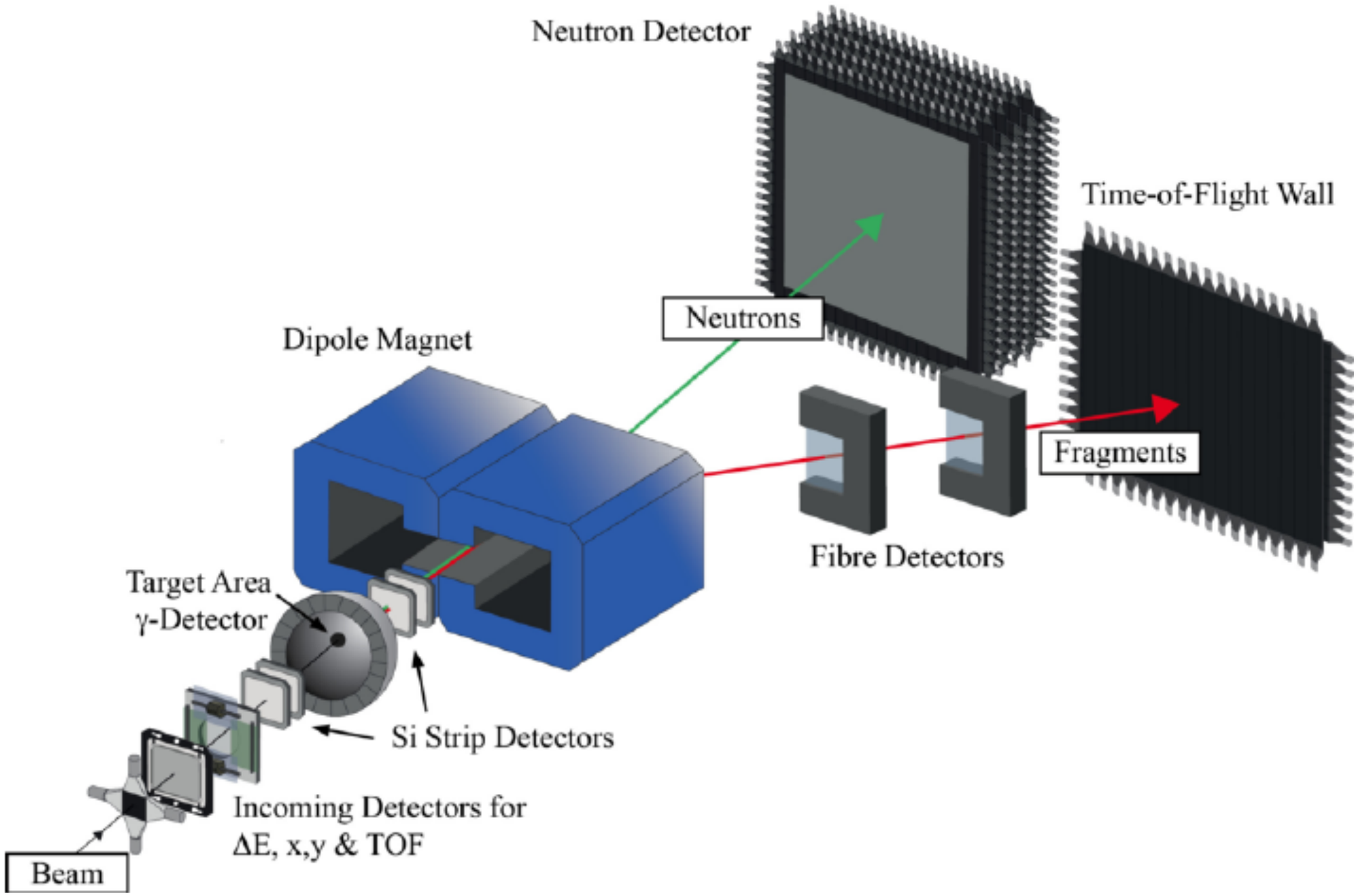


Inner shell knock-out



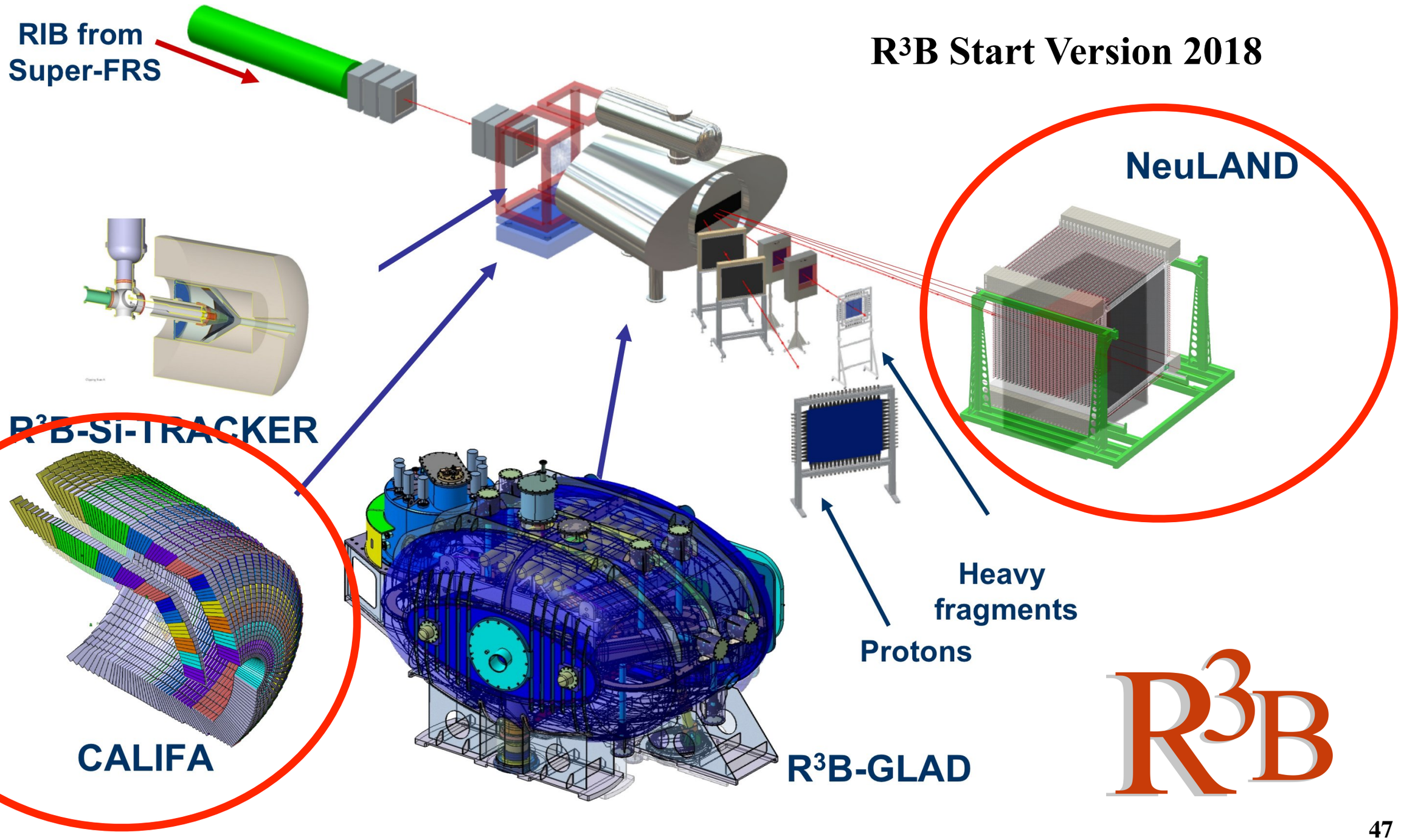


From LAND/R³B …



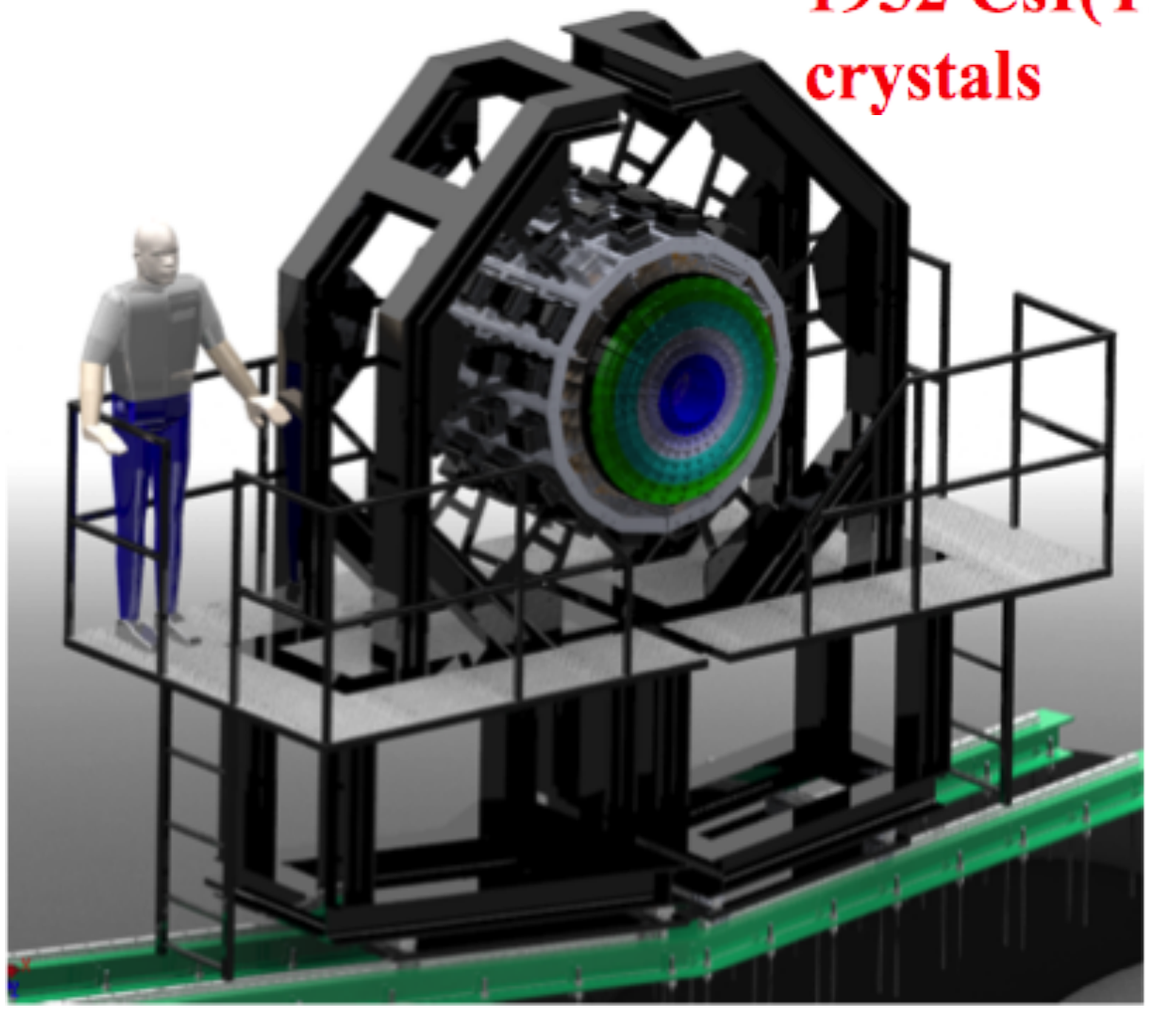
Towards R³B @ FAIR

Reactions with Relativistic Radioactive Beams



CALIFA

CALorimeter for the **I**n-**F**light detection of g**A**mma rays and light charged particles



1952 CsI(Tl) crystals

Extensive energy range

photons: 0 – 20 MeV

protons: 0 – 300 MeV

High energy resolution

1 – 10 %

Working conditions

γ-ray spectrometer

γ-ray calorimeter

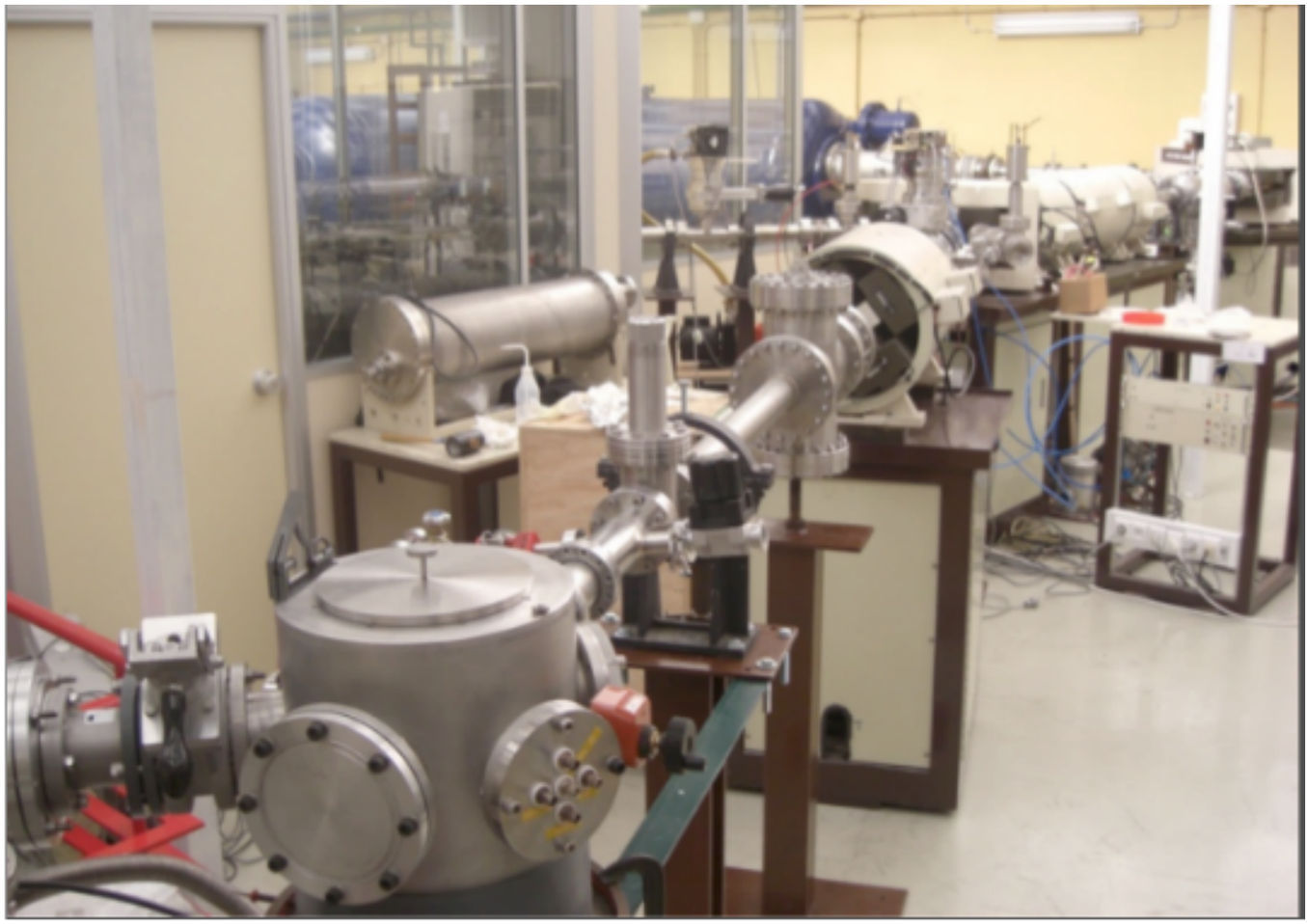
Hybrid detector

CALIFA Benchmark @ Lisbon

PIGE reaction

$^{27}Al(p,\gamma)^{28}Si$

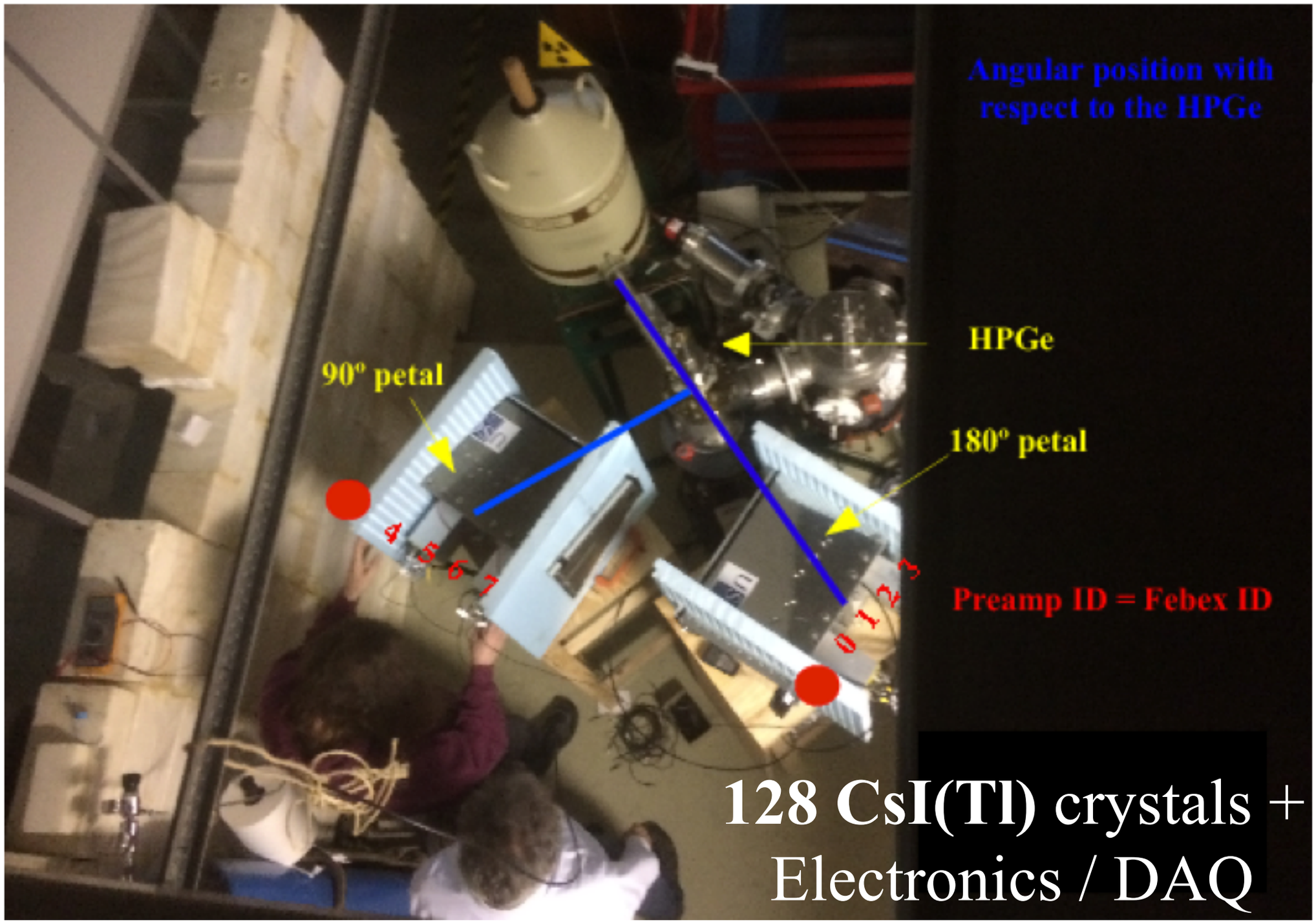
to produce $\gamma > 10$ MeV
to challenge **CALIFA prototype**



Nuclear reaction line @ tandem accelerator at LATR-CTN

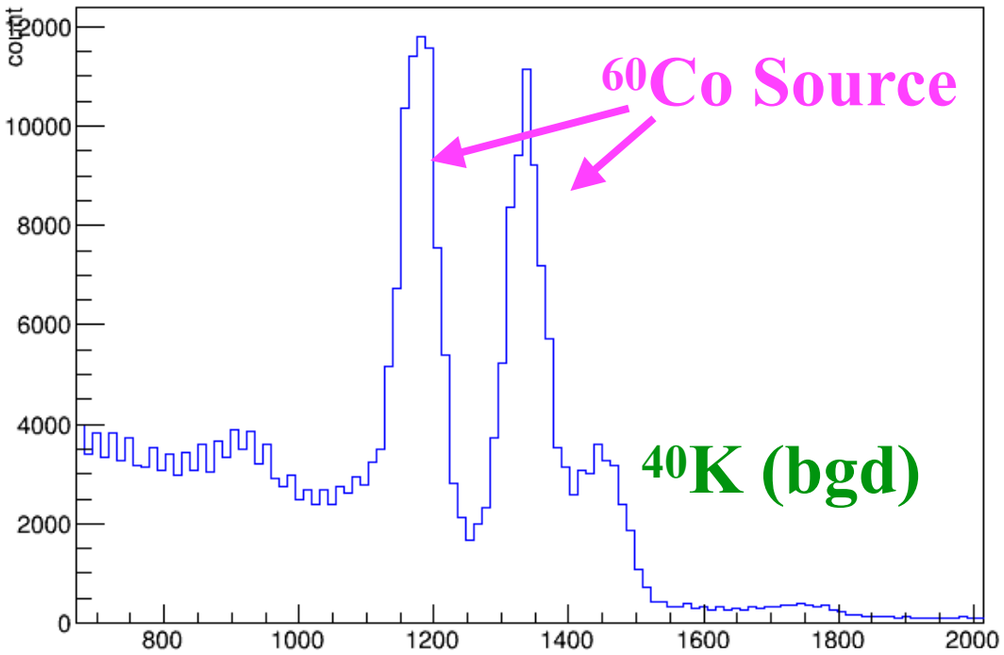
More Information under
http://www.ctn.tecnico.ulisboa.pt

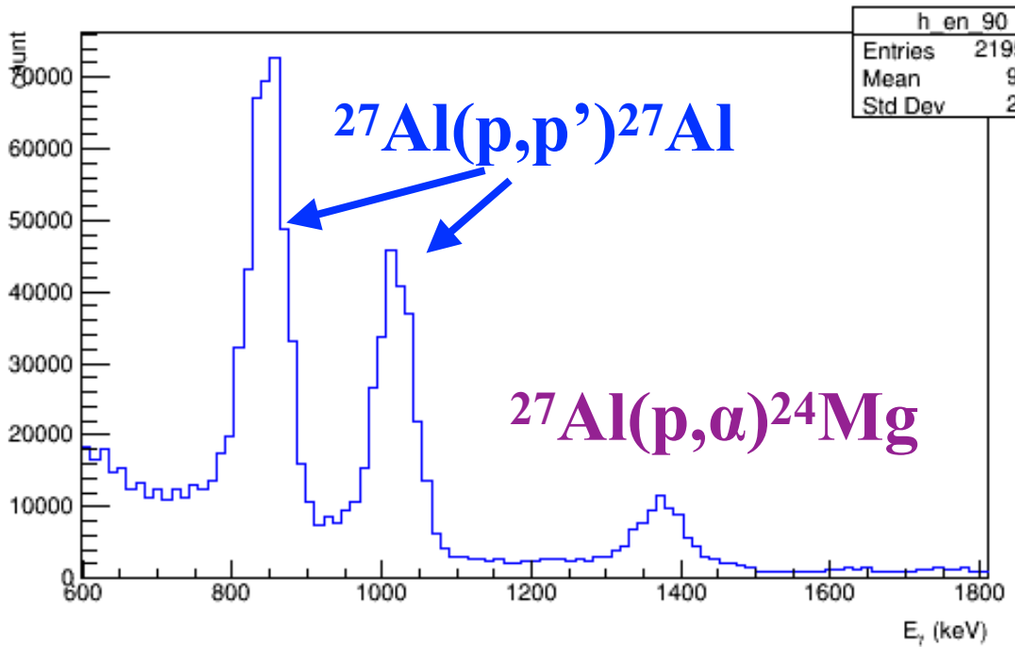
CALIFA Benchmark @ Lisbon

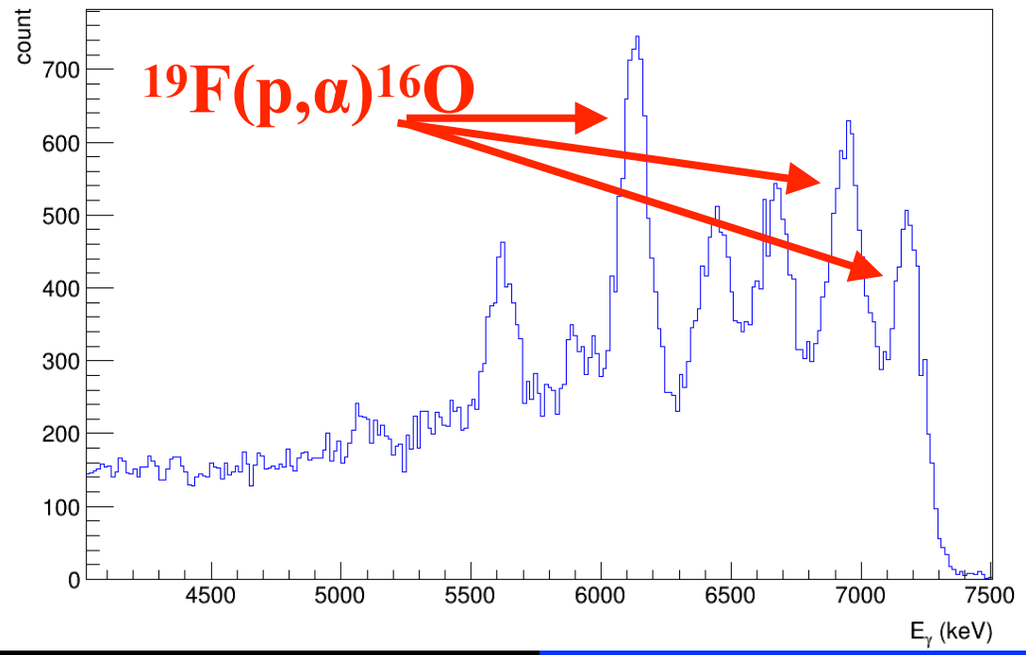


CALIFA Benchmark @ Lisbon

Individual Crystal response



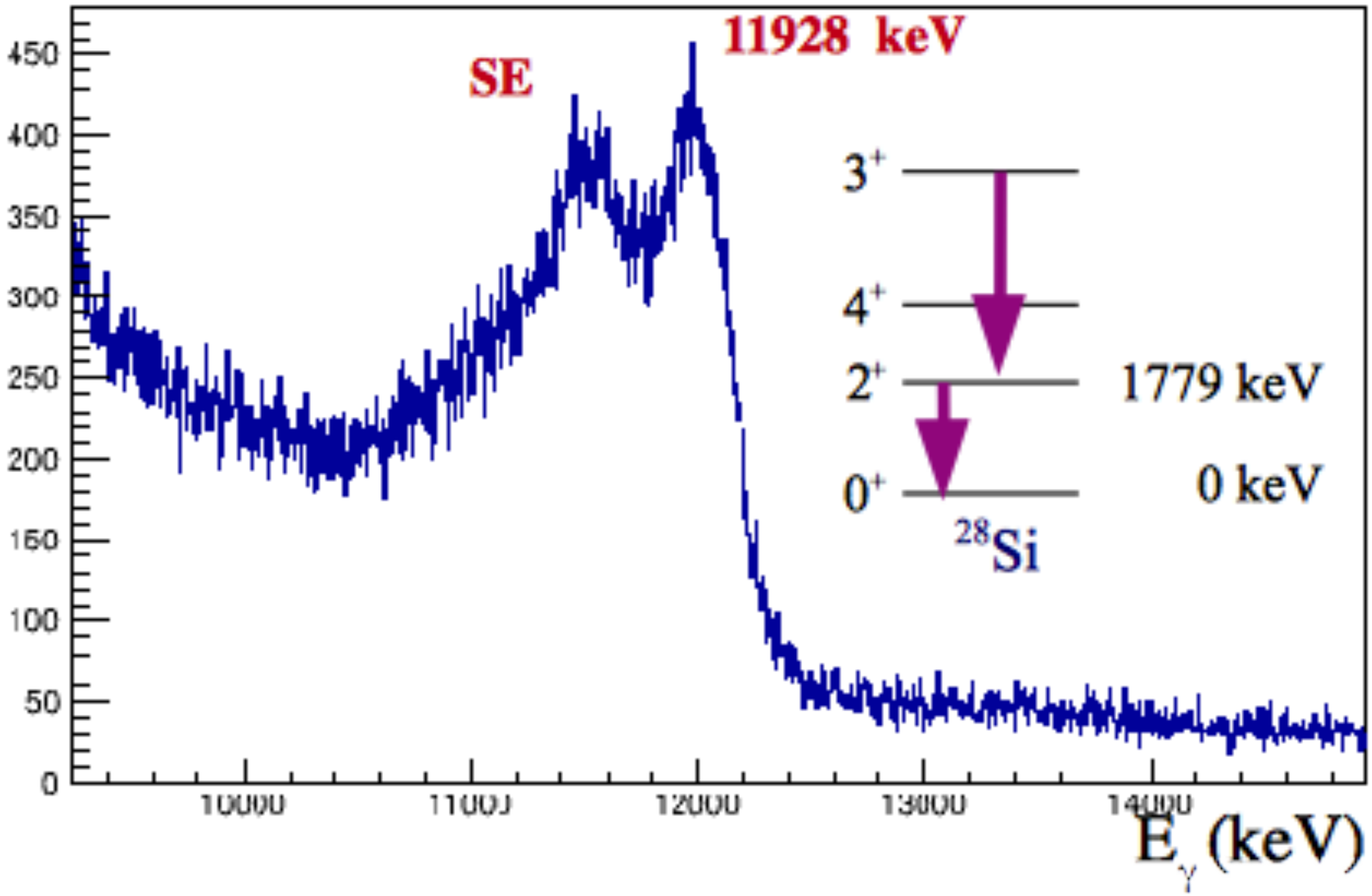




CALIFA Benchmark @ Lisbon

Calorimetric response

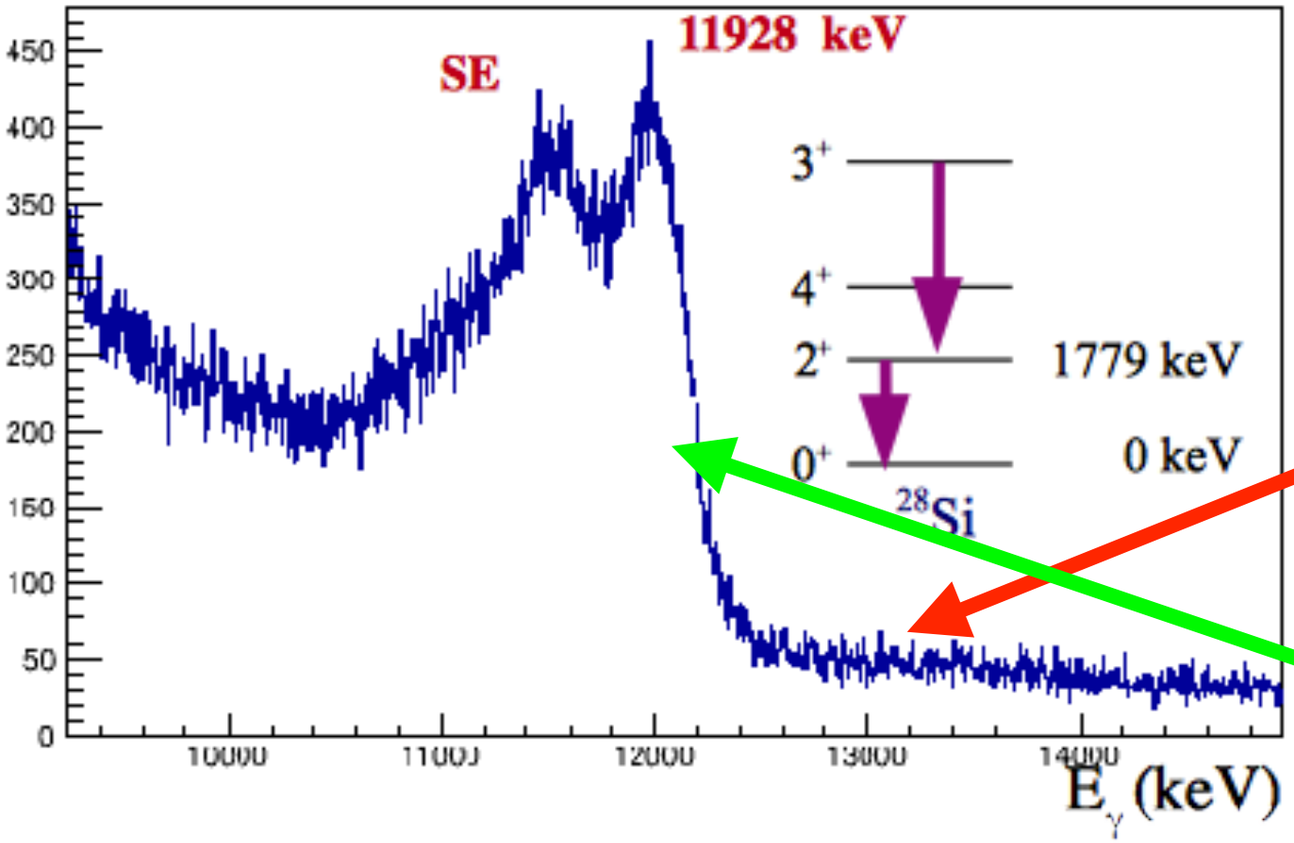
$^{27}Al(p,\gamma)^{28}Si^*$ (E_{ex} ~13.7 MeV)

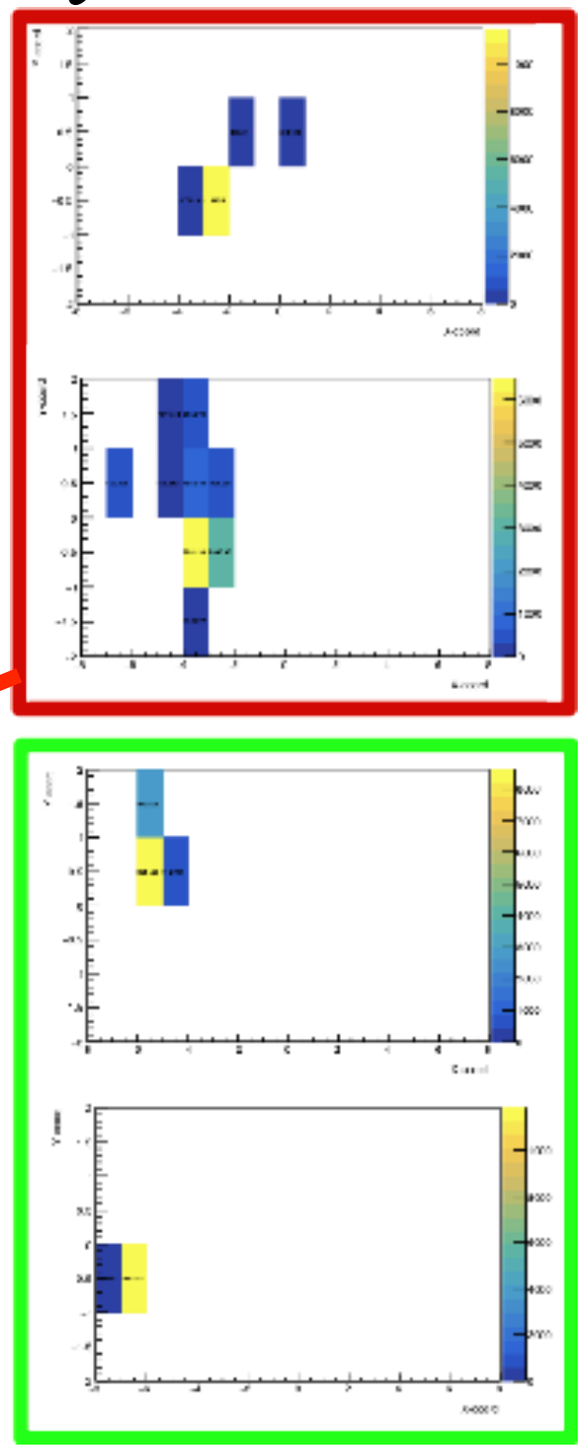


CALIFA Benchmark @ Lisbon

Topographic Analysis

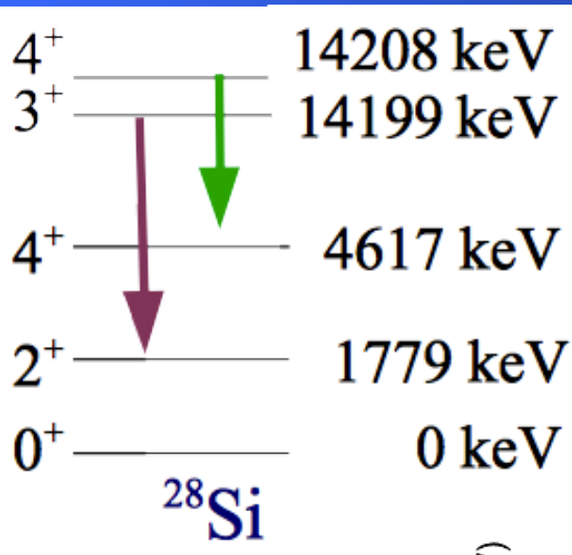
$^{27}Al(p,\gamma)^{28}Si^*$ (E_{ex} ~13.7 MeV)



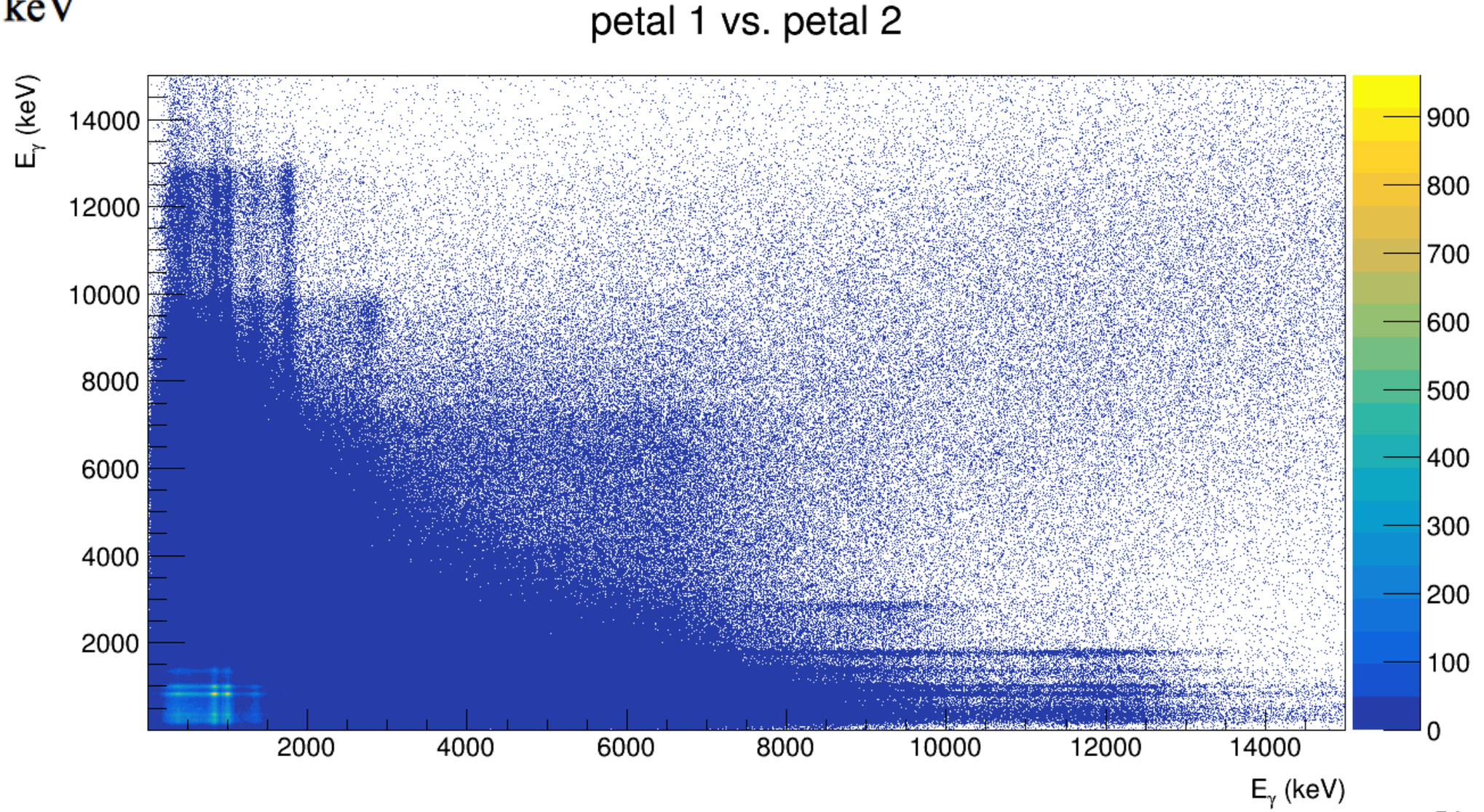


Pattern recognition using **ANNs**?

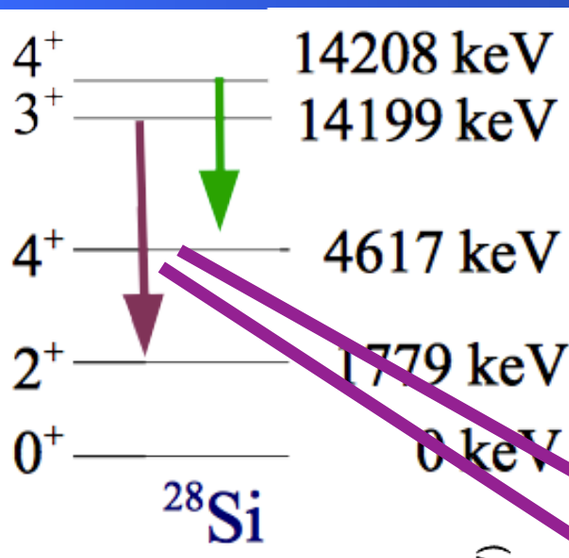
CALIFA Benchmark @ Lisbon



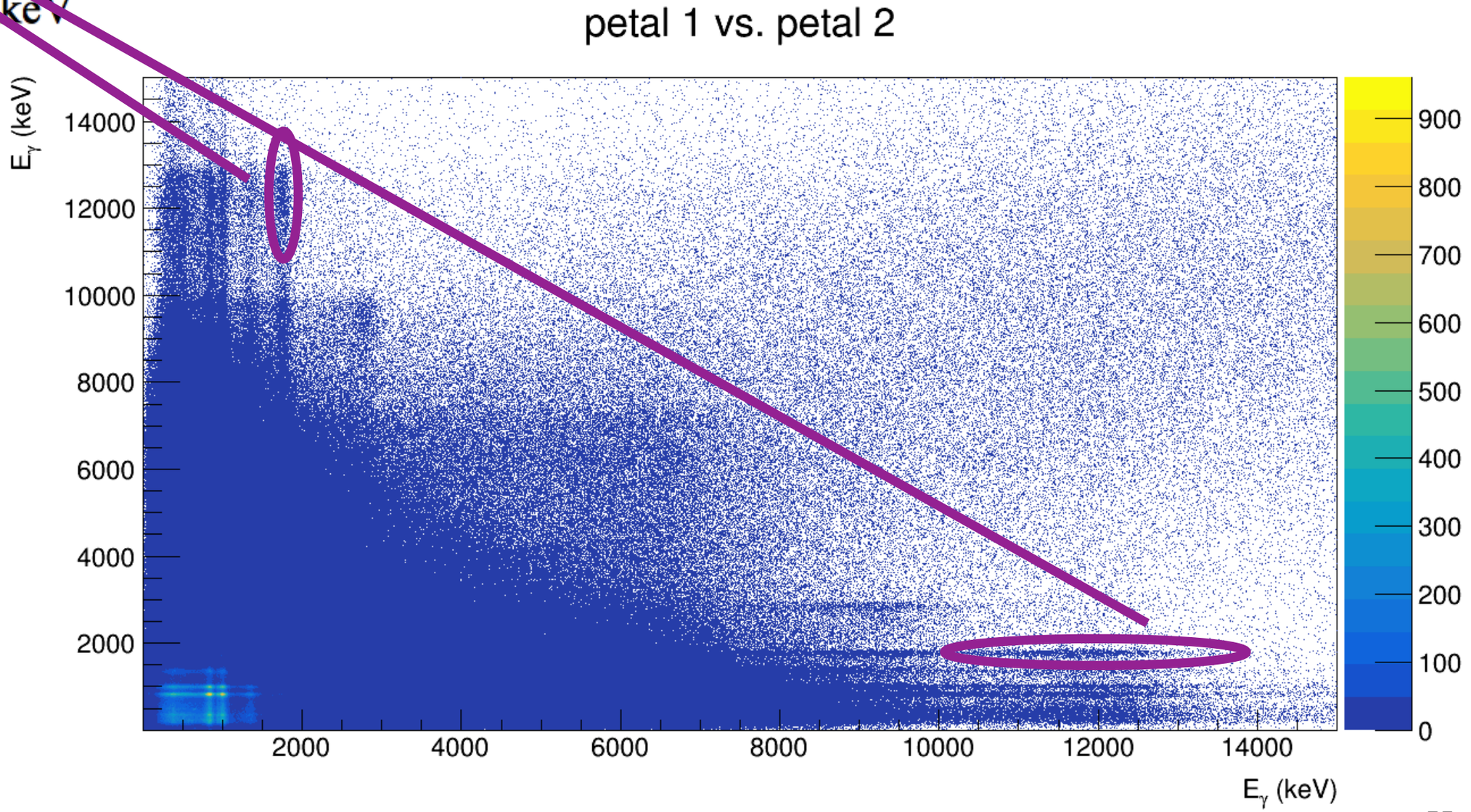
Populating the **14199 & 14208 keV** resonances of ^{28}Si



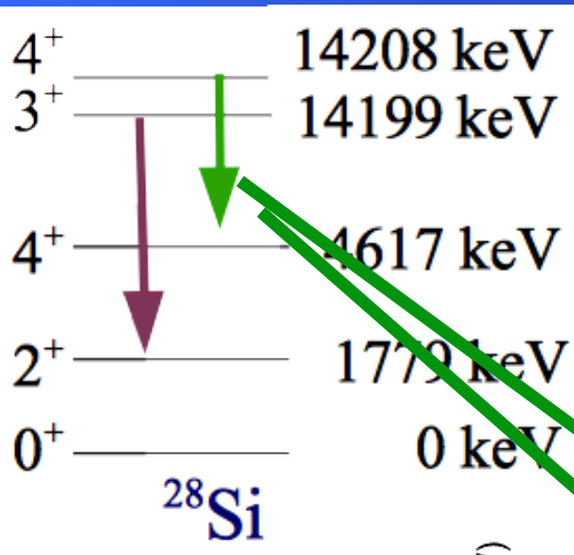
CALIFA Benchmark @ Lisbon



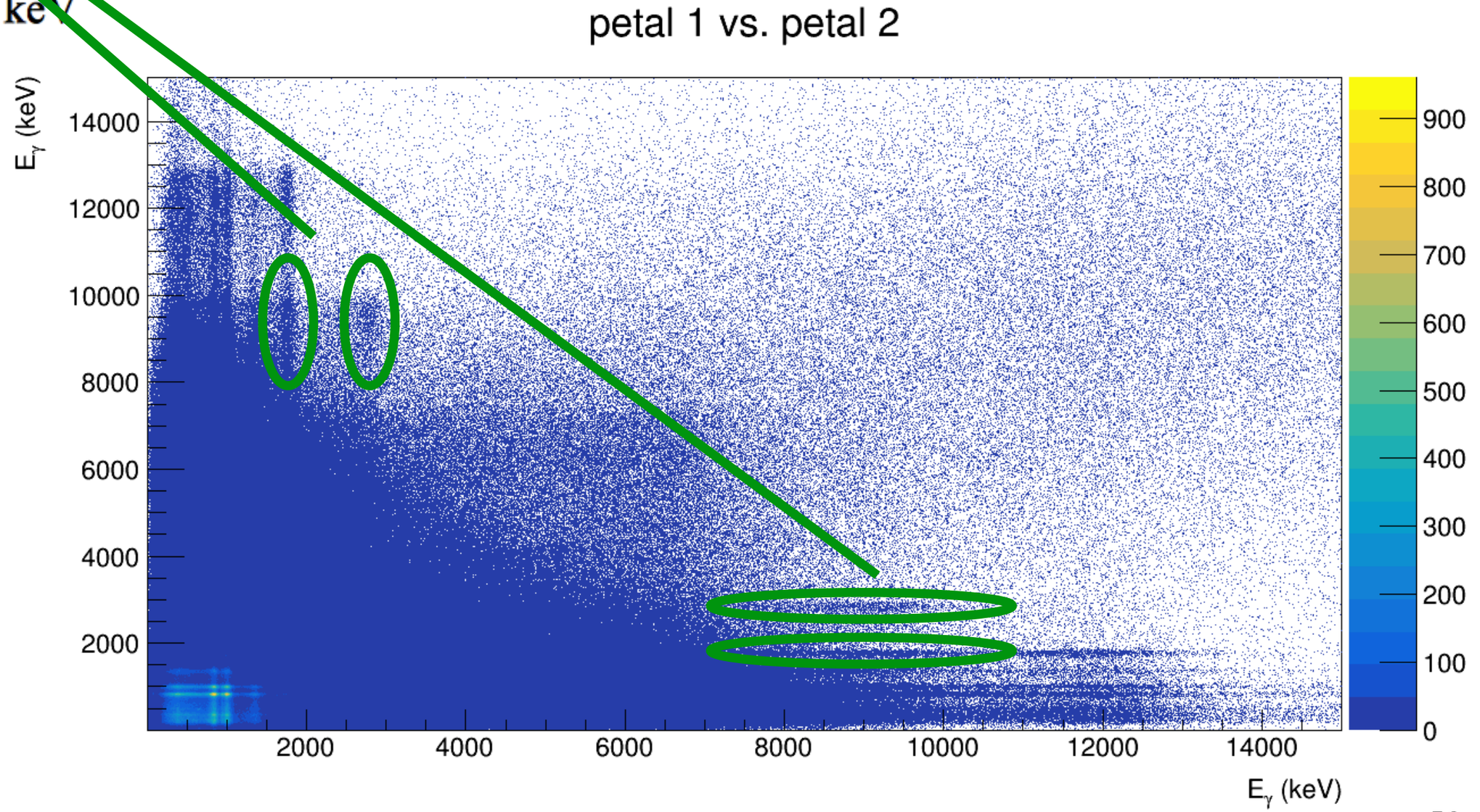
Populating the **14199 & 14208 keV** resonances of ^{28}Si



CALIFA Benchmark @ Lisbon

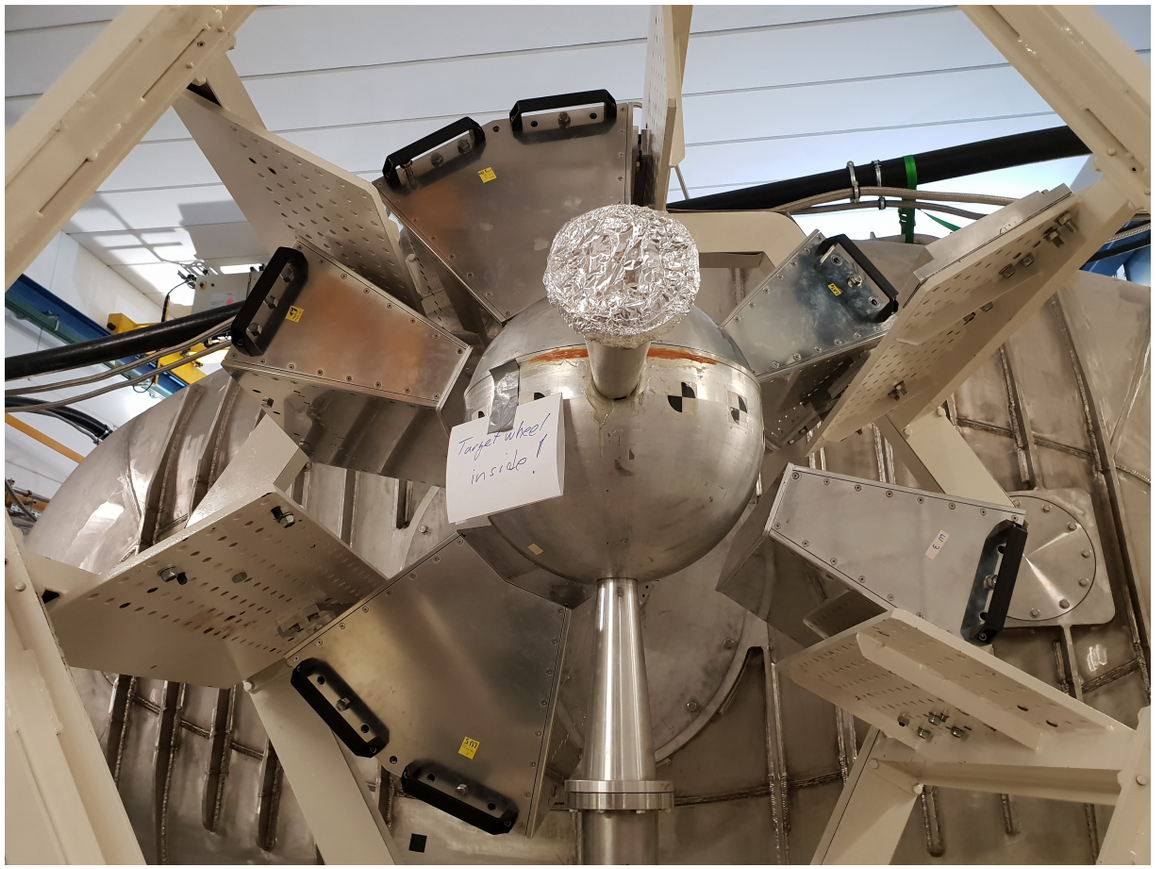


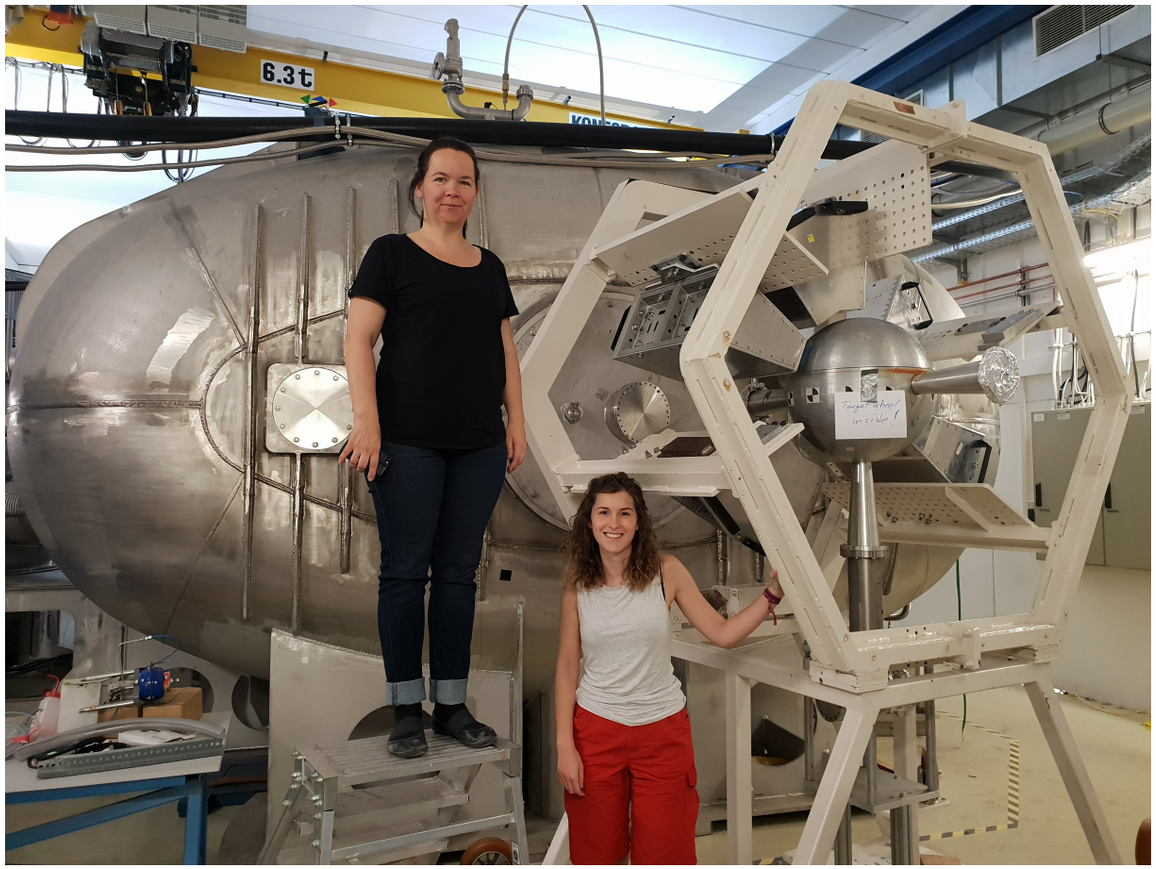
Populating the **14199 & 14208 keV** resonances of ^{28}Si



Towards Phase-0

Commissioning phase **beginning 2019**

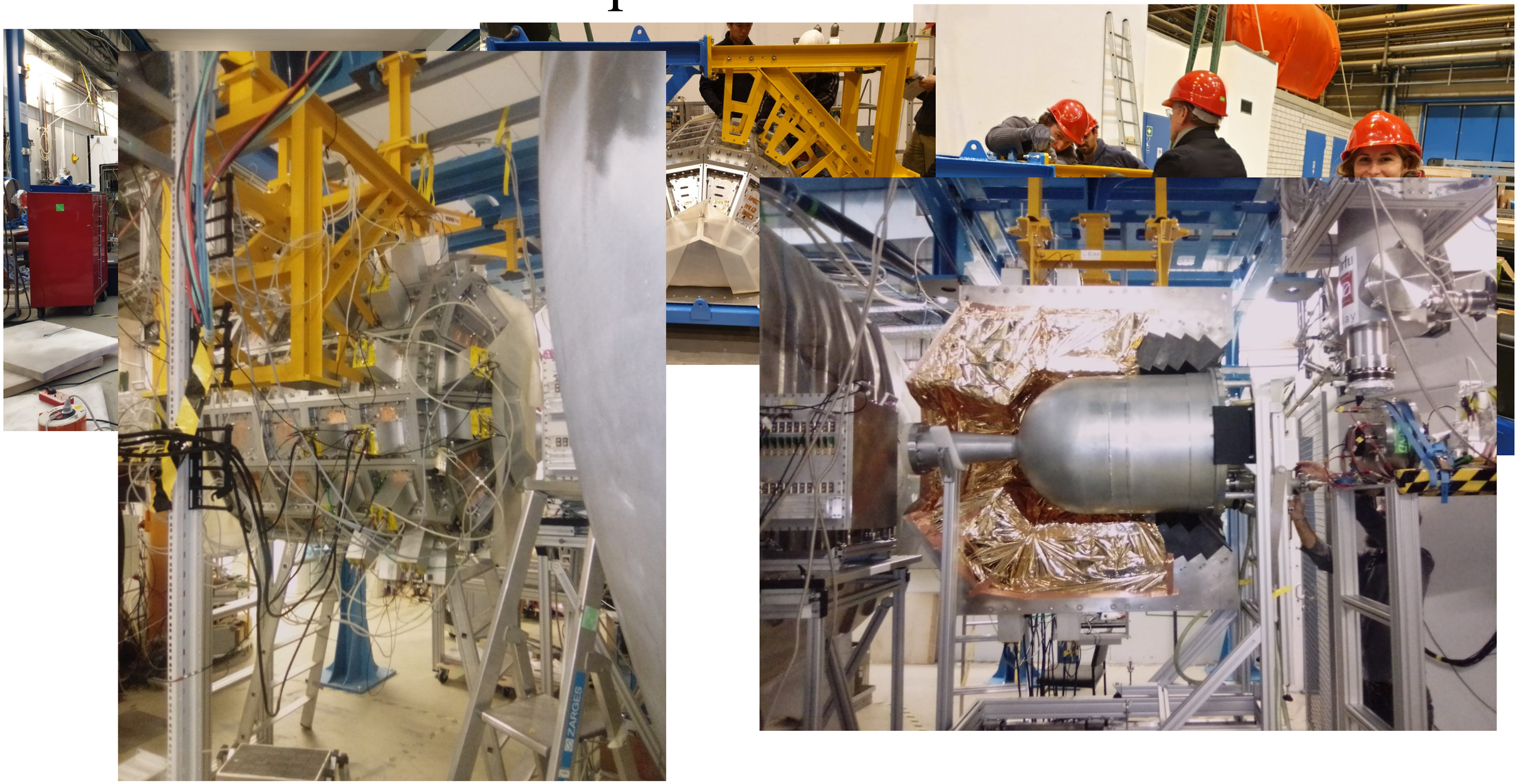




Preparations in July 2018

Towards Phase-0

First experiments **in 2020**



Full forward part of **CALIFA barrel** mounting in **Nov-Dec 2019**

People @ Lisbon

Ana Henriques

Paulo Velho

Pamela Teubig

Elisabet Galiana

Beatriz Pereira Manuel Xarepe Francisco Barba Luísa Baptista

Master

Ricardo Pires José Nunes

Pre-Master

D. Galaviz
L. Peralta

Exp.

R. Crespo
E. Cravo

Theory

FAIR Civil Construction

Events

Ground-breaking ceremony, July 4

adopted from N. Kalantar

FAIR Civil Construction

FAIR CONSTRUCTION SITE
STATUS NOVEMBER 2019

FACILITY FOR ANTIPROTON AND ION RESEARCH IN EUROPE GMBH
DARMSTADT, GERMANY