# Knock-out reactions on exotic nuclei at relativistic energies

**Daniel Galaviz Redondo**

*LIP-Lisbon*

*Departamento de Física*

*Faculdade de Ciências da U-Lisboa*

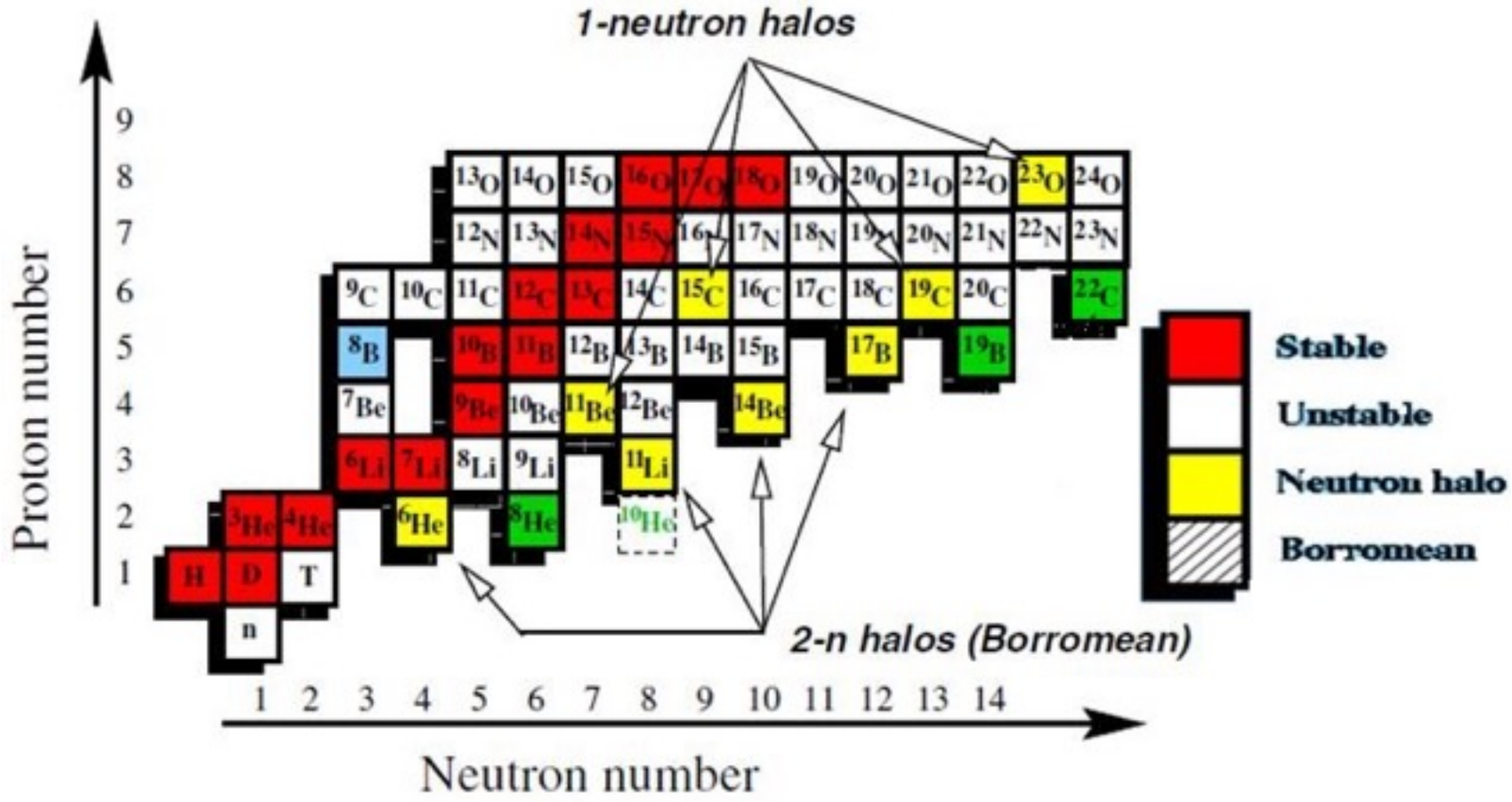
Braga, IGFAE-LIP Workshop

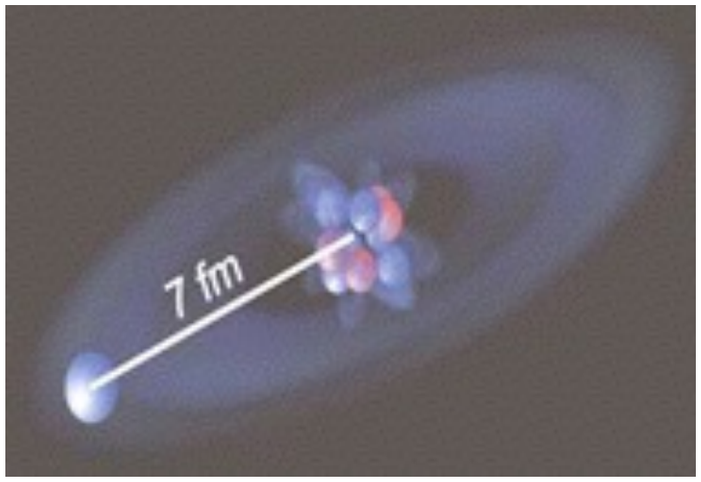
May 4th, 2018

# Outline

- Motivation:
  - **Halo** nuclei
  - Reaction formalism for **QFS** on a **proton target**
- Experiment **S393** at cave C
  - Experimental setup (**LAND/R$^3$B**)
  - Results on **particle-exclusive** and **particle-inclusive** **neutron knock-out** on a **proton target**

# Halo nuclei

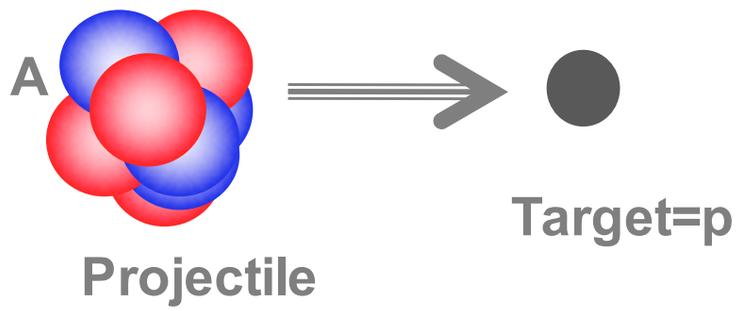



$^{11}$Be

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

# Reaction theory



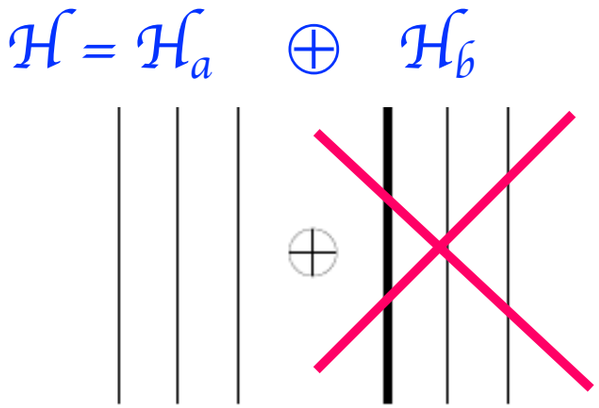

A+1 many body problem


Projectile = Core(Heavy Fragment) + N

Three body problem

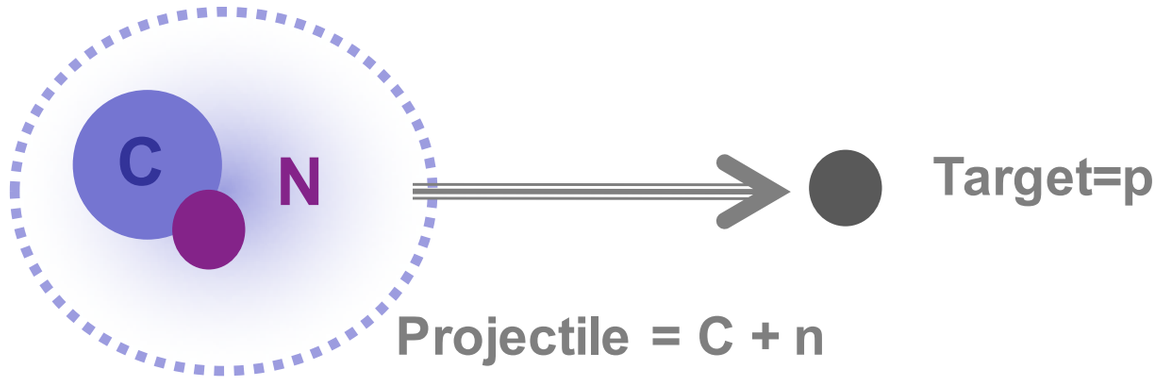
## Space Truncation

- **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

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

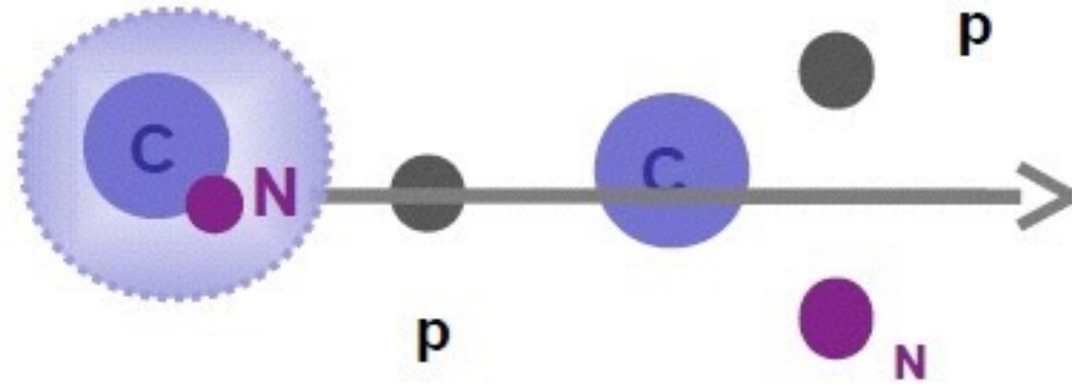
Free propagator

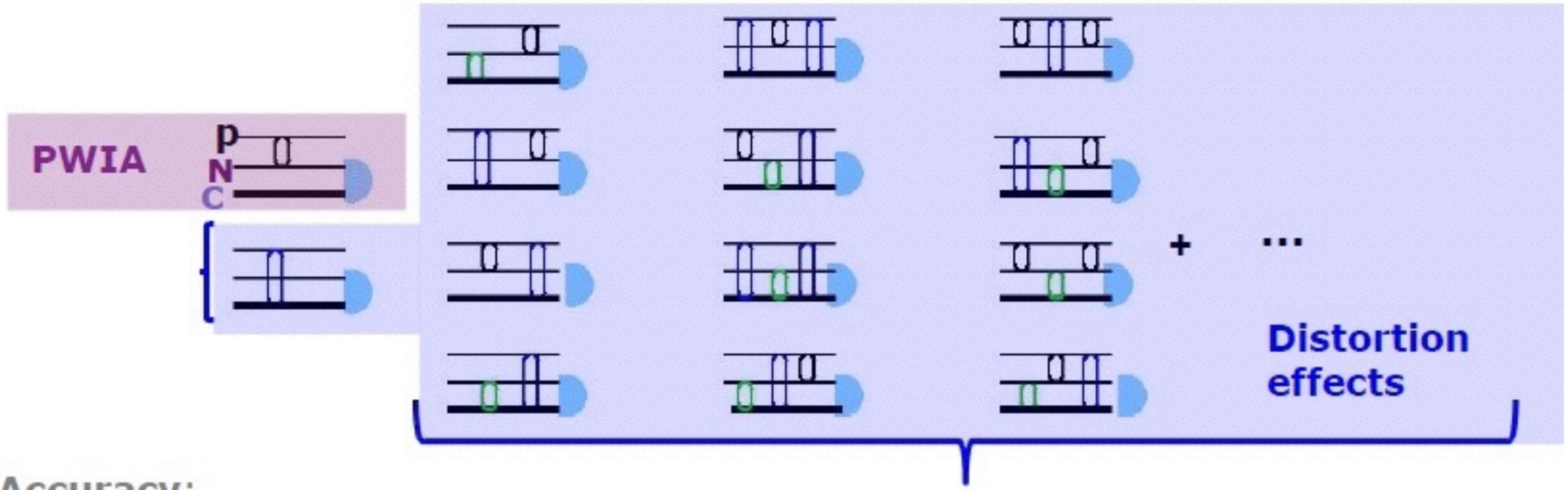
Tool for investigating:

★ **Single particle** properties

★ **Spectroscopic factors**

# Reaction theory: Faddeev/AGS




Accuracy:

Dynamics: accurate treament of terms involving **N-C rescattering contributions**

Structure: good description of the N-C interaction

# Reaction theory

## Faddeev/AGS suited!

- Kinematically fully exclusive cross sections :

$$d^5\sigma / dS d\Omega_Z d\Omega_N (mb/MeV\,sr^2) \qquad dS = \sqrt{dE_N^2 + dE_Z^2}$$

$$Z = C \text{ or p}$$

- Double cross sections:

$$d^2\sigma / dE_p d\theta_p (\text{mb/MeV rad}) \quad d^2\sigma / dE_N d\theta_N (\text{mb/MeV rad}) \quad d^2\sigma / \theta_p d\theta_N (\text{mb/ rad}^2)$$

- Semi-inclusive cross sections: $Z = \text{C,p,N}$

  - $d\sigma / d\theta_Z (mb/sr)$ ◇ Angular distributions
  - $d\sigma / dE_{rel} (mb/MeV)$ ◇ Energy spectrum
  - $d\sigma / dp_Z^x (mb/MeV/c)$ ◇ Transverse momentum distribution
  - $d\sigma / dp_Z^z (mb/MeV/c)$ ◇ Longitudinal momentum distribution

- Inclusive: Total cross sections:

Kinematic Integration

Physics information lost

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

| | $S_n$ (MeV) | g.s. ($J^\pi$) | 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)

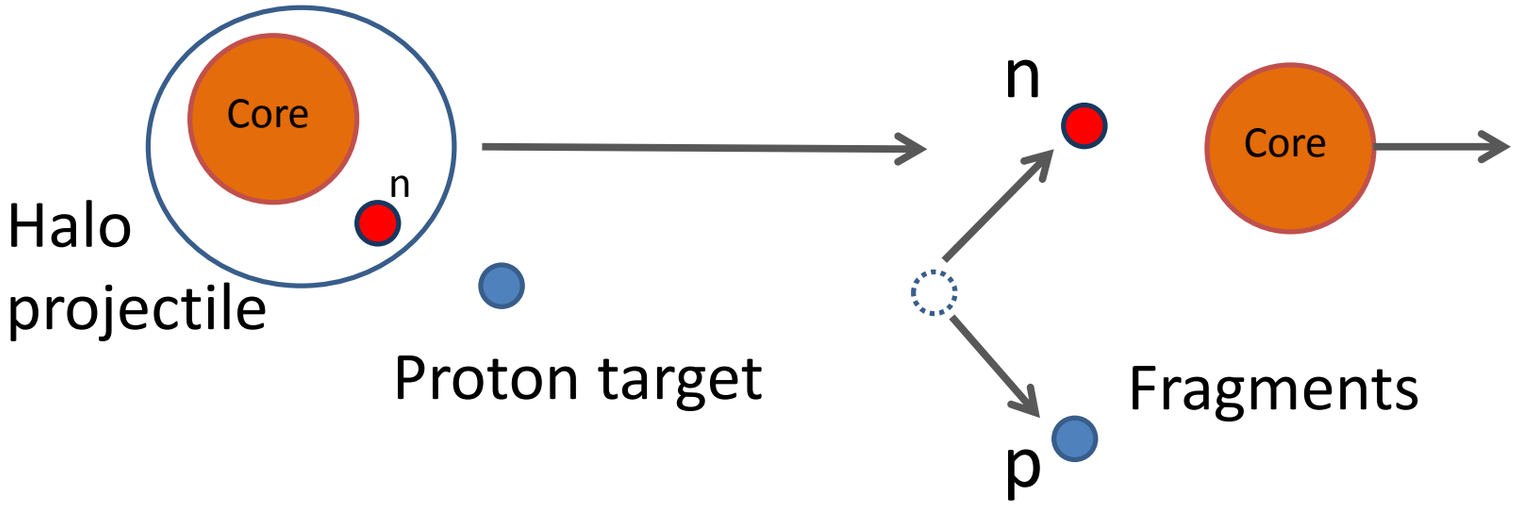
U. Datta Pramanik *et al.*, Phys. Lett. B **551**, 63 (2003)

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

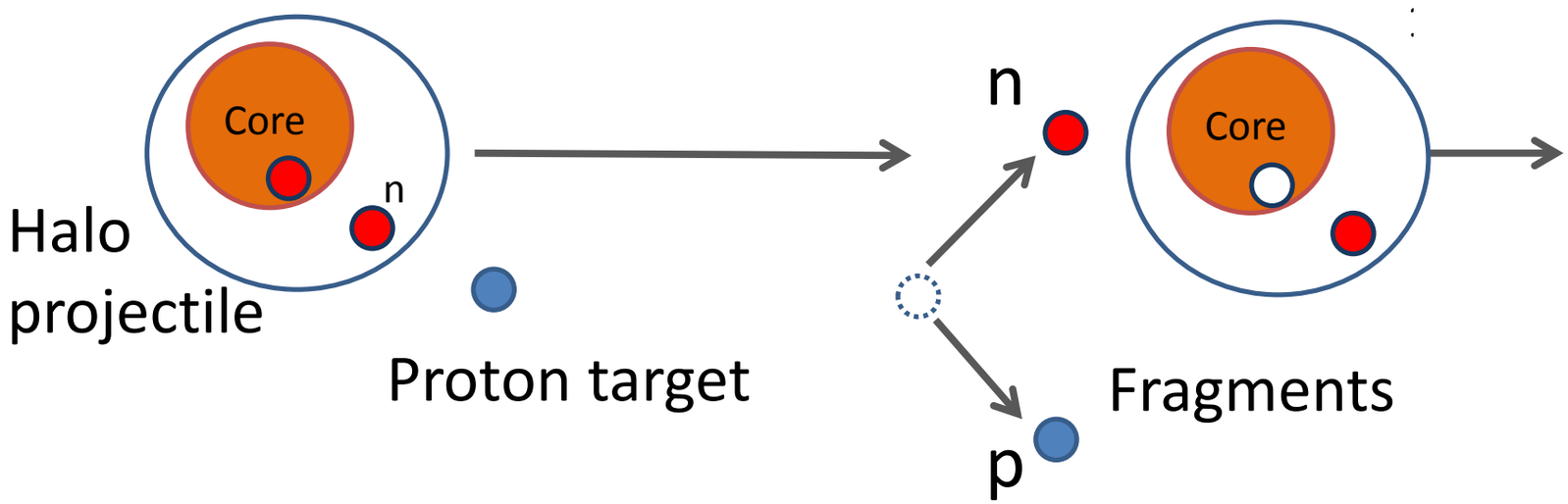
Suitable cases for the verification of the **reaction mechanism** studying its **break-up** on a **proton** target at **relativistic energies**

# Nucleon knock-out contributions

**Valence knock-out**

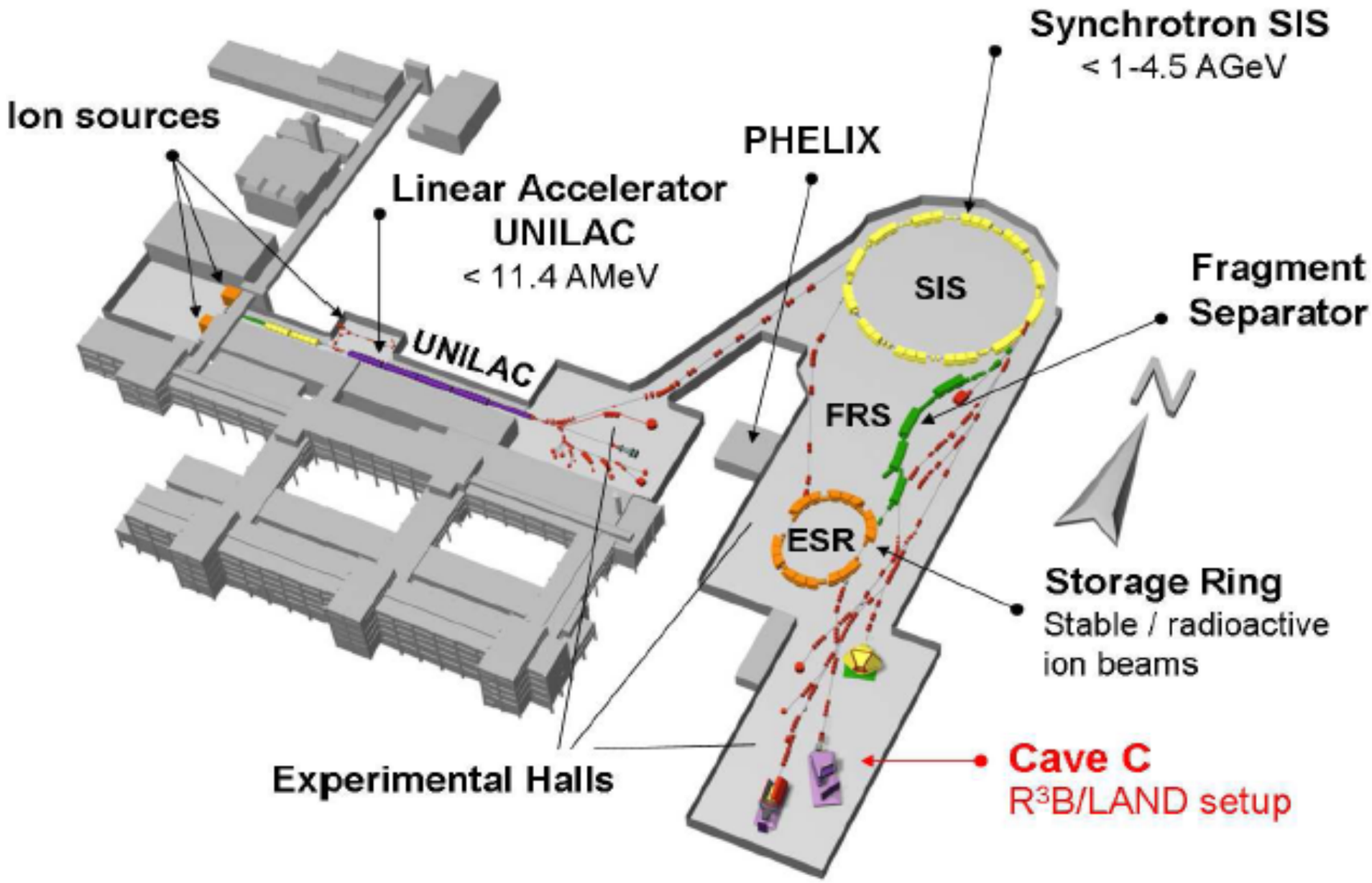



**Inner shell knock-out**




1

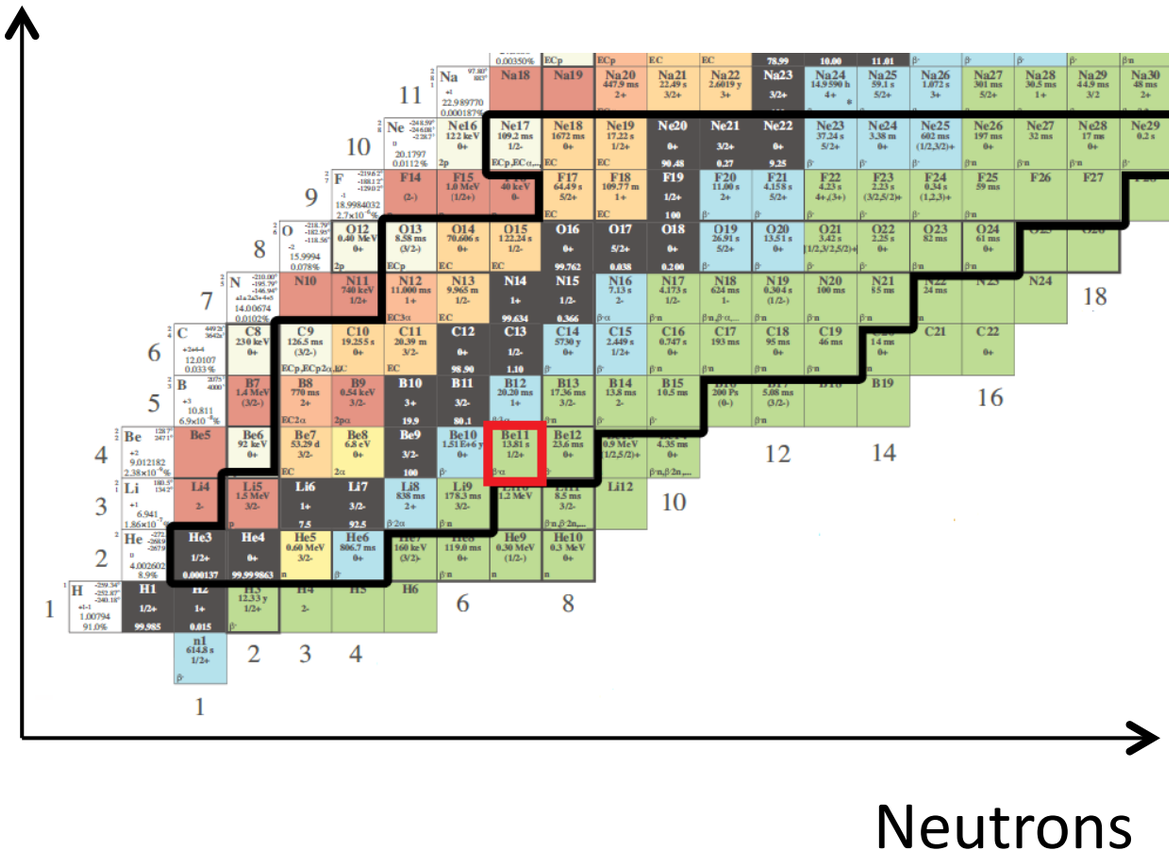
# Experiment S393 at Cave C



# 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"



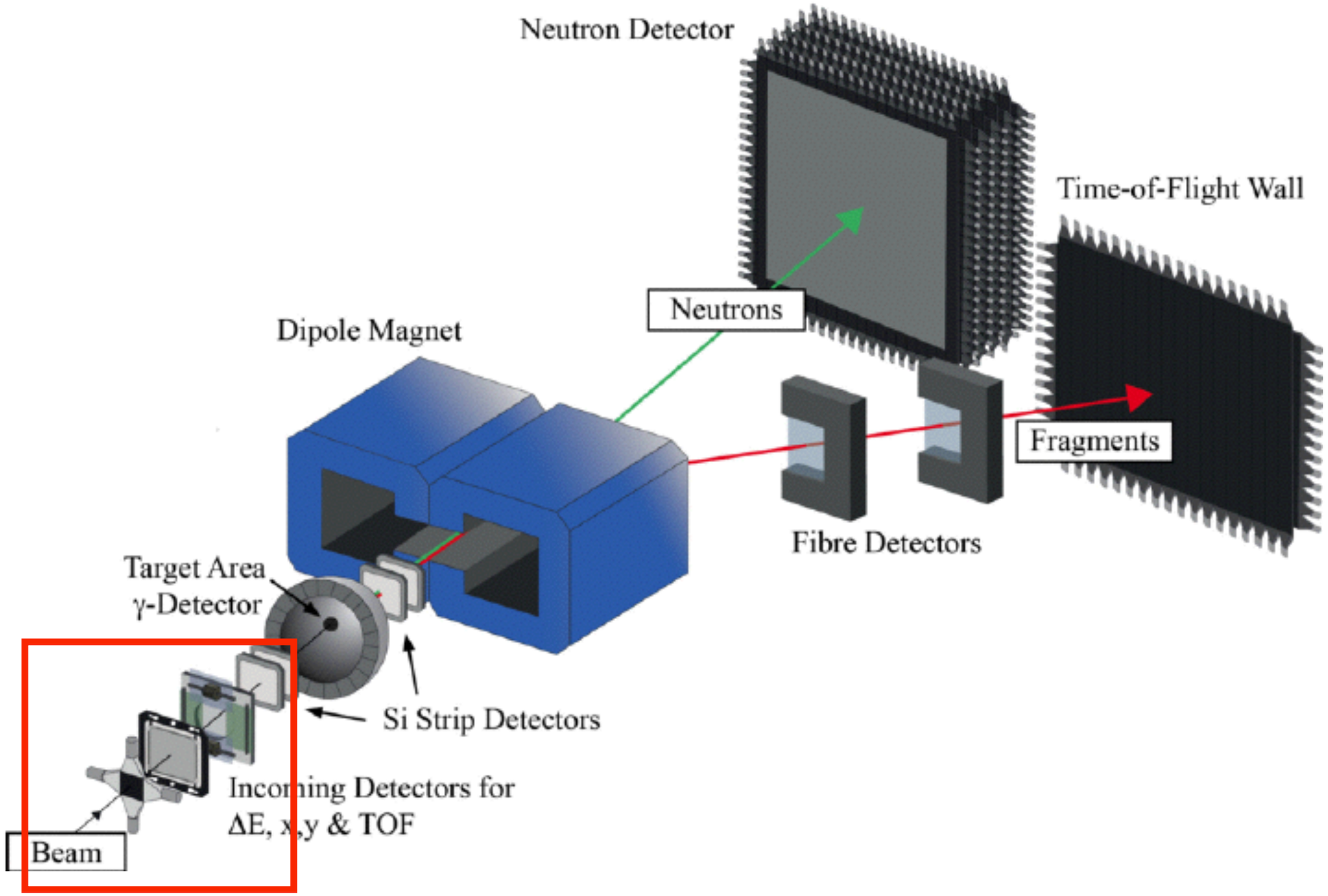

- Primary beam: $^{40}$**Ar** (600 MeV/u)

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

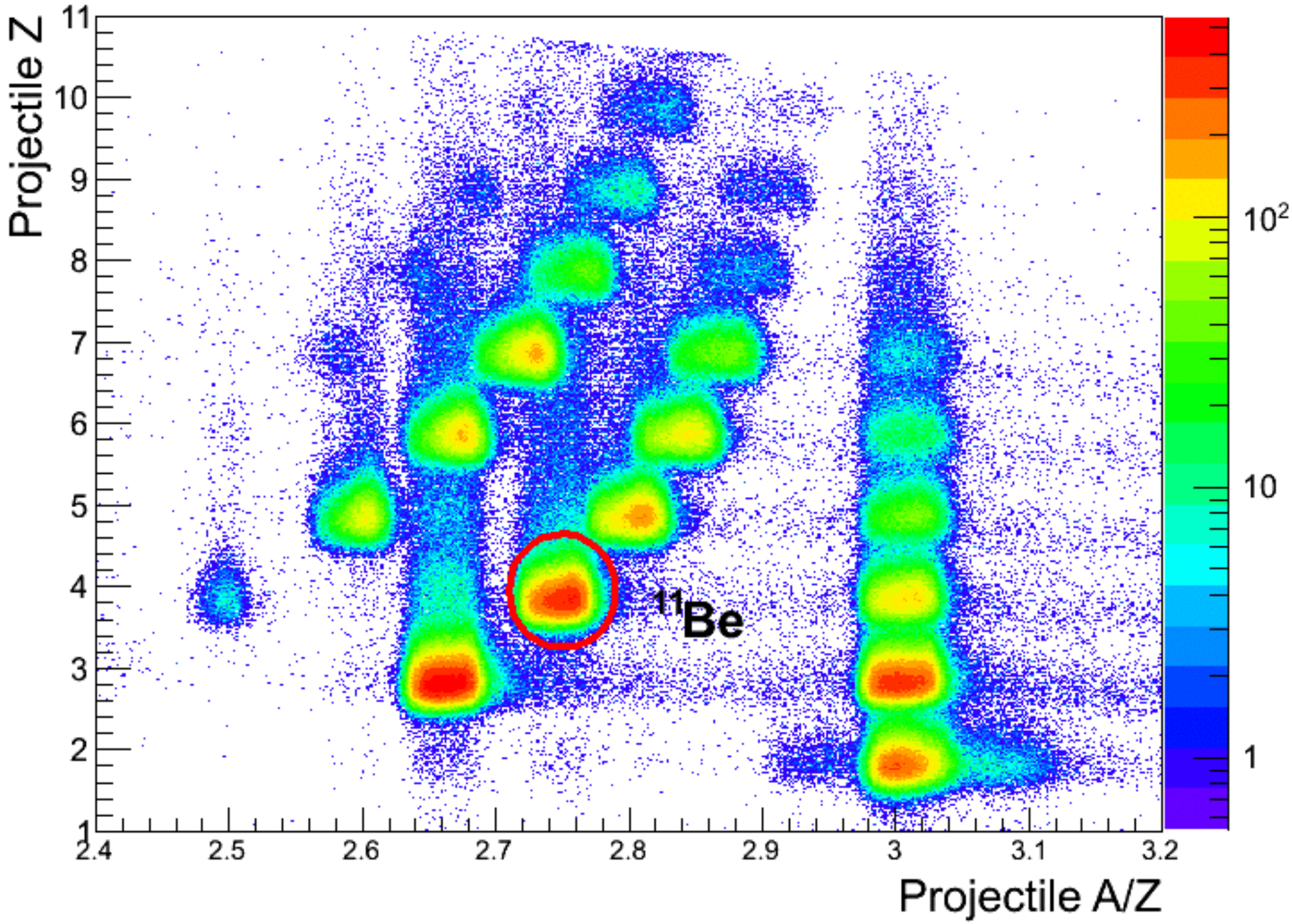
- Secondary **cocktail beam** @ (500 MeV/u)
  **6** different **settings**:
  $4 < Z < 10$
  $1{,}5 < A/Z < 3$

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

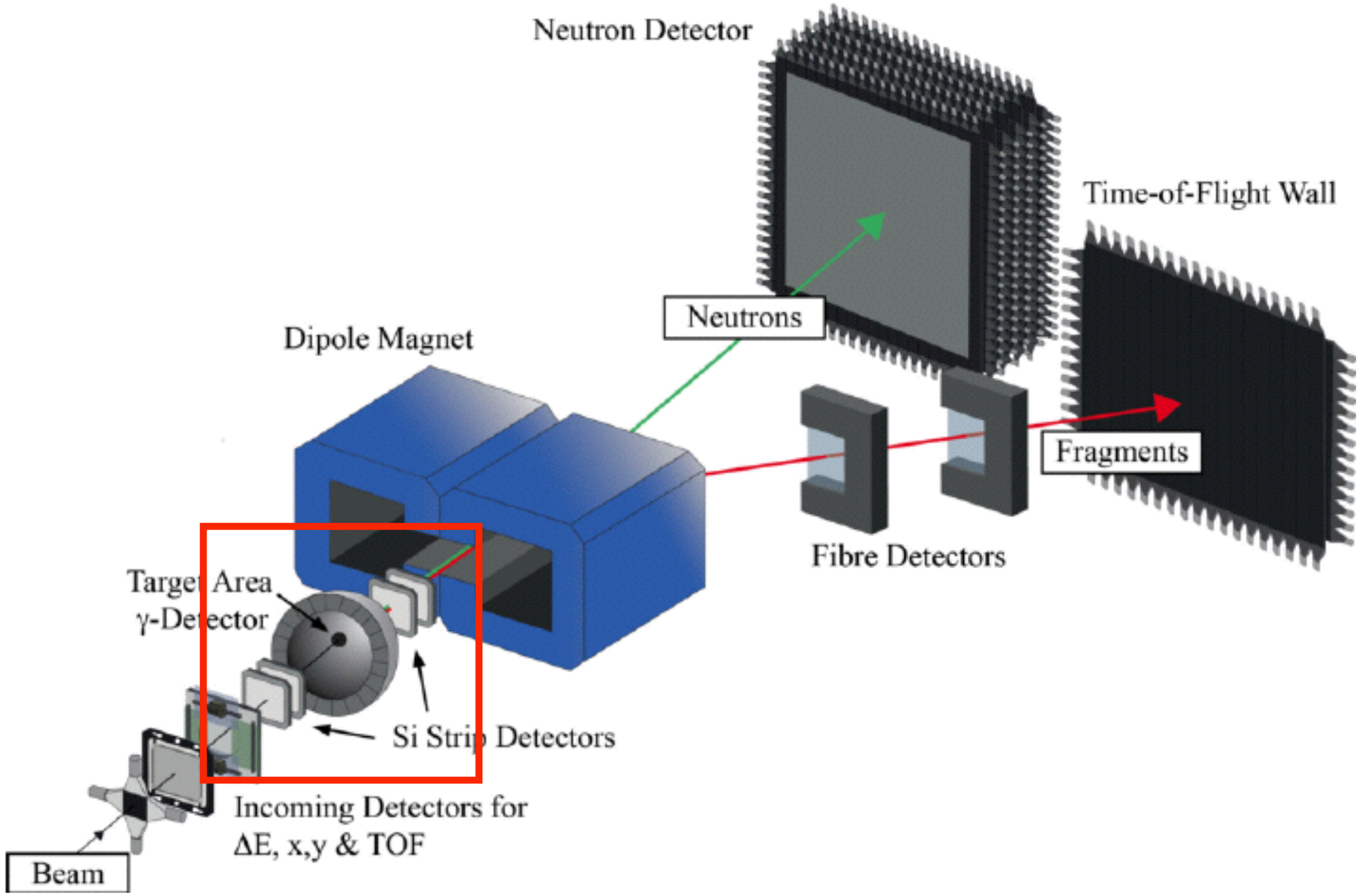
# LAND/R$^3$B setup



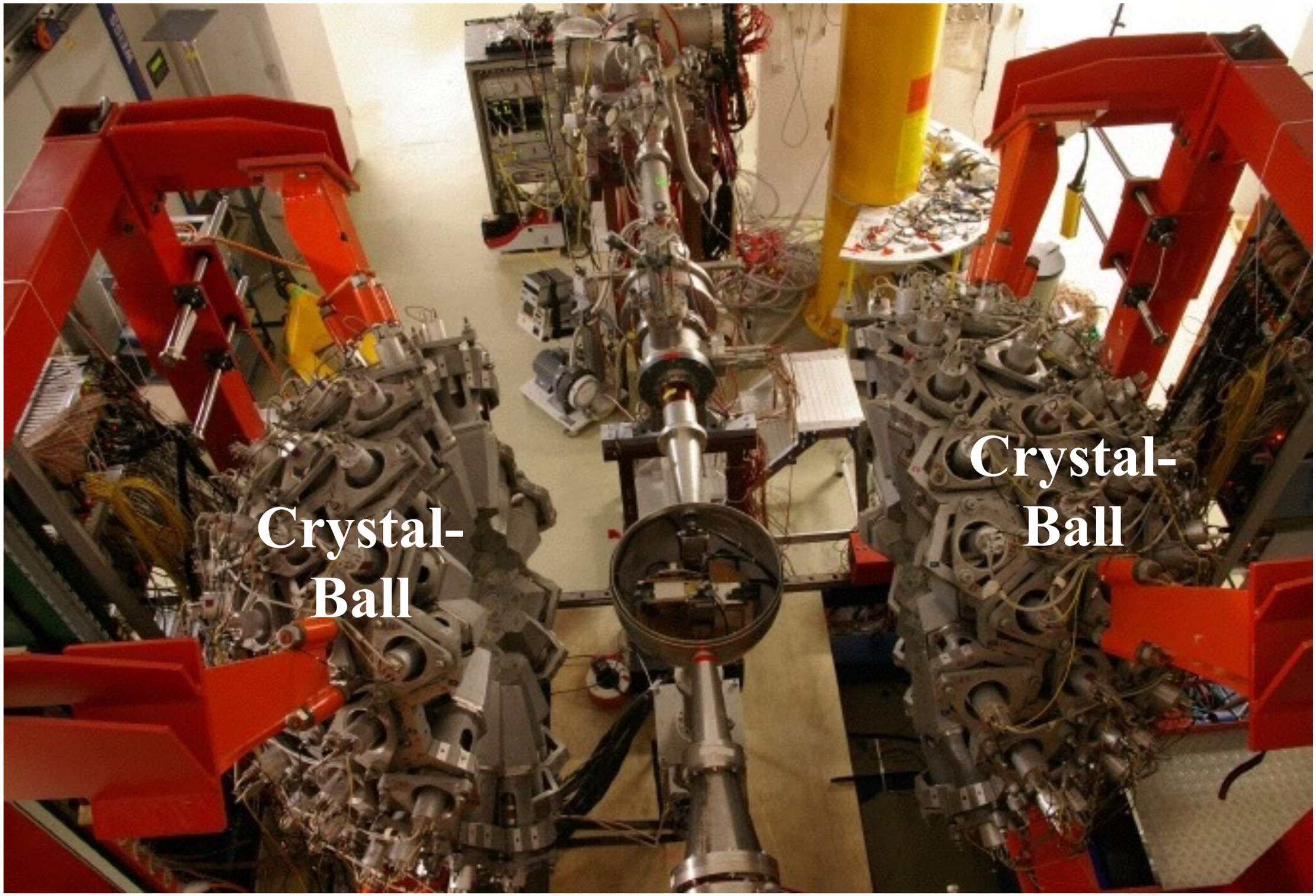
# Incoming Beam Identification



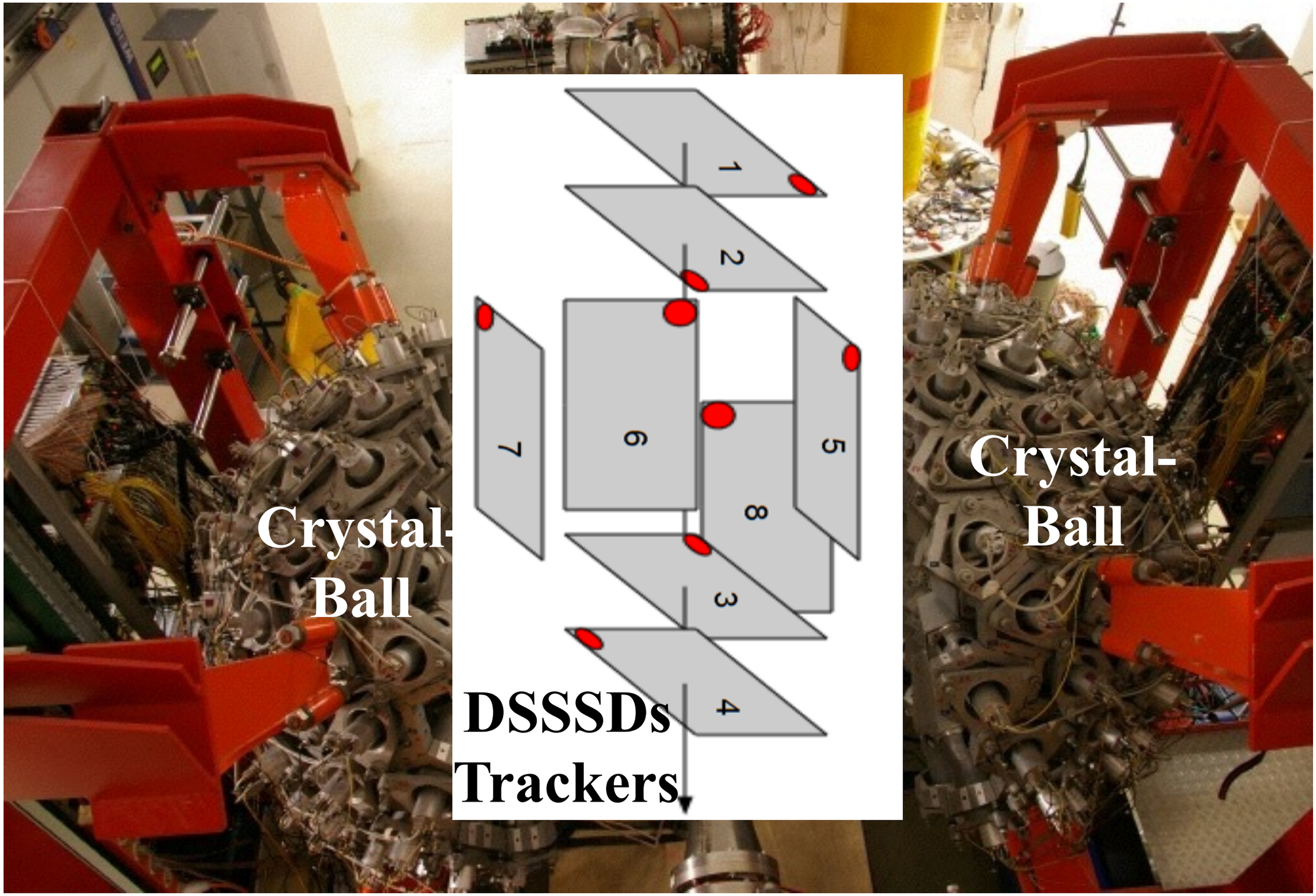
# LAND/R$^3$B setup

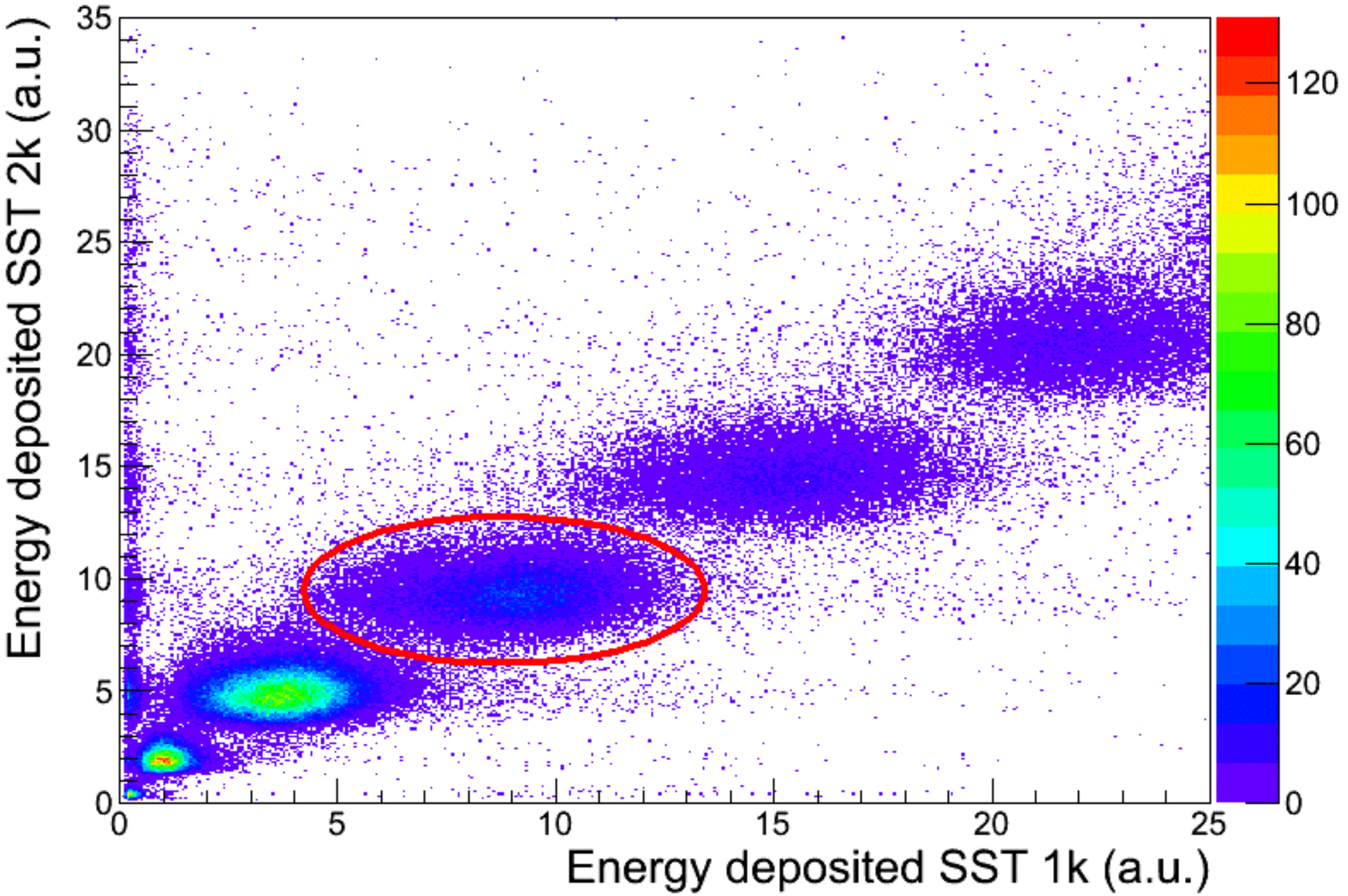


# Target detectors

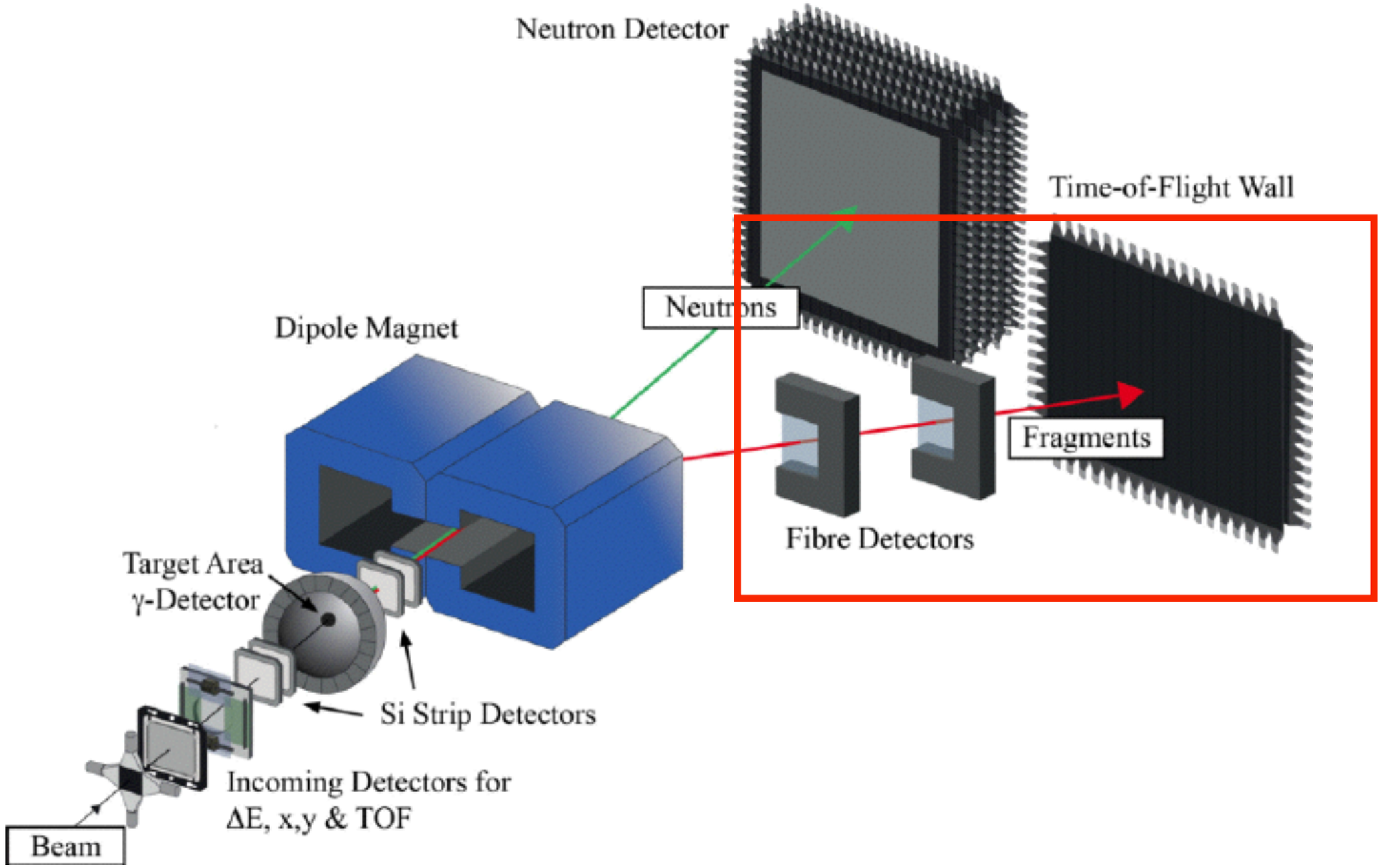


# Target detectors

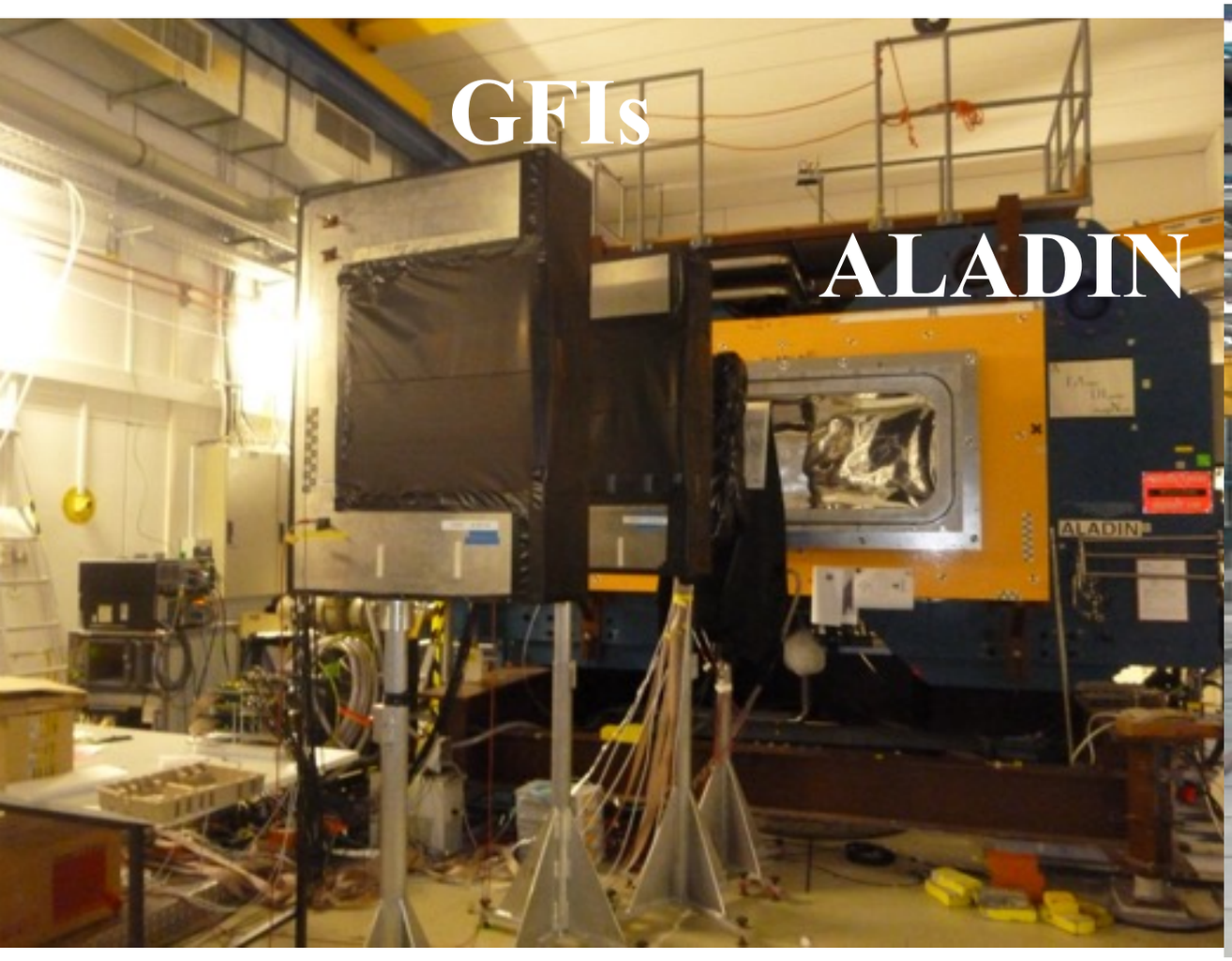



Energy deposited SST 2k (a.u.)
Energy deposited SST 1k (a.u.)
0
5
10
15
20
25
30
35
120
100
80
60
40
20
0

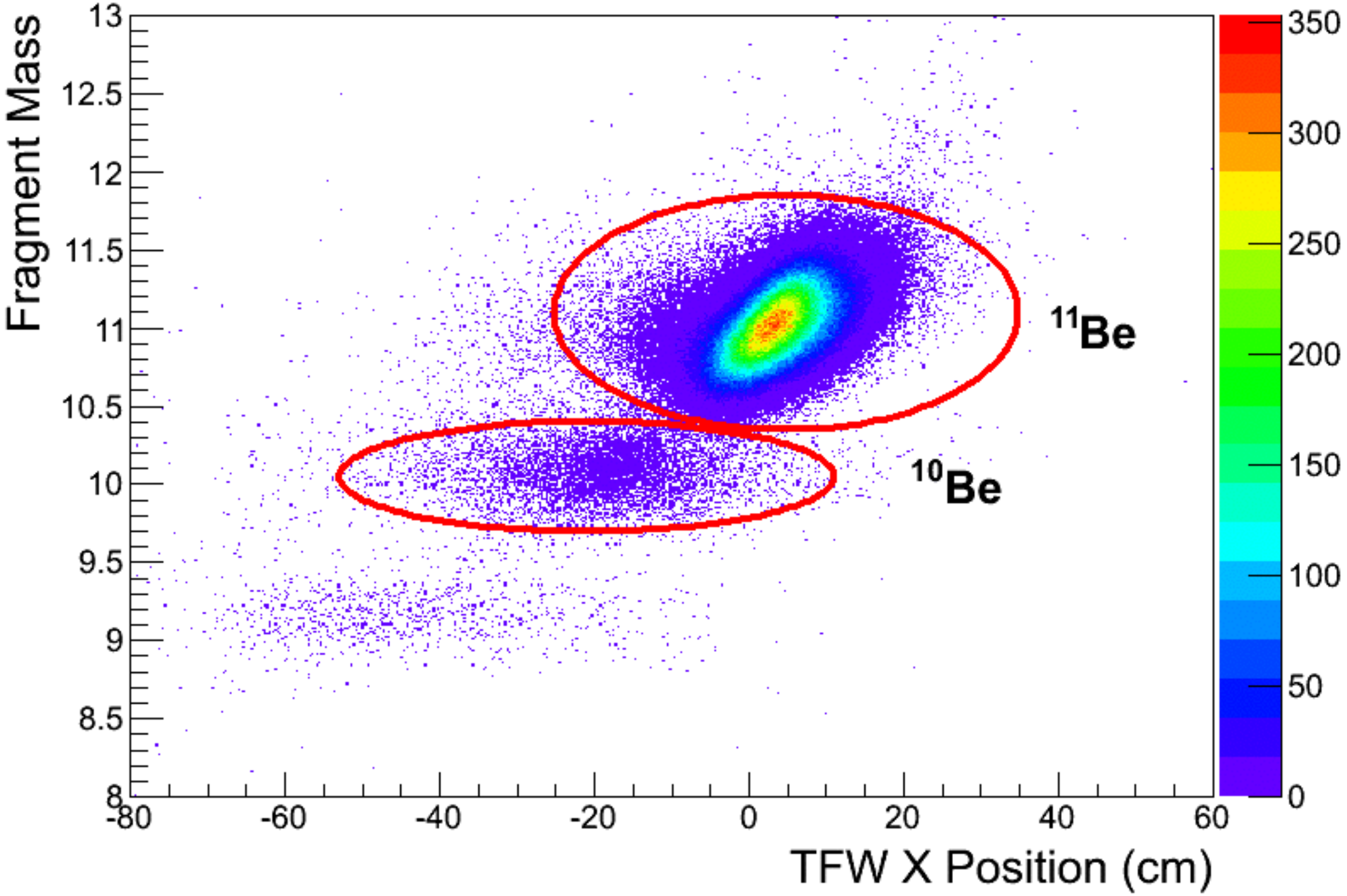
# LAND/R$^3$B setup



# Heavy Fragment branch

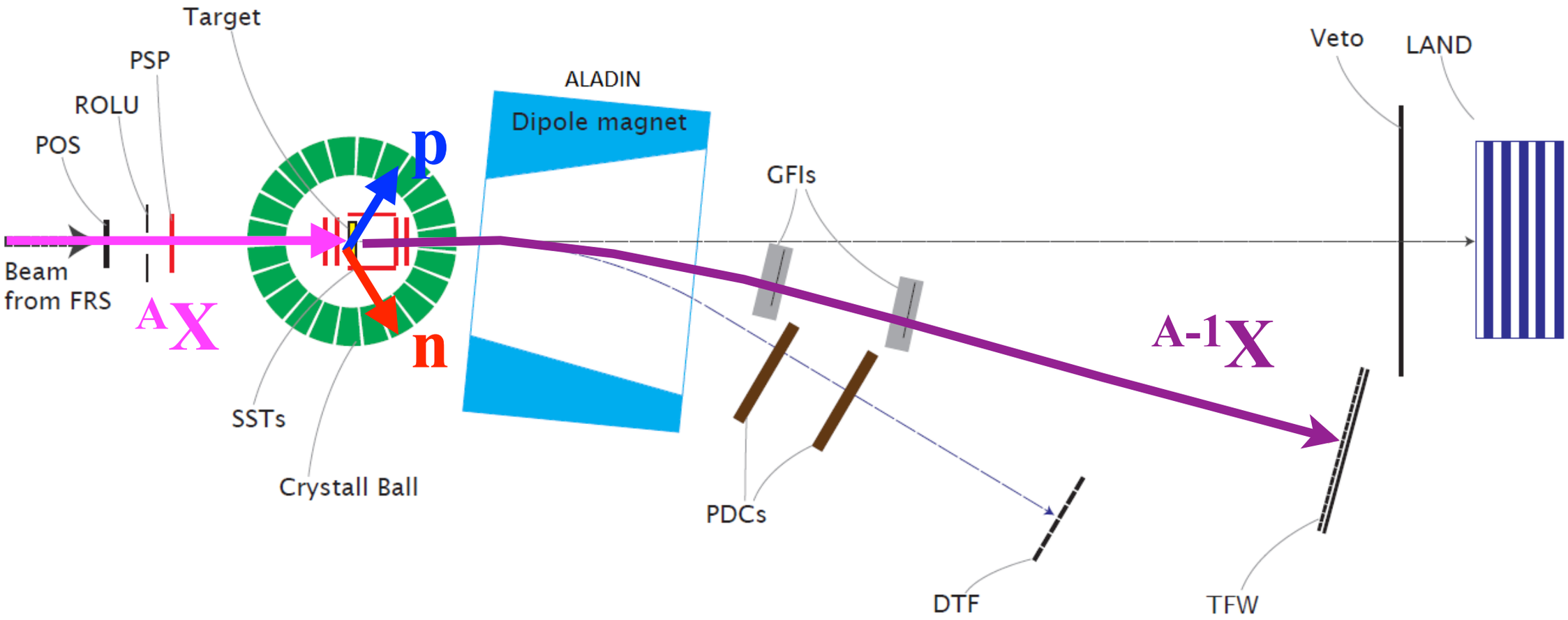



# Heavy fragment identification



# LAND / R³B Setup

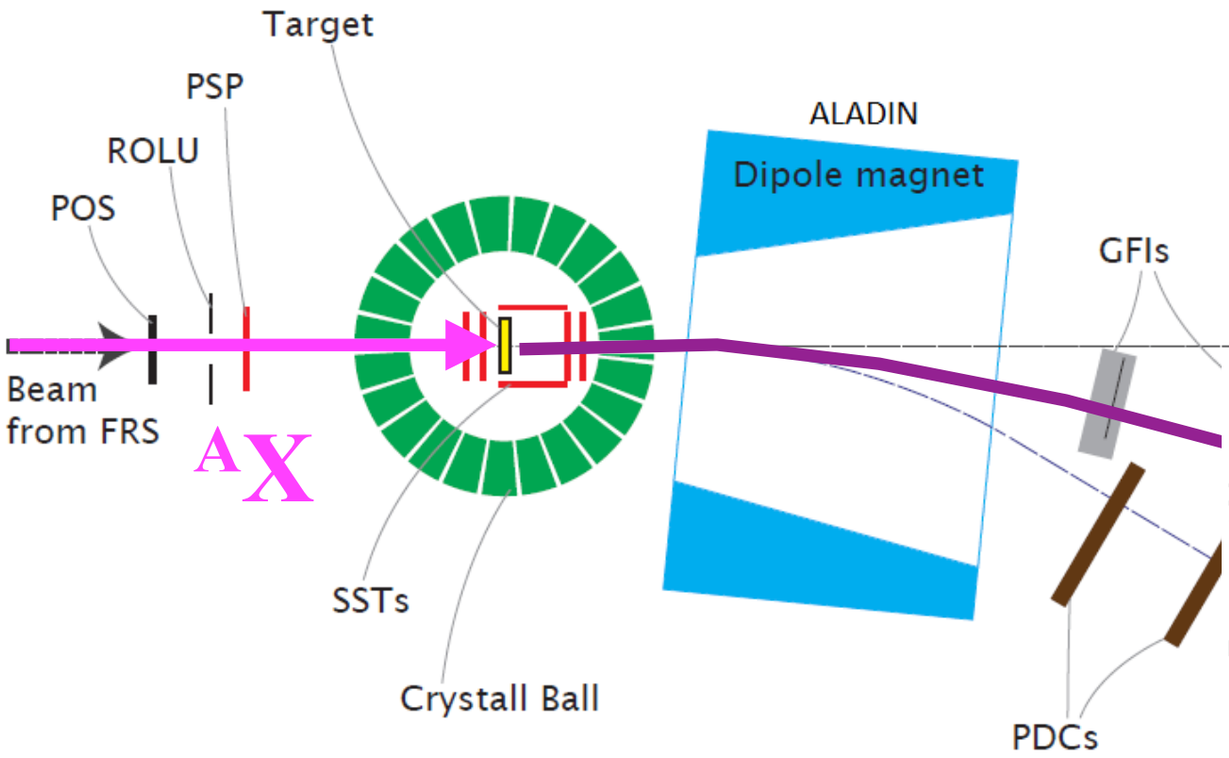
Reaction: $^{A}X(p,pn)^{A-1}X$

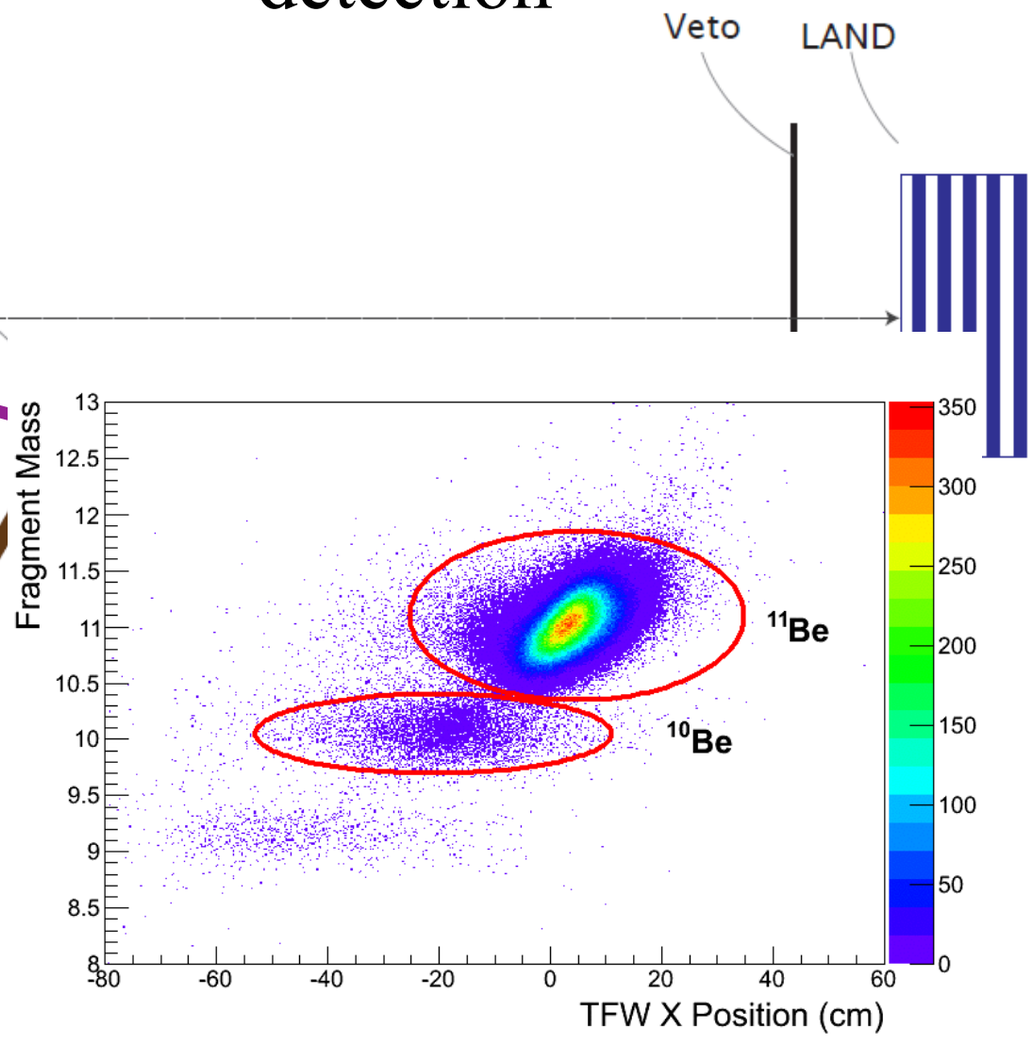


# LAND / R³B Setup

## **Particle Inclusive** knock-out reaction

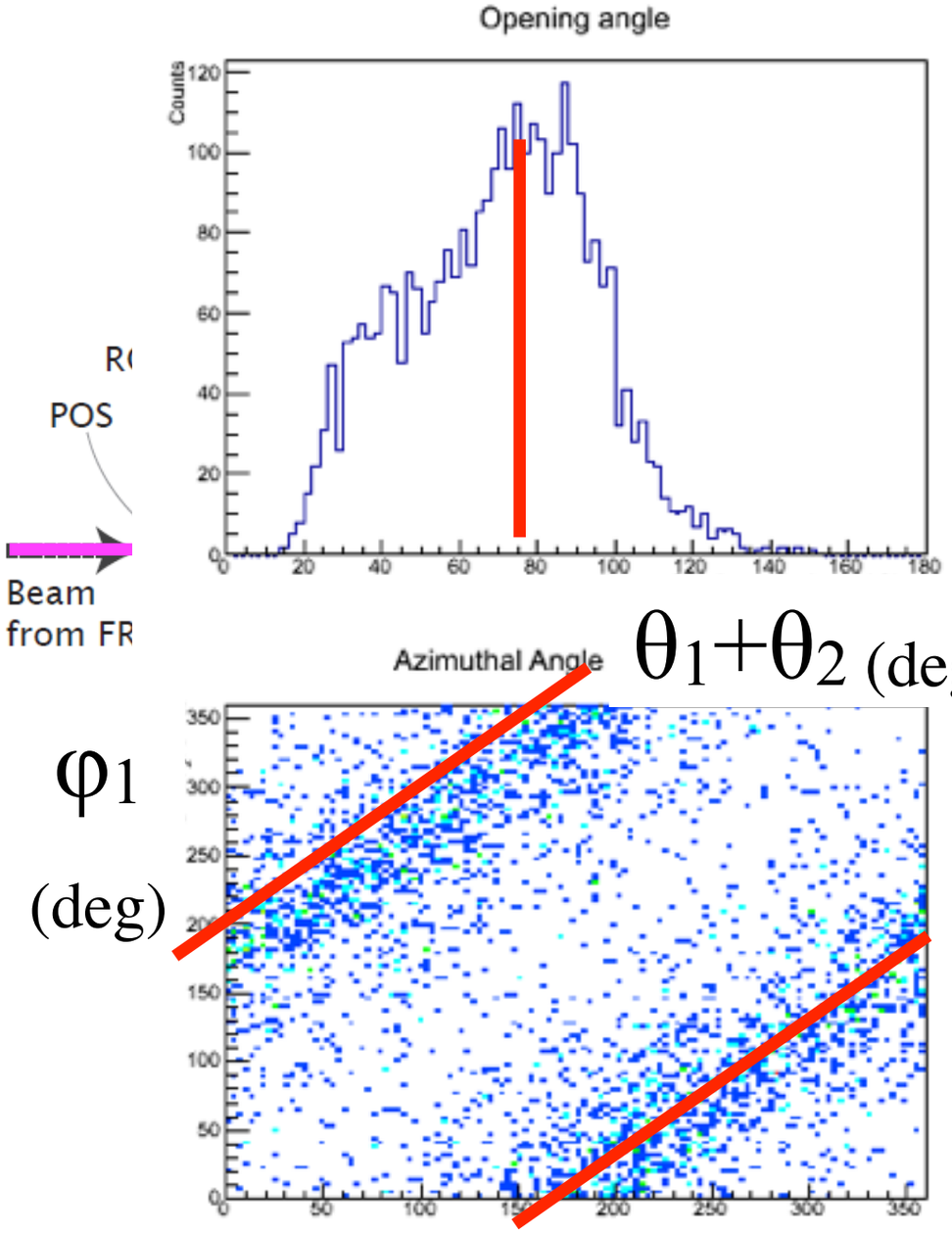
Only **heavy fragment** detection



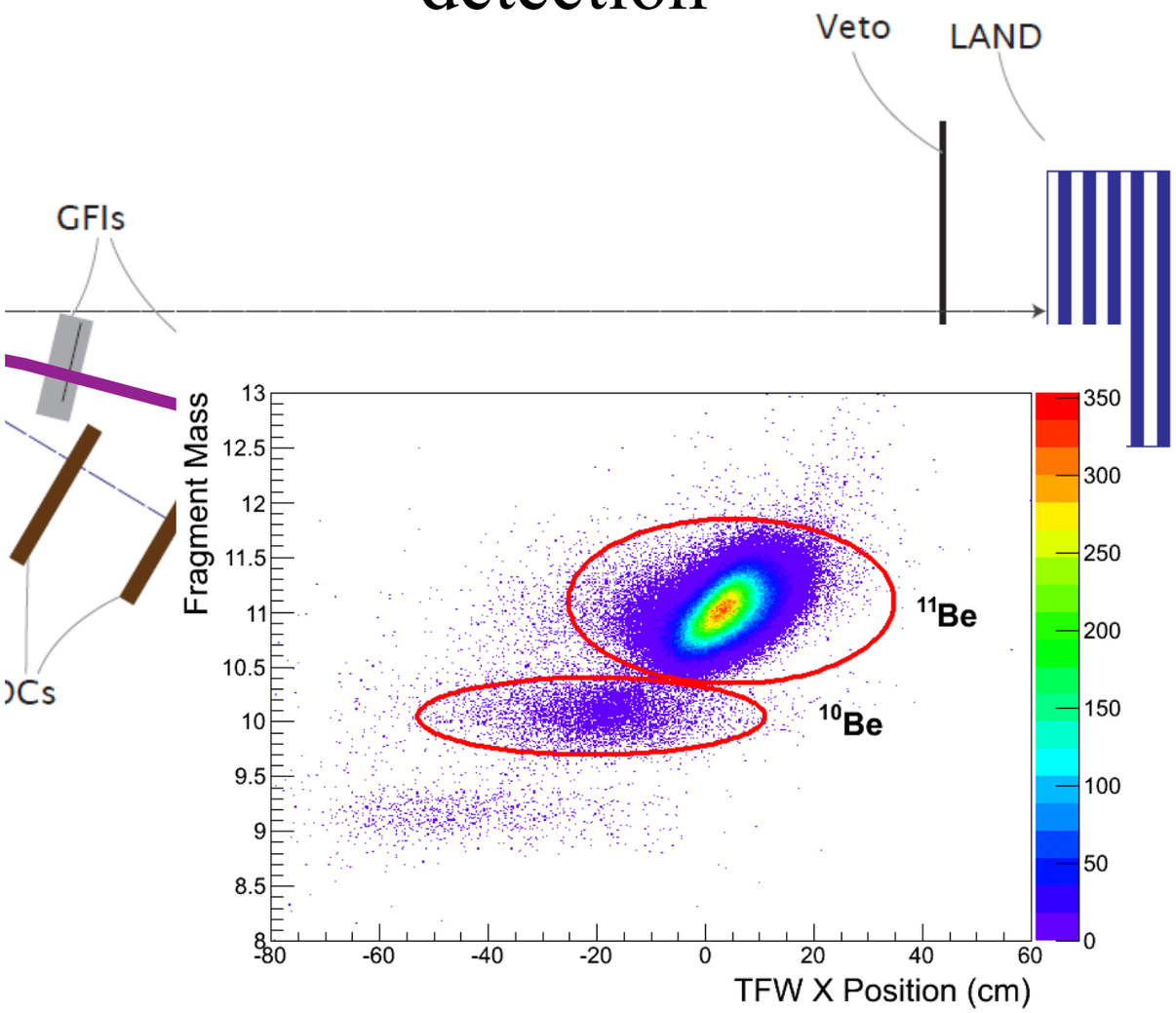



# LAND / R³B Setup

## **Particle Exclusive** knock-out reaction



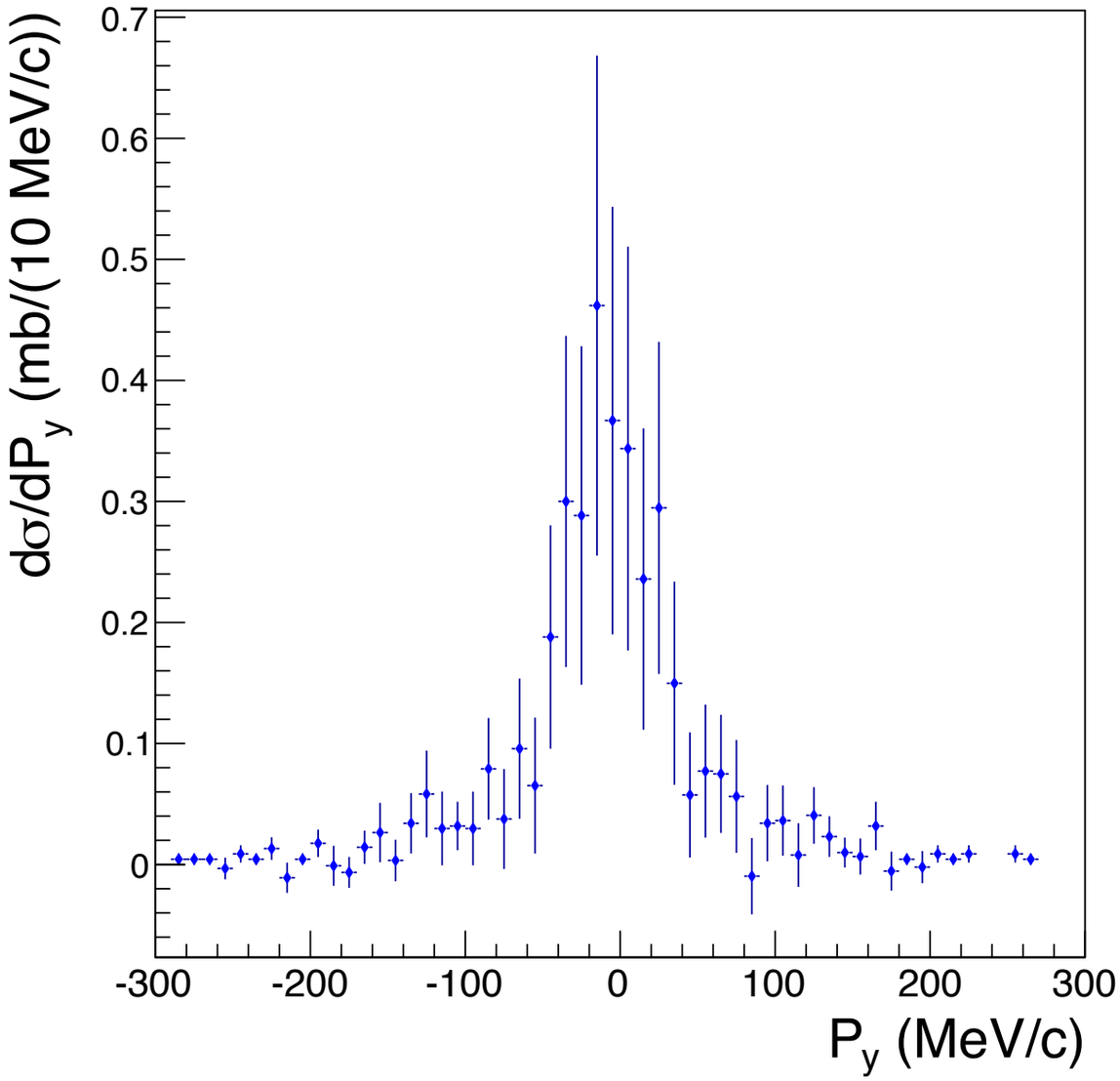

**Heavy fragment** + **p** + **n**
detection



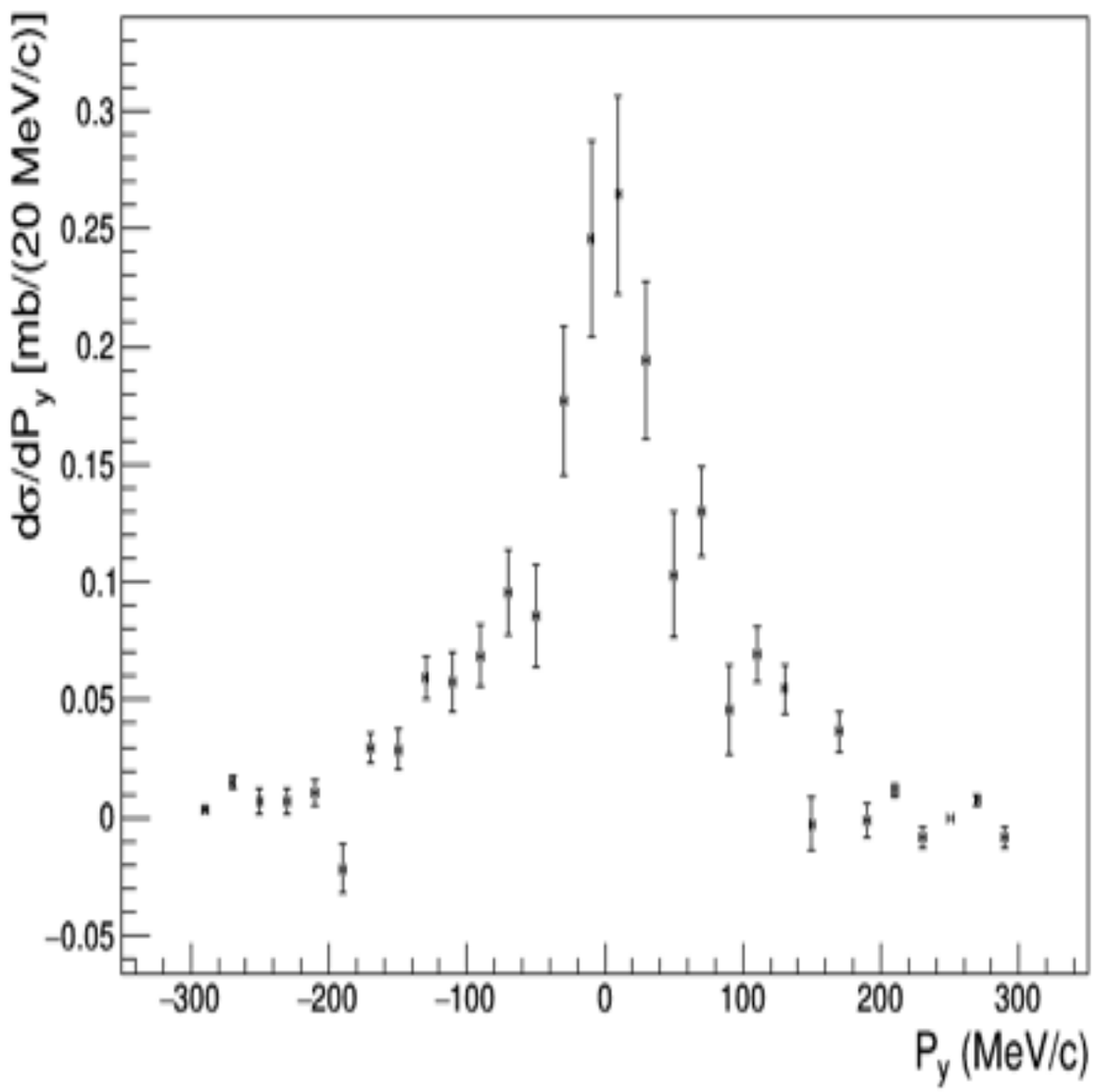
# Momentum distributions

## **Particle Exclusive** knock-out reaction

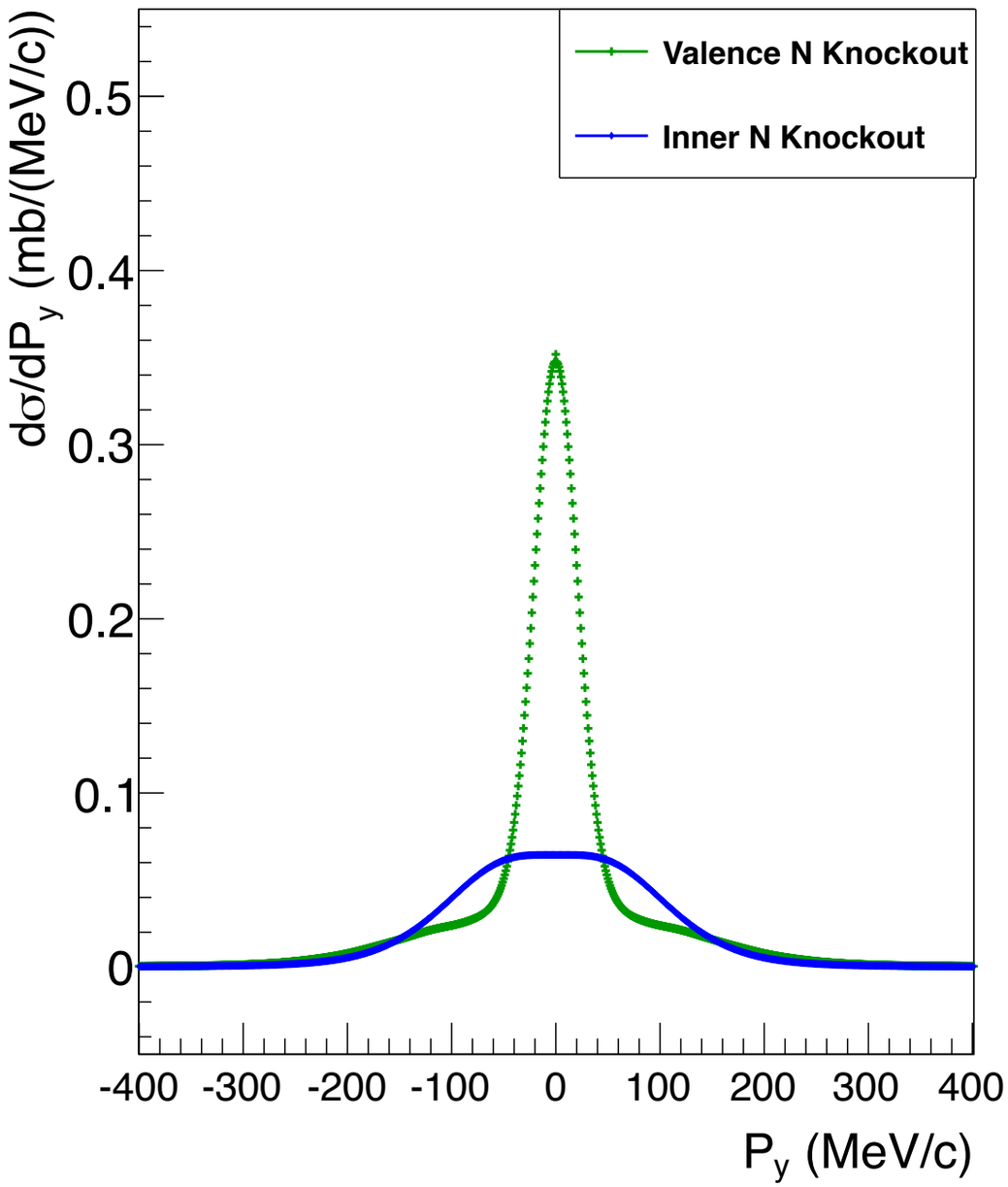
### $^{11}$Be




### $^{15}$C



# Momentum distributions




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

Allows the evaluation of different knock-out contributions

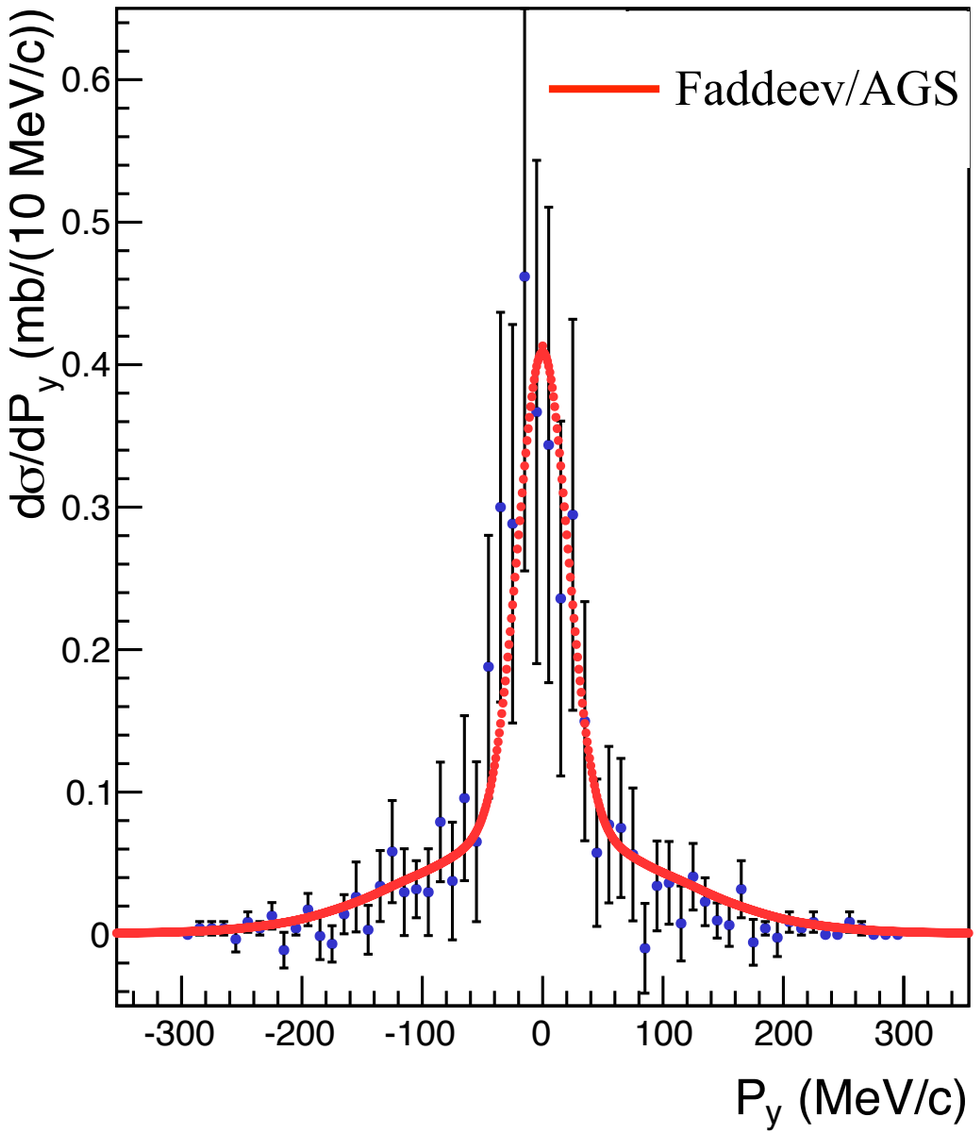
$$\sigma_{total} = a\ \sigma_{valence} + b\ \sigma_{inner}$$

The different **weights** are obtained via minimization of the reduced $\chi^2$ function.

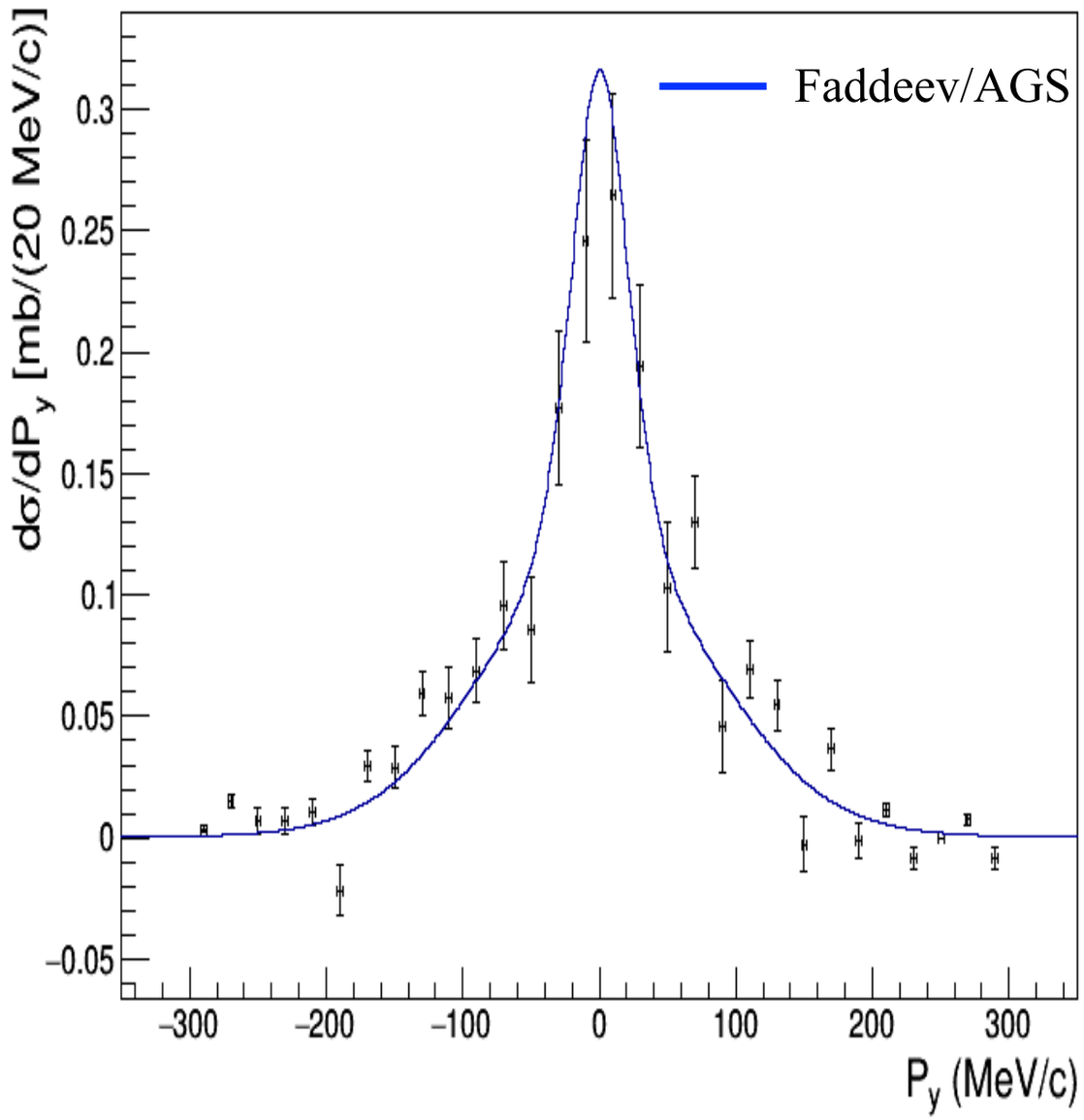
# Momentum distributions

## **Particle Exclusive** knock-out reaction

### $^{11}$Be



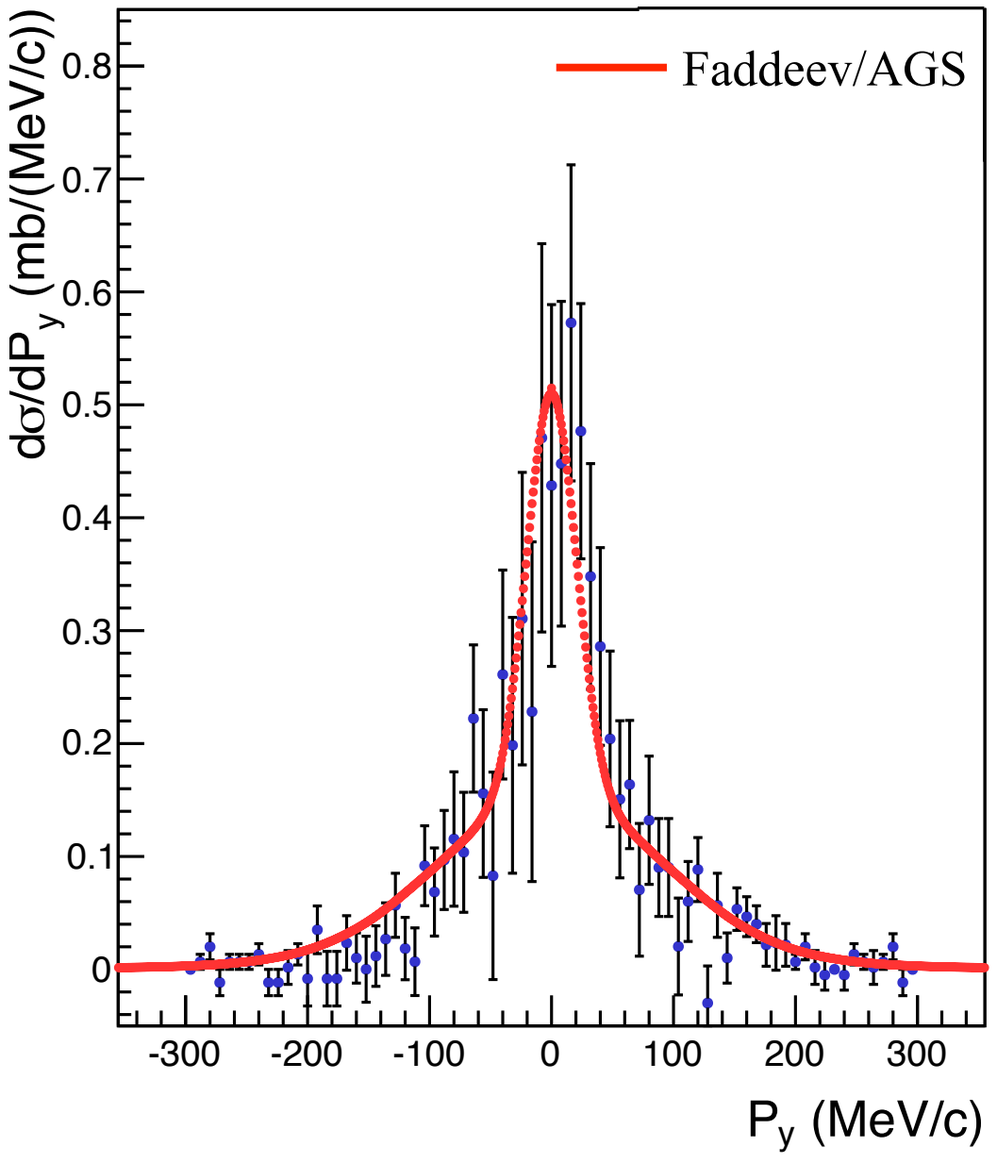

### $^{15}$C



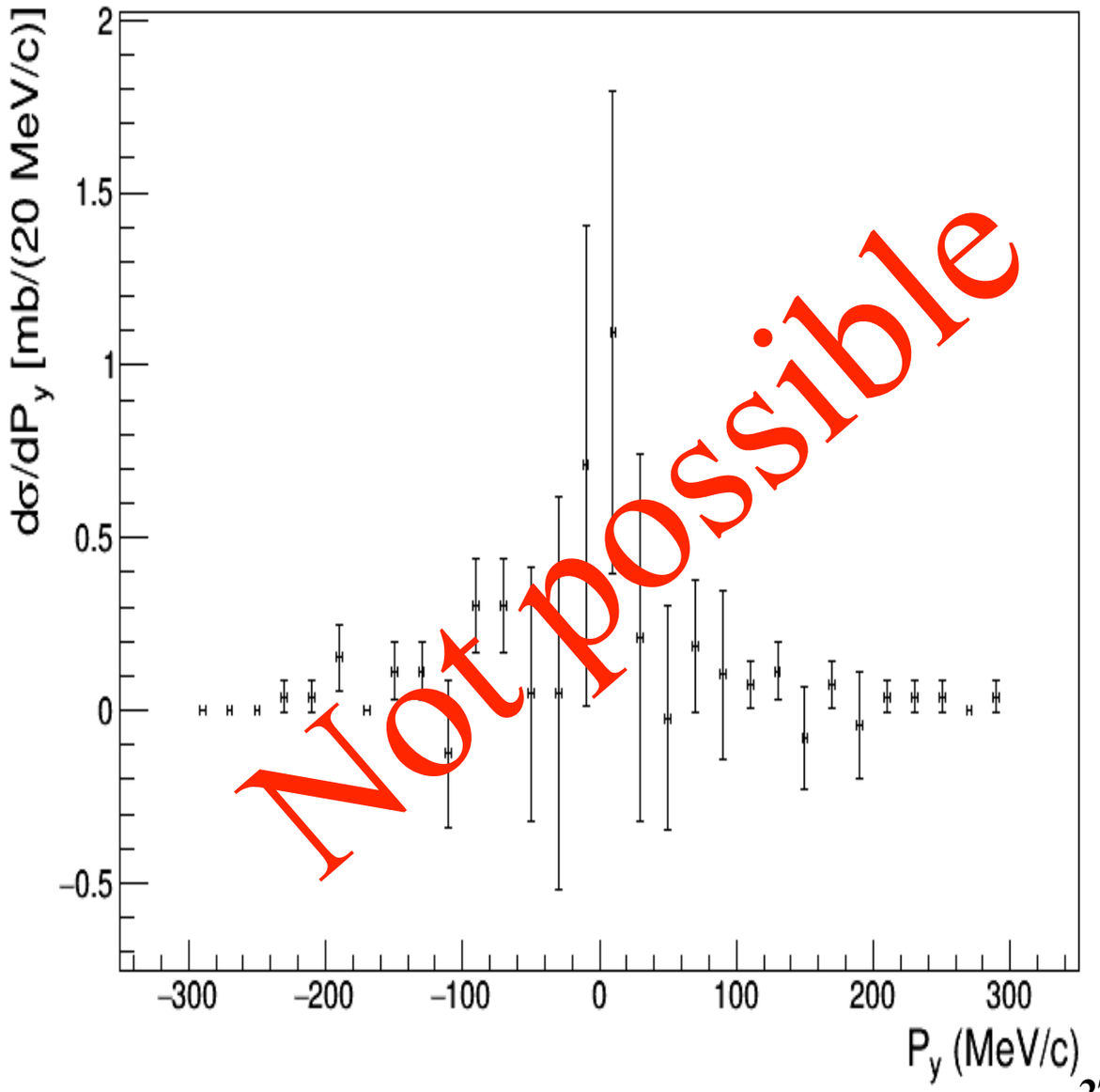
# Momentum distributions

## **Particle Inclusive** knock-out reaction

### $^{11}$Be



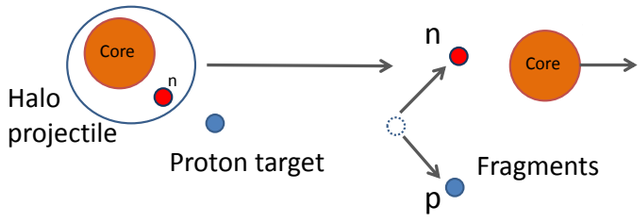

### $^{15}$C



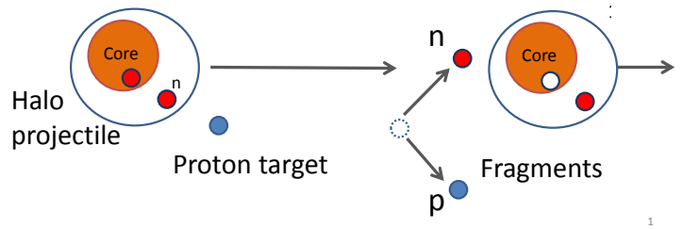
# Knock-out cross sections

| | 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 $\sigma_{inner}$ | 23 mb | — | 7 mb | 18 mb |

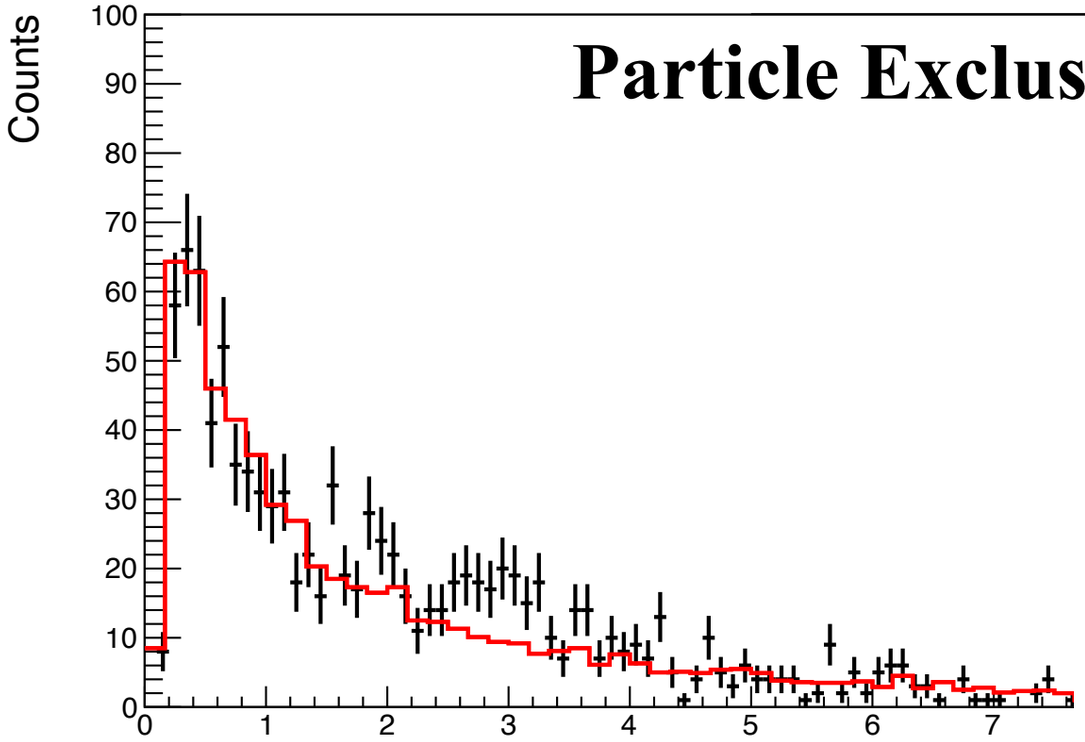
**Valence knock-out**



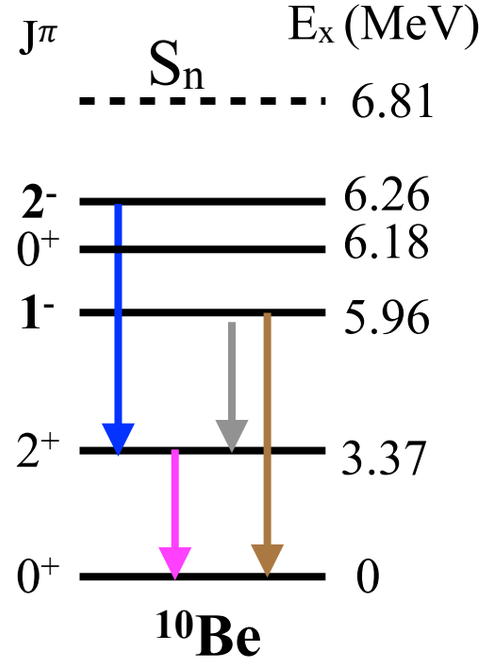

**Inner shell knock-out**

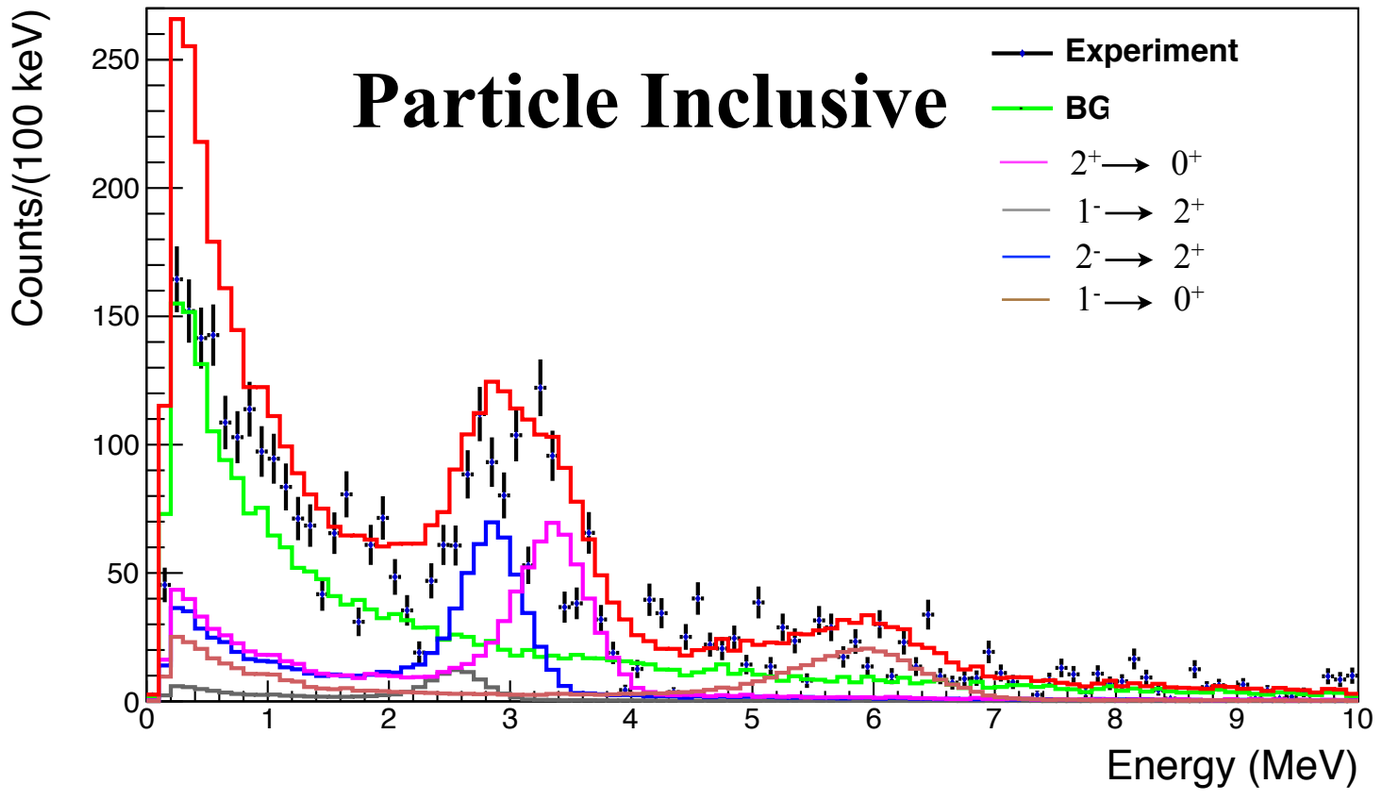


# Photon spectrum with X-Ball

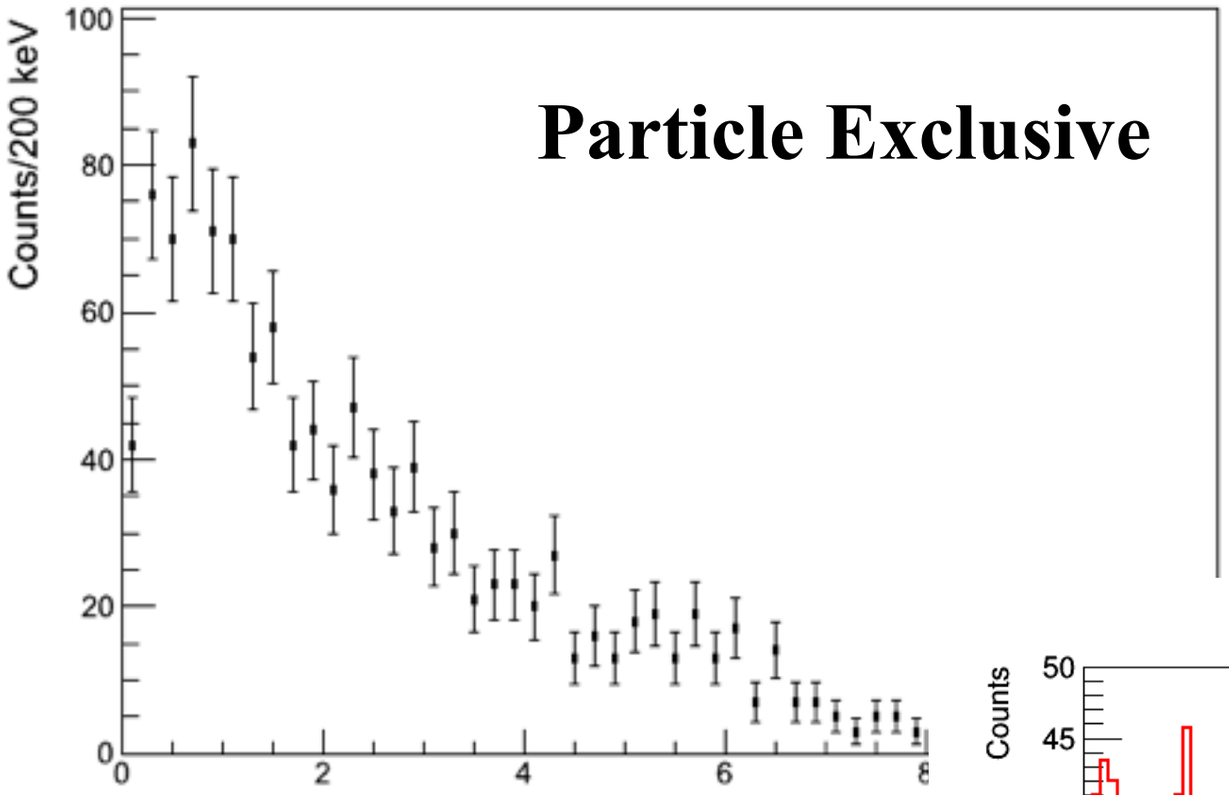



## $^{11}Be(p,pn)^{10}Be$

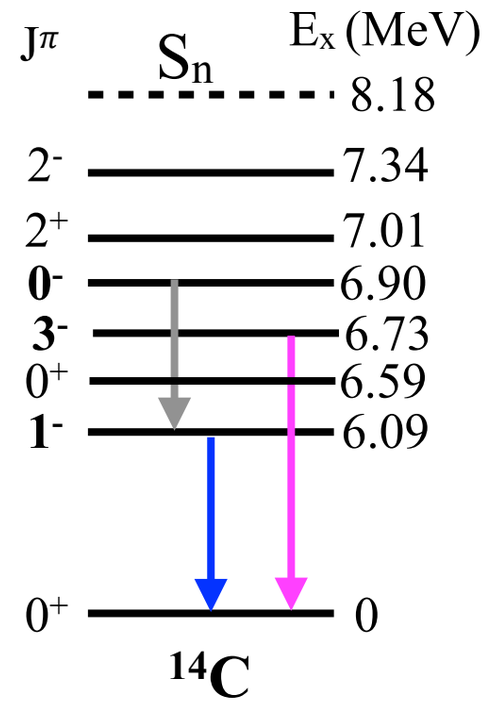


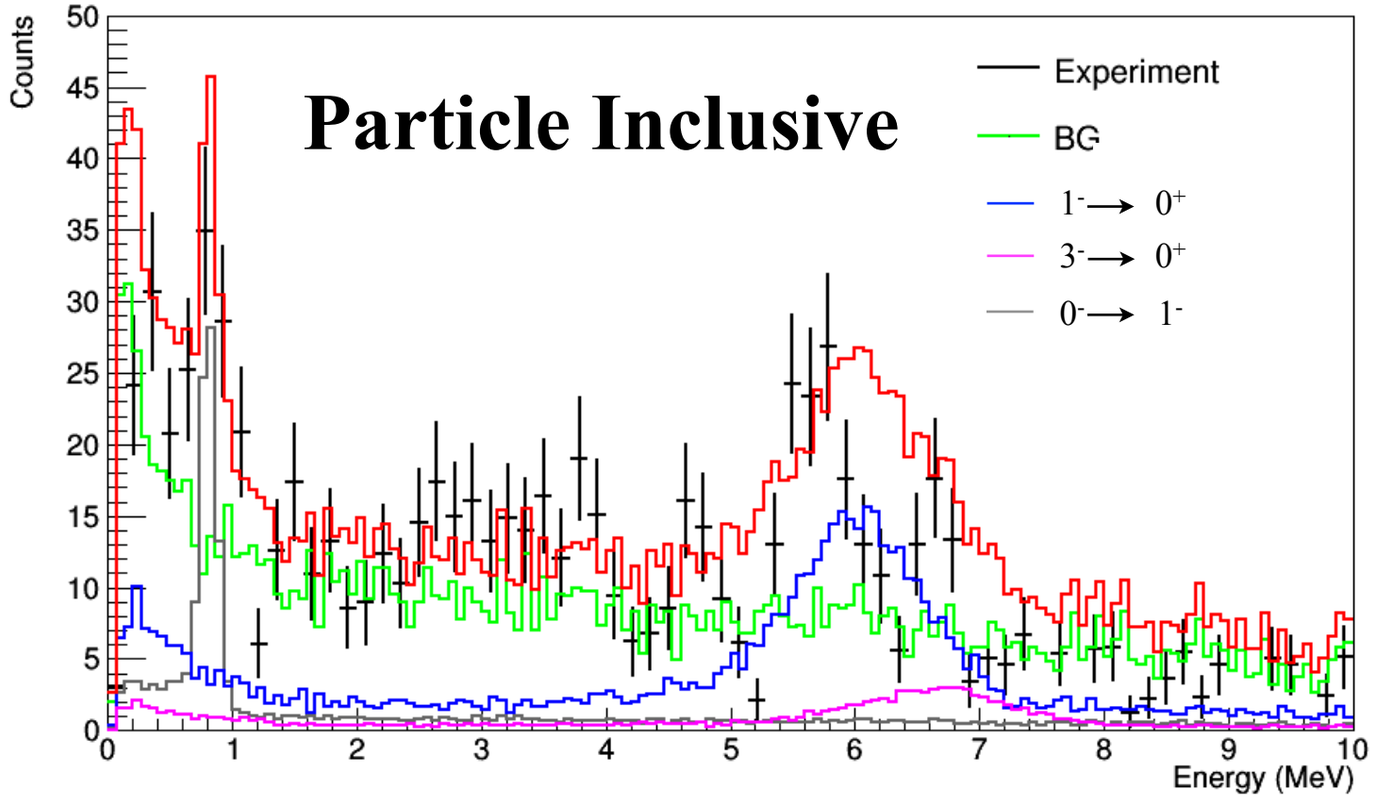



# Photon spectrum with X-Ball




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



# Additional R³B analysis

★ **M. Holl** (TU-Darmstadt): Knock-out studies of neutron-deficient Carbon isotopes

★ **L. Atar** (TU-Darmstadt): Knock-out studies of neutron-rich Oxygen isotopes

★ **P. Díaz** (USC): Knock-out studies of neutron-rich N=14 and N=15 nuclei

★ **J.M. Boillos** (USC): Knock-out studies of neutron-deficient nuclei

# People @ Lisbon


Ana Henriques

Paulo Velho


Pamela Teubig

Elisabet Galiana

D. Galaviz
L. Peralta

Exp.

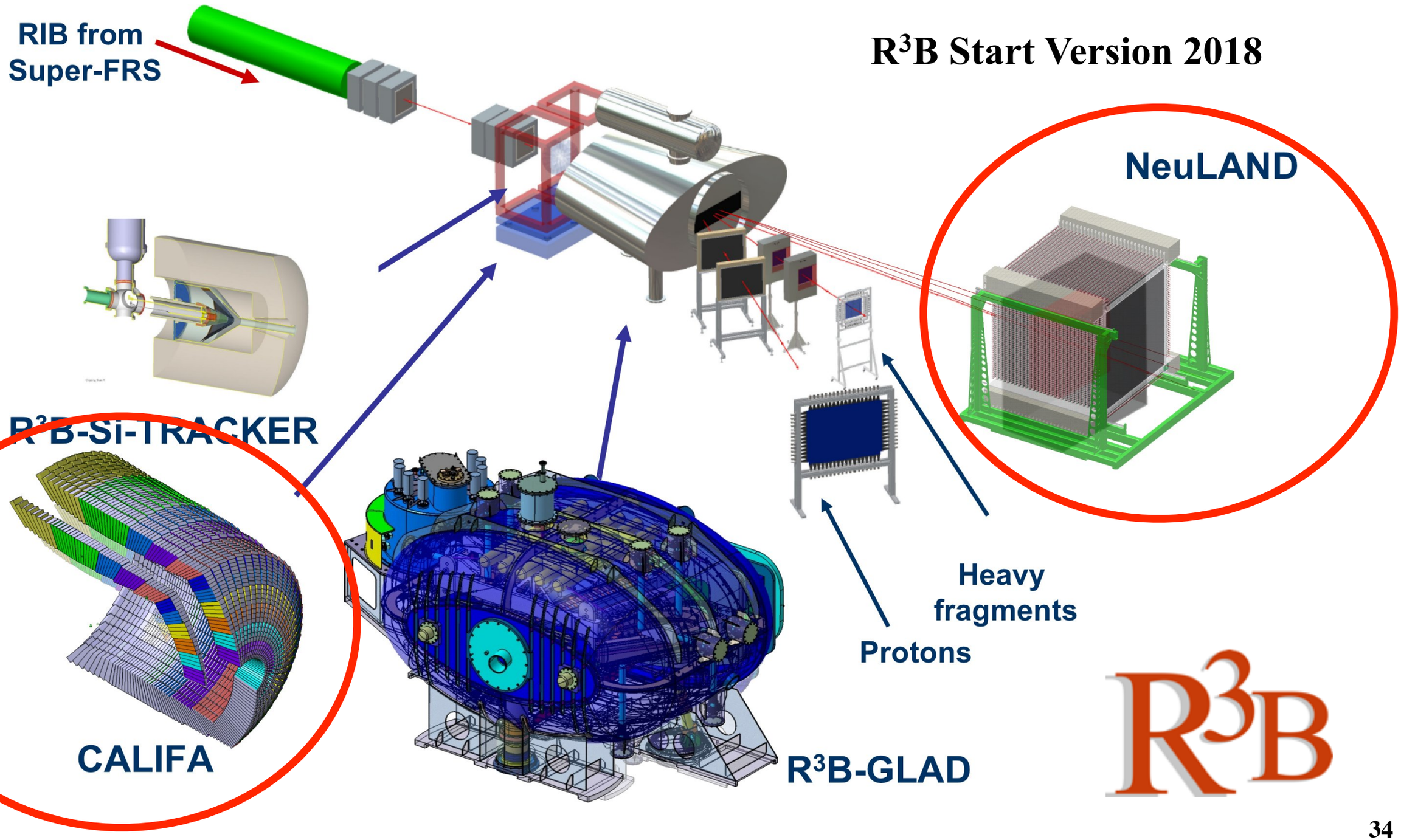
R. Crespo
E. Cravo

Theory

# Start Backup Slides

# Towards Phase-0

## Reactions with Relativistic Radioactive Beams

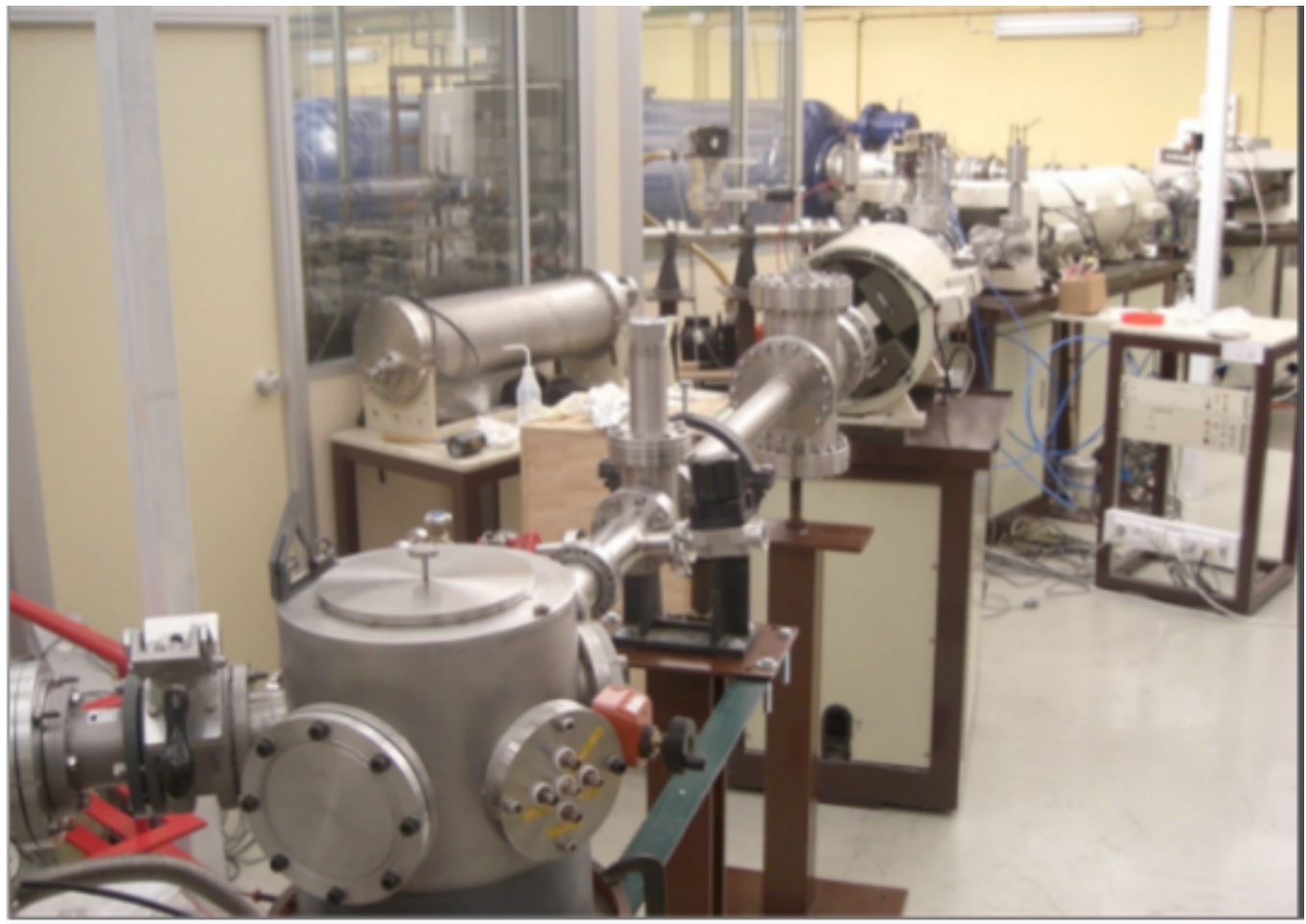


# CALIFA Benchmark @ Lisbon

## PIGE reaction

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

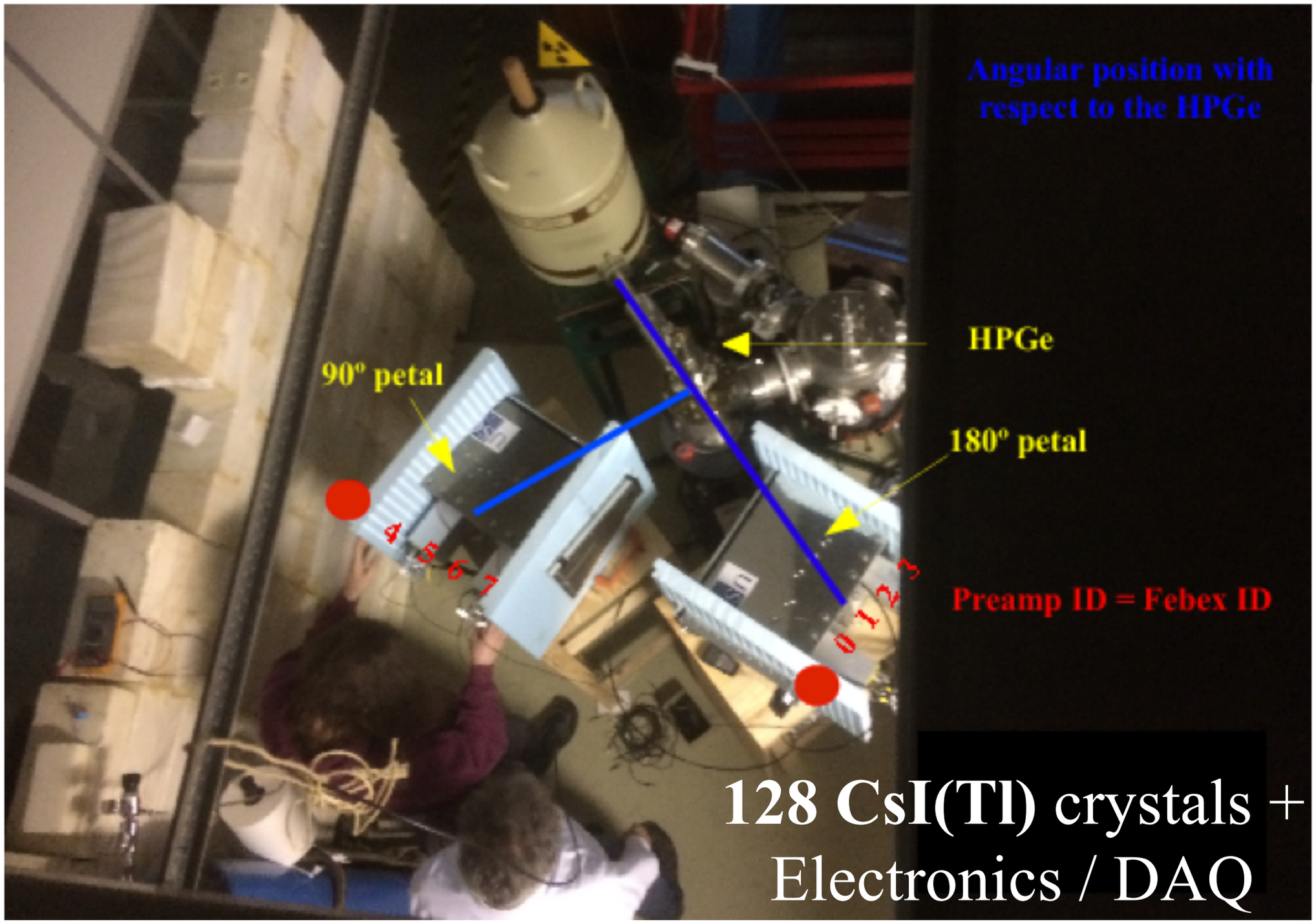
to produce $\gamma > 10$ MeV
to challenge **CALIFA prototype**



Nuclear reaction line @ tandem accelerator at LATR-CTN

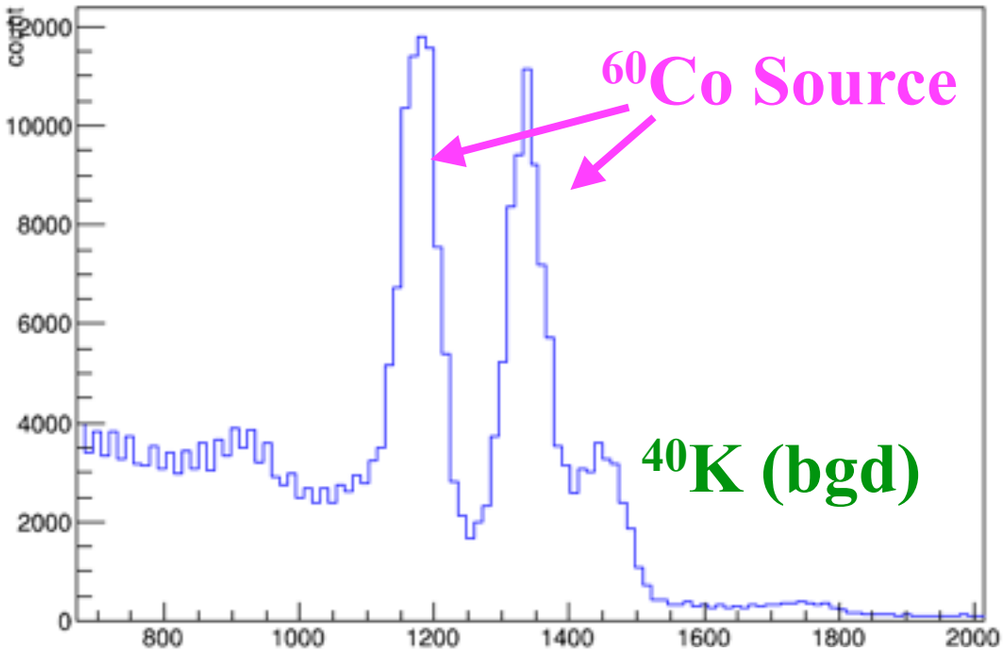
More Information under
http://www.ctn.tecnico.ulisboa.pt

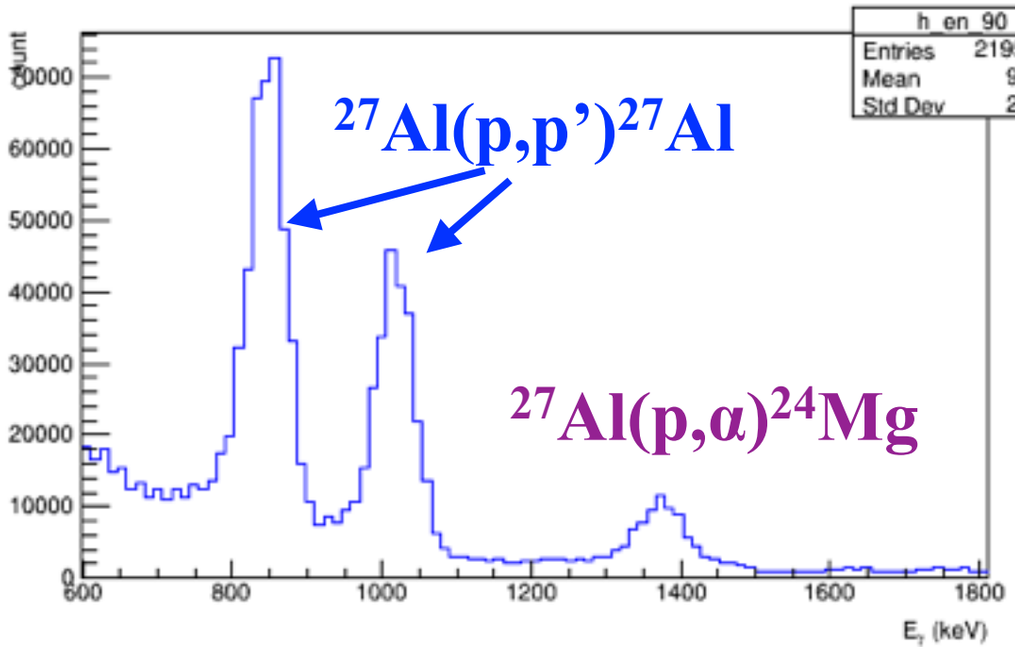
# CALIFA Benchmark @ Lisbon

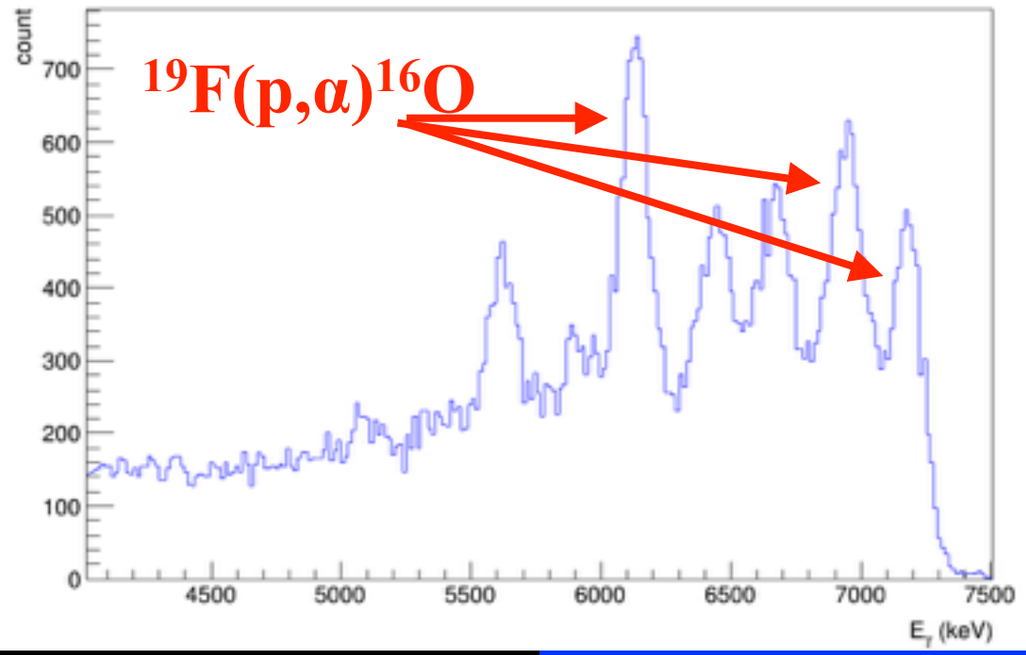


# CALIFA Benchmark @ Lisbon

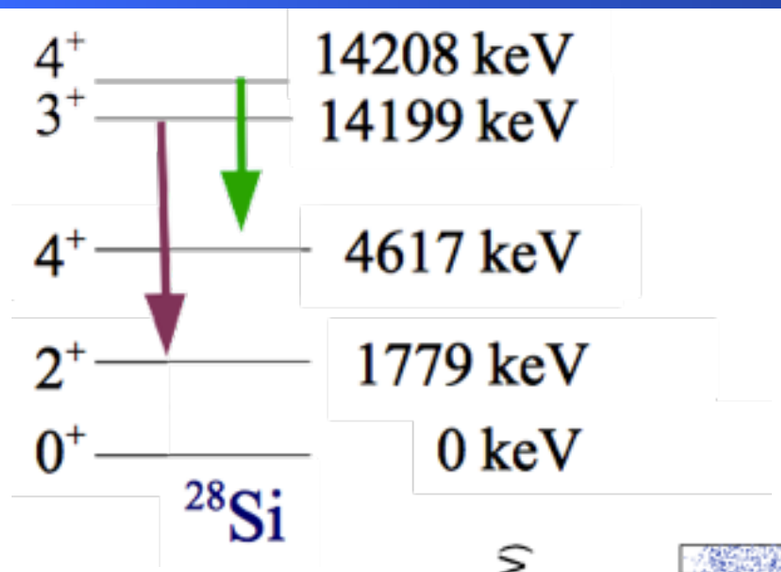
## Individual Crystal response



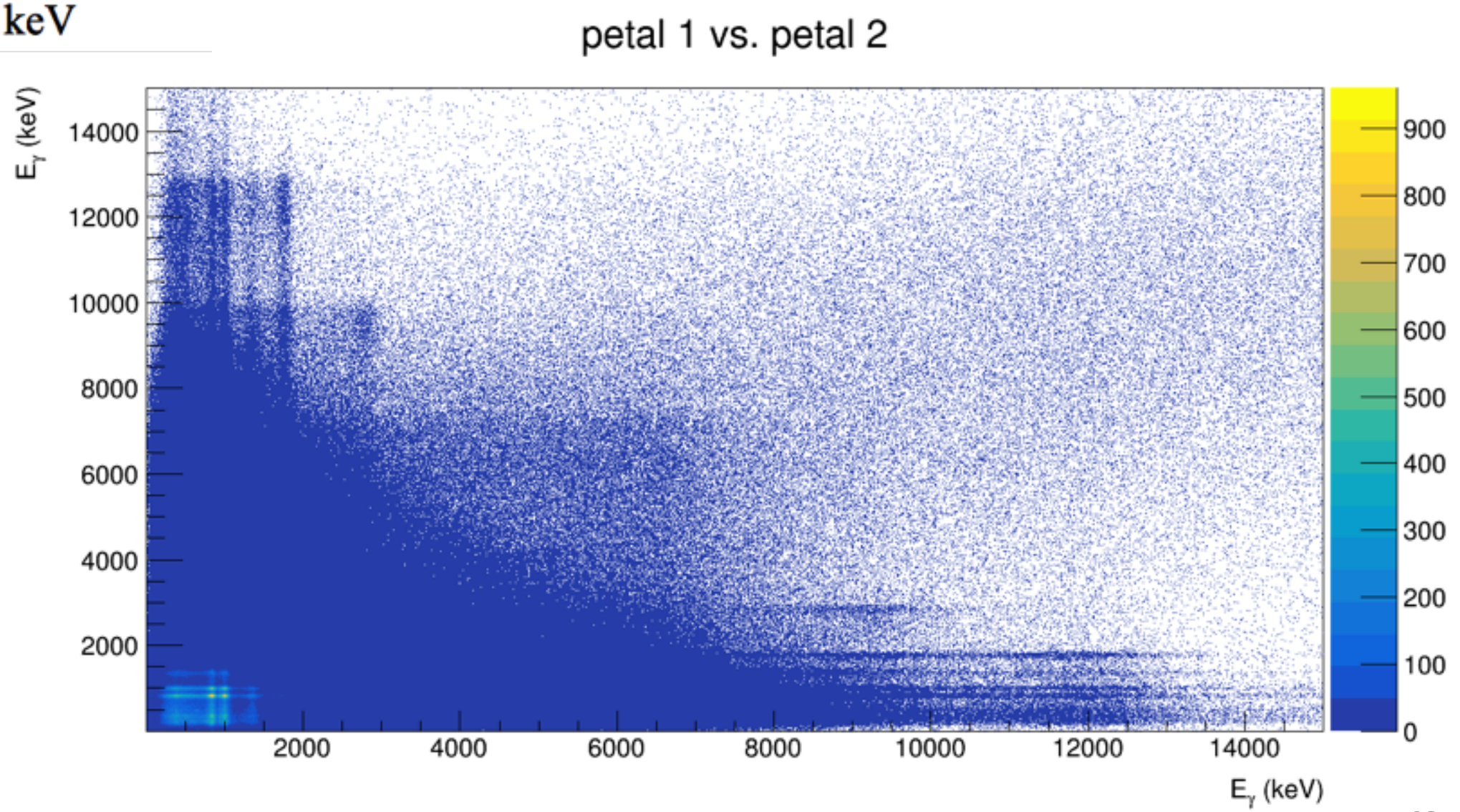



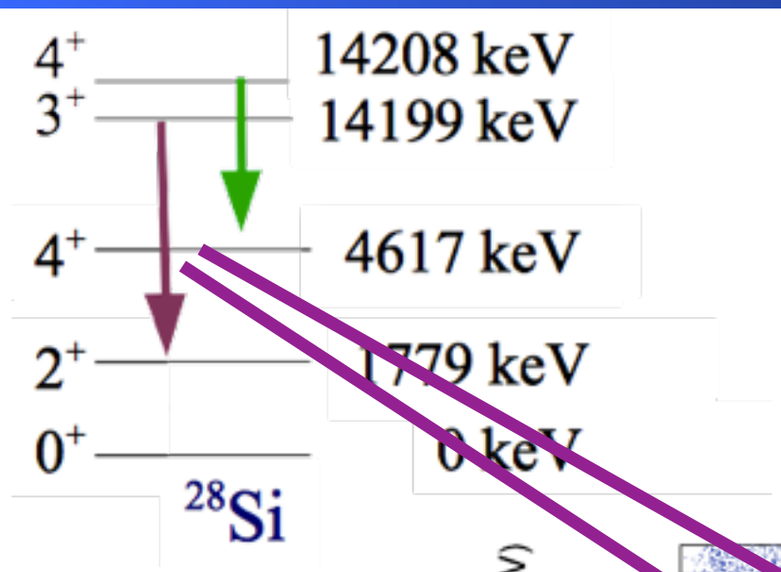
# CALIFA Benchmark @ Lisbon



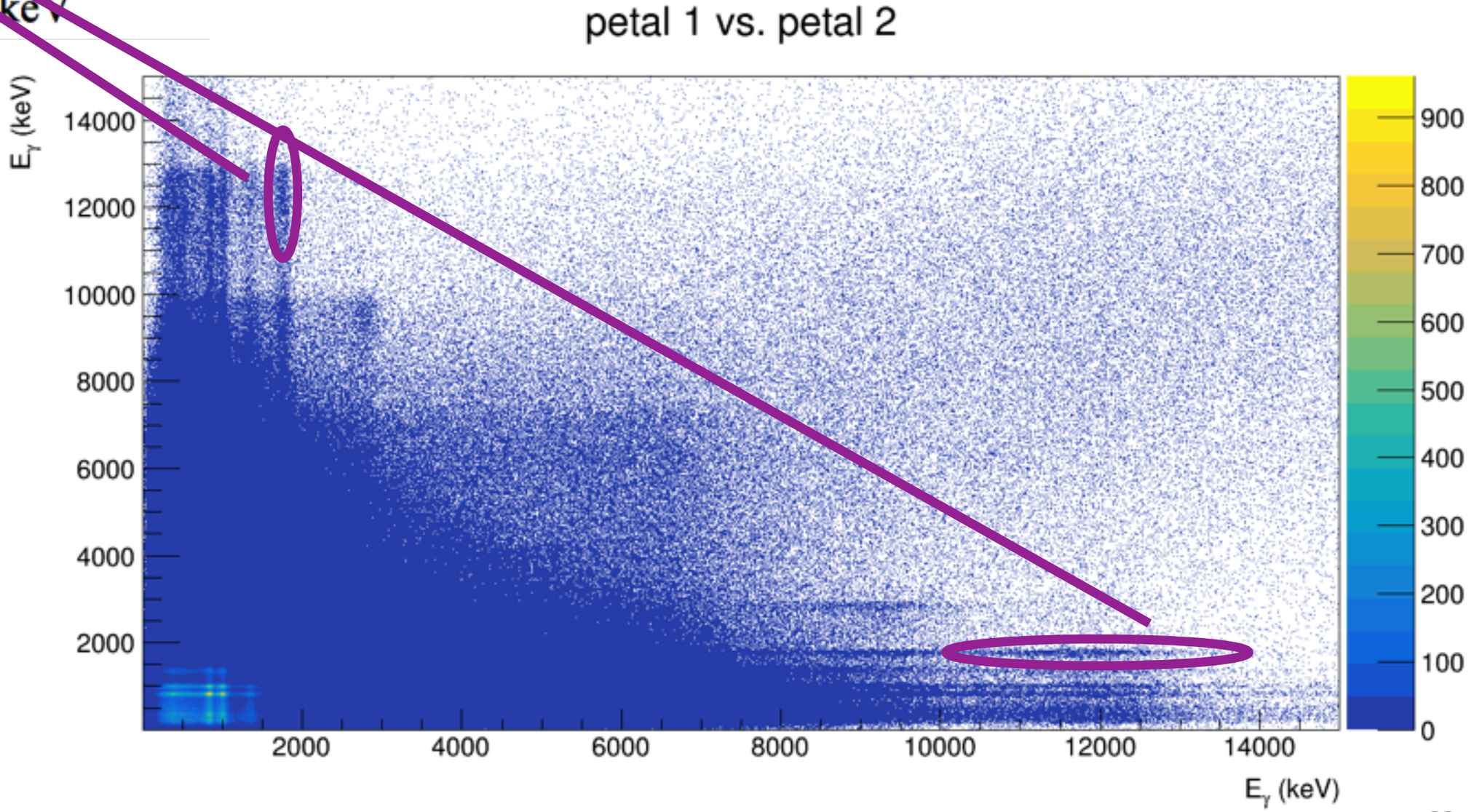

Populating the **14199 & 14208 keV** resonances of $^{28}$Si



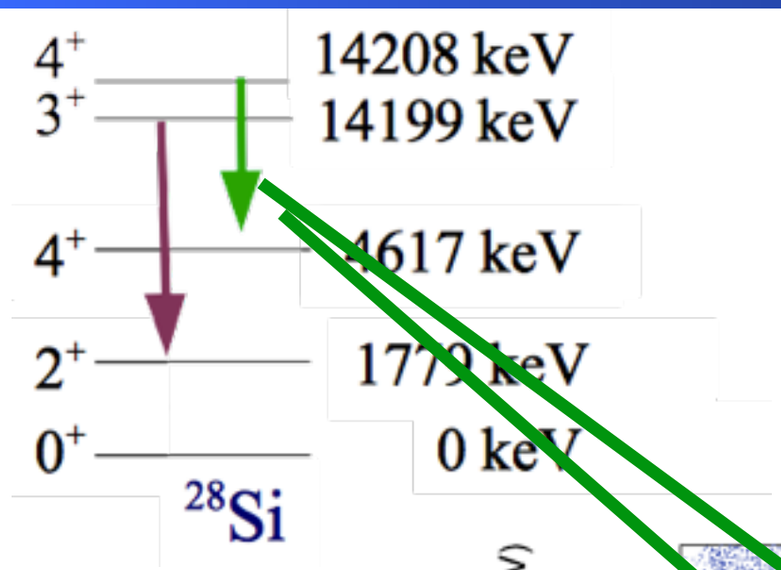
# CALIFA Benchmark @ Lisbon



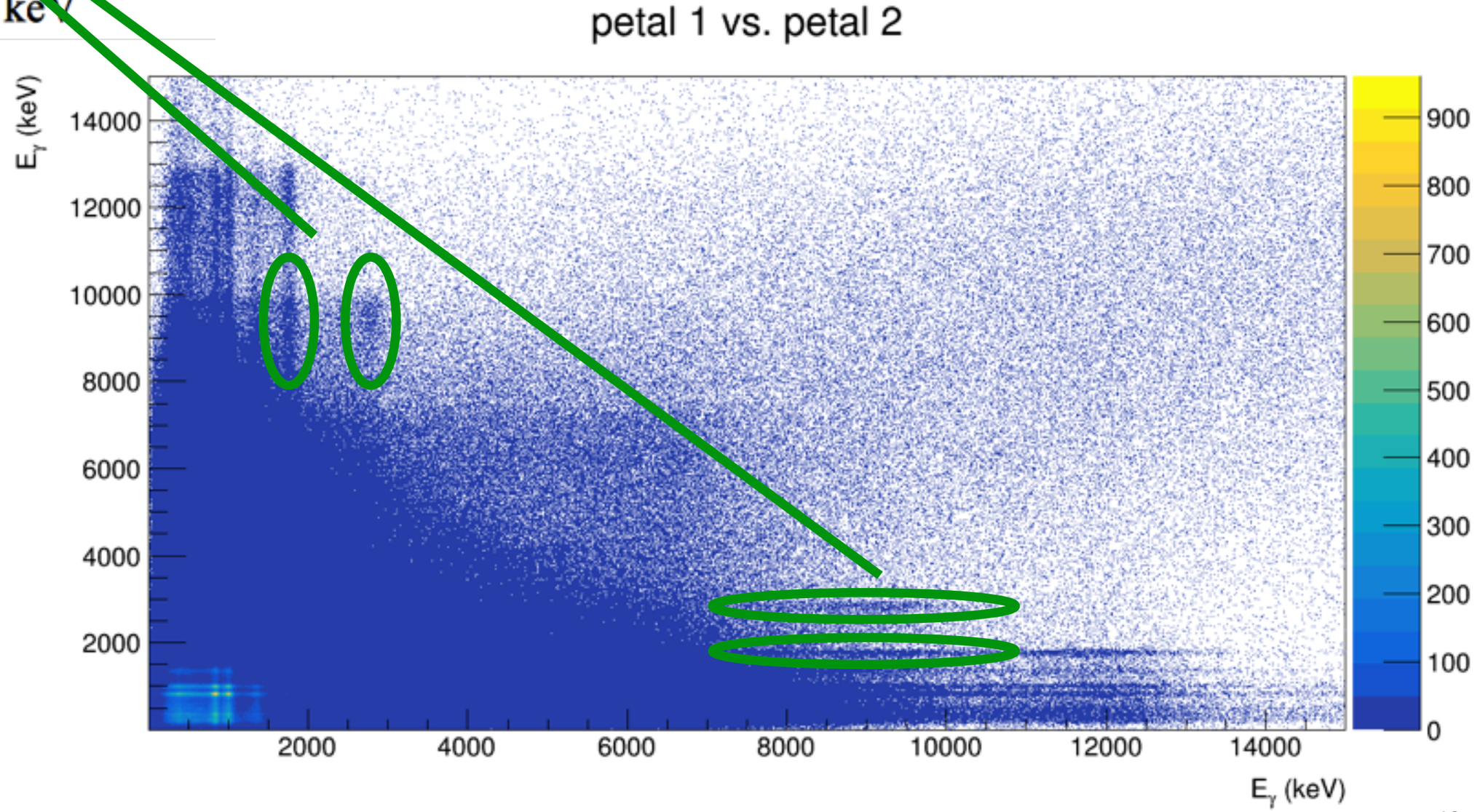

Populating the **14199 & 14208 keV** resonances of $^{28}$Si



# CALIFA Benchmark @ Lisbon




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



# Summary

- Use of **Faddeev/AGS** formalism to study **knock-out** reactions

- Application to halo nuclei: **$^{11}$Be** & **$^{15}$C**

- Extraction of **exclusive** and **inclusive** knock-out cross sections

- Benchmark of **CALIFA** prototypes with **high-energy photons**