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A. Drouart<sup>1</sup>, T. Huang<sup>2</sup>, T.L. Khoo<sup>2</sup>, F.G. Kondev<sup>2</sup>, W. Korten<sup>1</sup>, T. Lauritsen<sup>2</sup>,  
D.H. Potterveld<sup>2</sup>, G. Savard<sup>2</sup>, M. Siciliano<sup>1</sup>, Ch. Theisen<sup>1</sup>, M. Vandebrouck<sup>1</sup>, M. Zielinska<sup>1</sup>

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## Journée P2IO

Online, Nov. 27<sup>th</sup> 2020



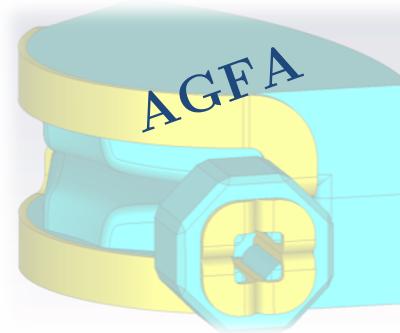
Towards the heavy and superheavy elements:  
MultiNucleon Transfer experiment  
with AGFA/Gammasphere at Argonne  
and status of SIRIUS at S<sup>3</sup>



# Content

## 1. Heavy and Superheavy elements

- Physics motivations



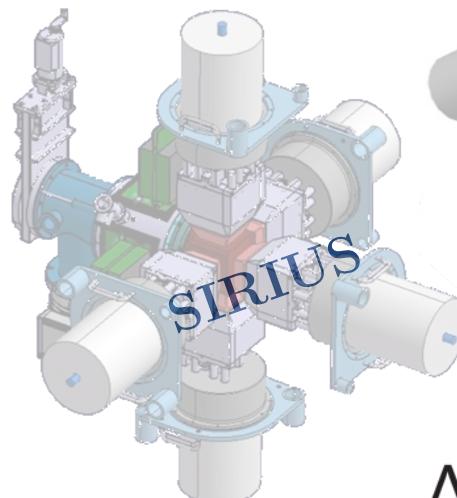
## 2. MNT experiment @ATLAS/Argonne

- Optical simulations
- Accepted experiment – proposal #1786
- Data analysis and outlooks



## 3. Status of SIRIUS @S3/GANIL

- $S^3$  in the SPIRAL2 project
- SIRIUS at the focal plane of  $S^3$
- SIRIUS test bench at CEA/IRFU



# Physics objectives: SHE

Superheavy nuclei?  
Island of stability?

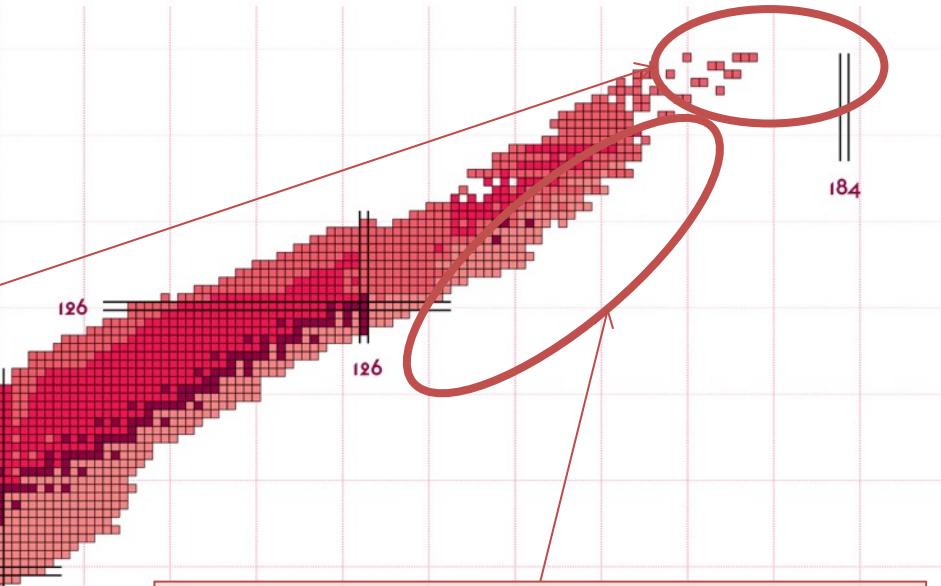
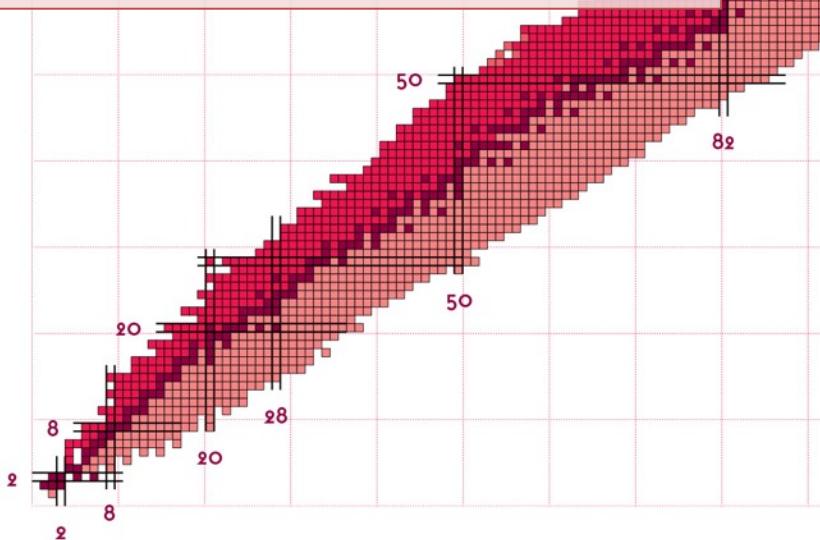
↑ protons

CARTE DES NOYAUX  
Noyaux radioactifs  
Noyaux stables

## Limits of the fusion-evaporation method

- Superheavy nuclei up to Z=118
- GSI, Dubna, RIKEN: Z = 119 or 120?
- Very low cross-sections
- Limited due to beam-target combination

## New detectors -> S<sup>3</sup>/SIRIUS



## MultiNucleon Transfer (MNT) reactions

- Heavy and superheavy nuclei?
- More neutron-rich nuclei
- Higher production cross-section?
- Not limited to beam-target combination

## New reaction mechanisms -> MNT

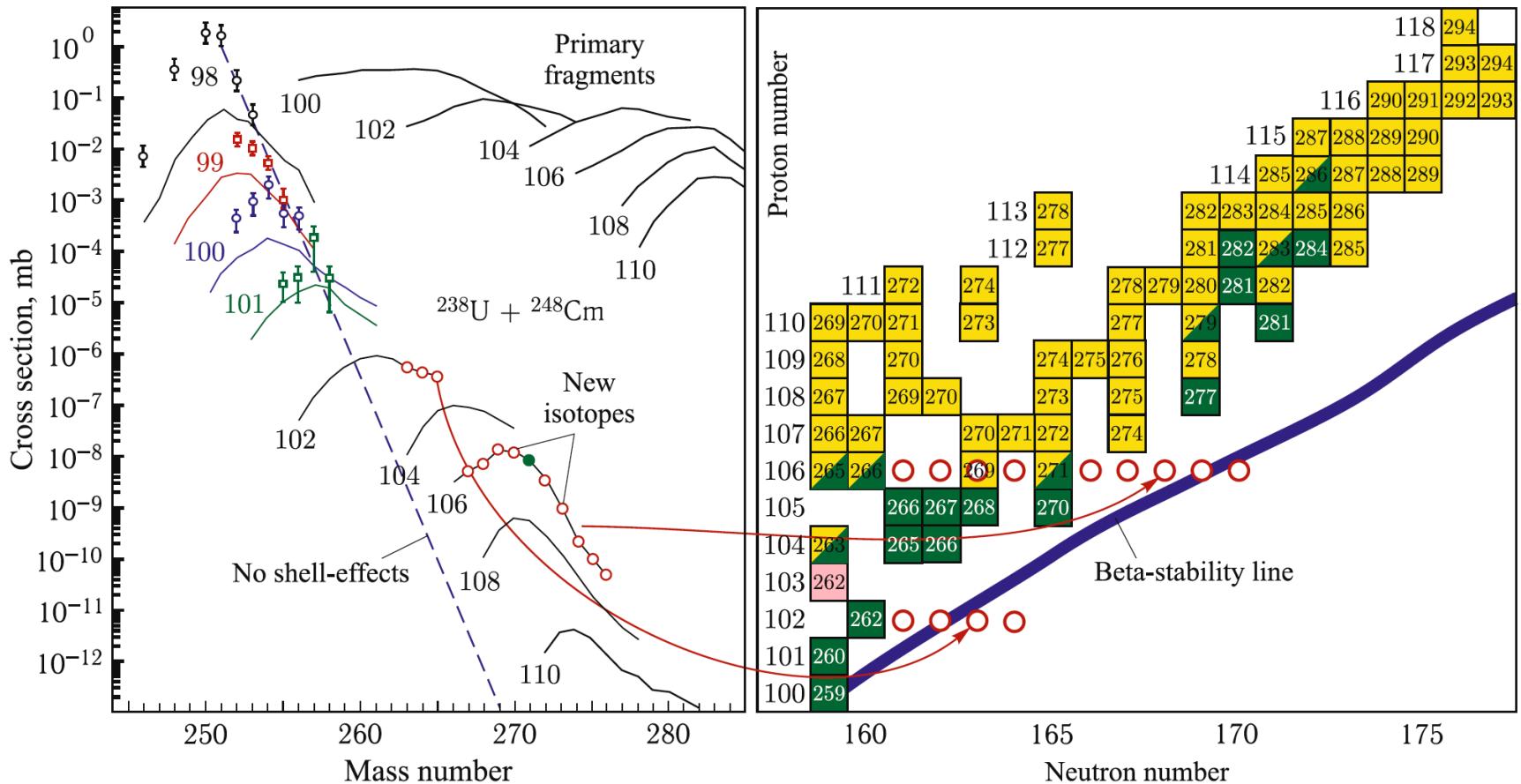
(Carte issue de l'Edition n°13 - juin 2020)



Production of heavy and superheavy elements

# Transfer reaction studies

Production of transfermium nuclei  
along the line of stability looks quite possible

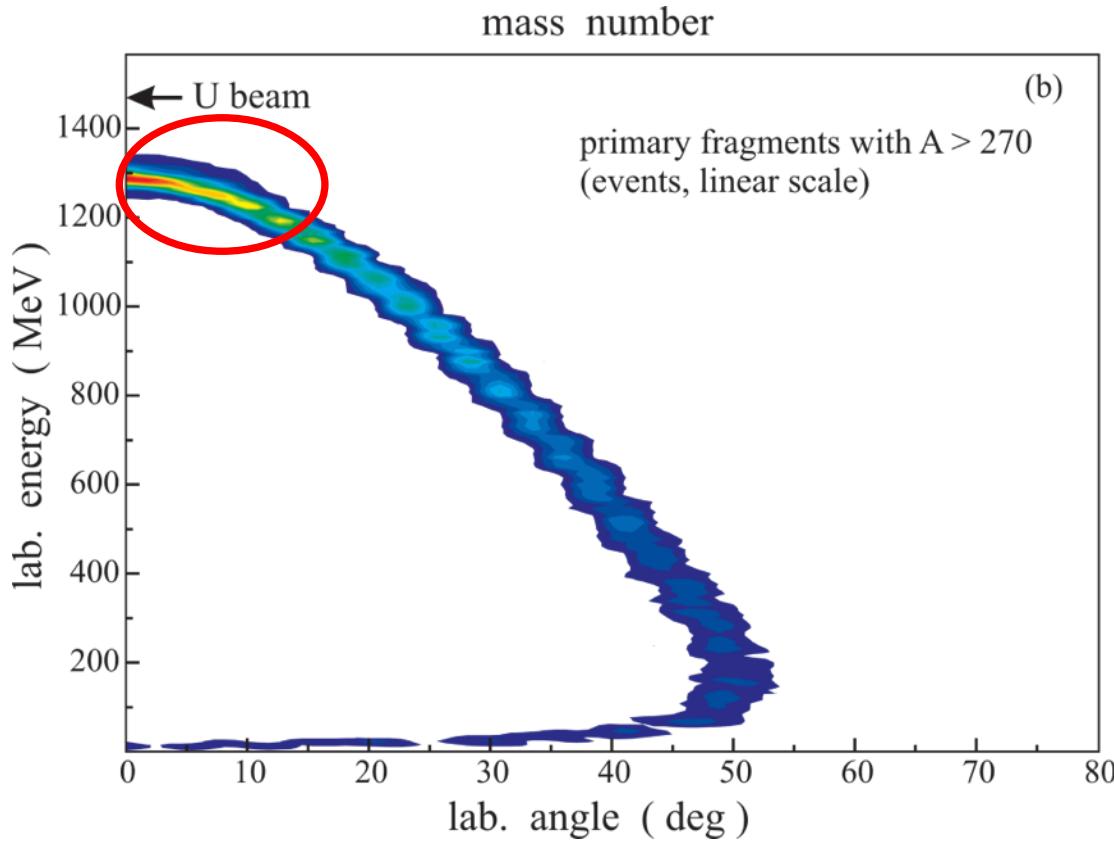


Rather wide angular distribution of reaction fragments:  
separators of a new kind are needed!



# Deep-inelastic studies at zero degree

V.I. Zagrebaev and W. Greiner, PRC 83 (2011) 044618



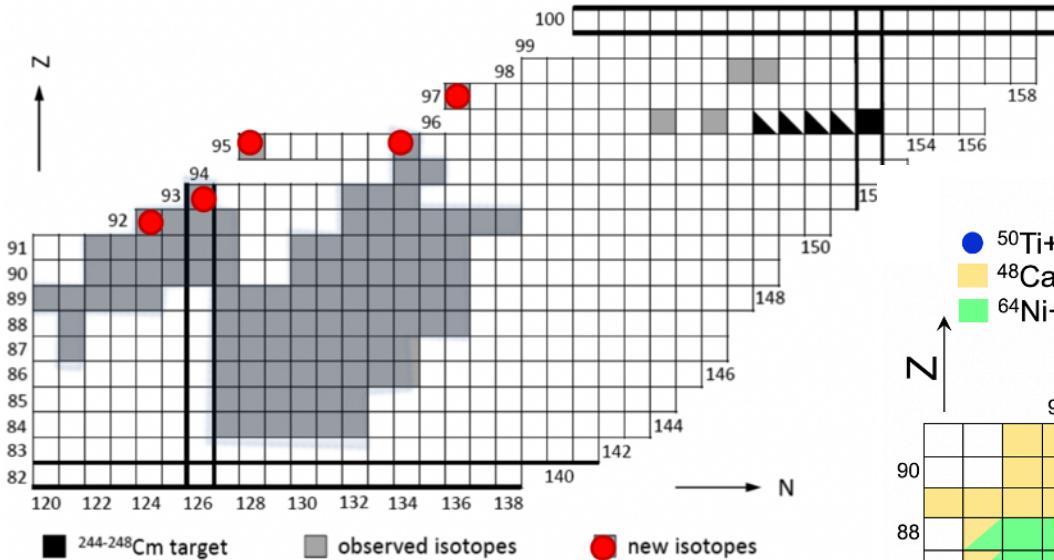
The angular distribution  
of the superheavy nuclei  
reveals grazing feature  
but is also **forward directed**.

Energy-angular distribution of primary heavy fragments ( $A > 270$ ) in the laboratory system.



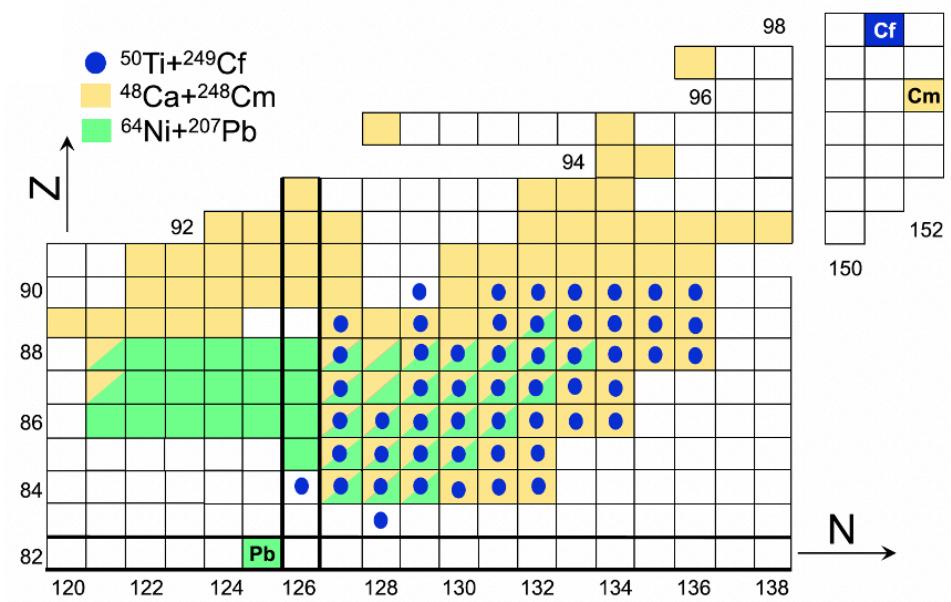
# Towards superheavy elements (MNT)

$^{48}\text{Ca} + ^{248}\text{Cm}$  @ (5.3 MeV/n)  
At SHIP (GSI) 0° spectrometer



S. Heinz, et al. Eur. Phys. J. A (2016) 52: 278

$^{50}\text{Ti} + ^{249}\text{Cf}$  @ (6.1 MeV/n)  
At TASCA (GSI) 0° spectrometer

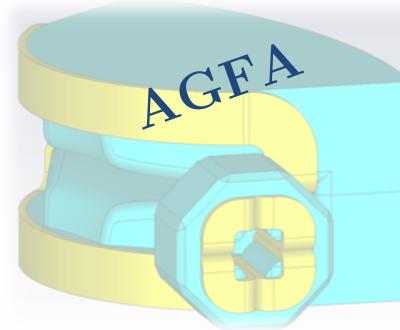


A. Di Nitto, et al. PLB 784 (2018) 199–205

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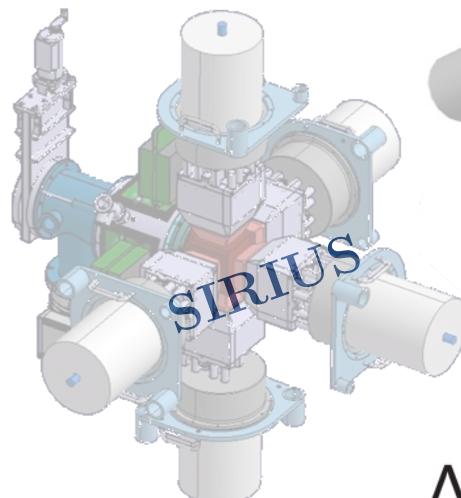
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- Optical simulations
- Accepted experiment – proposal #1786
- Data analysis and outlooks



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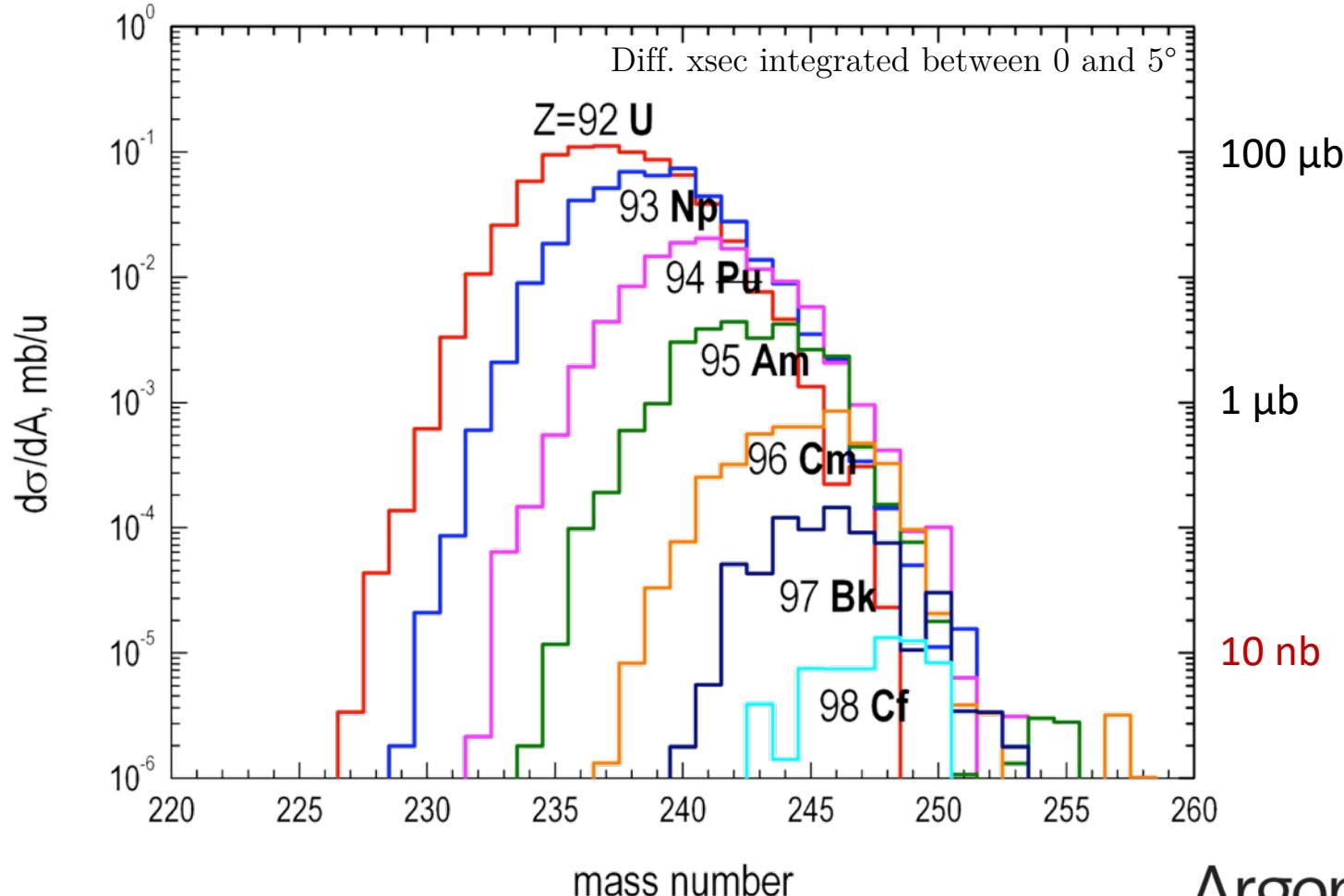
- $S^3$  in the SPIRAL2 project
- SIRIUS at the focal plane of  $S^3$
- SIRIUS test bench at CEA/Irfu



# Theoretical calculations: $^{136}\text{Xe} + ^{238}\text{U}$

A. Karpov and V.V. Saiko, Phys. Rev. C 96, 024618 (2017): **LANGEVIN MODEL SIMULATION**

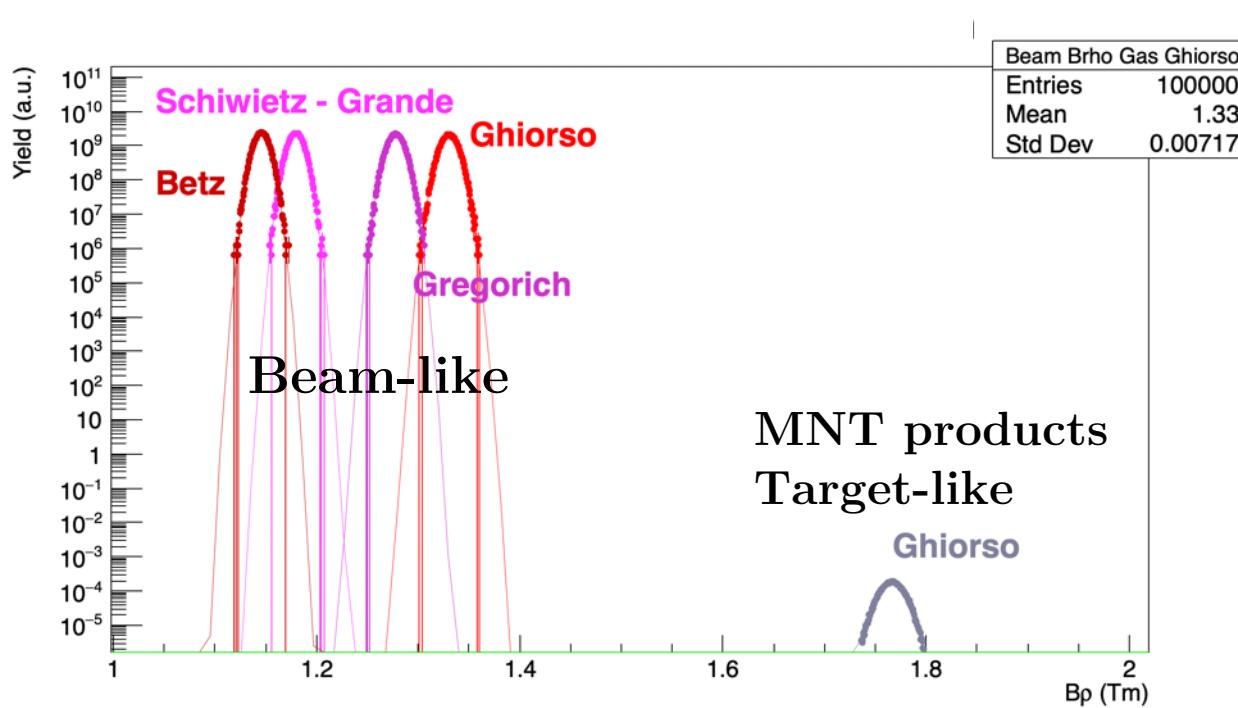
$^{136}\text{Xe} + ^{238}\text{U}$  @  $E_{\text{cm}} \sim 490$  MeV i.e.  $E_{\text{lab}} \sim 5.67$  MeV/n around  $0^\circ$



# First basics simulations

(Using Vamos gas-filled code by Ch. Theisen)

136Xe + 238U @3.7MeV/n around 0°



Reaction kinematics calculations:

$B\rho$  distribution of the beam and of the produced  $^{246}\text{Cm}$  nuclei.

Beam intensity: 20 pnA  
GS efficiency: 15% at 200 keV  
AGFA efficiency: 50%  
DSSD efficiency: 50% ( $\alpha$ ).

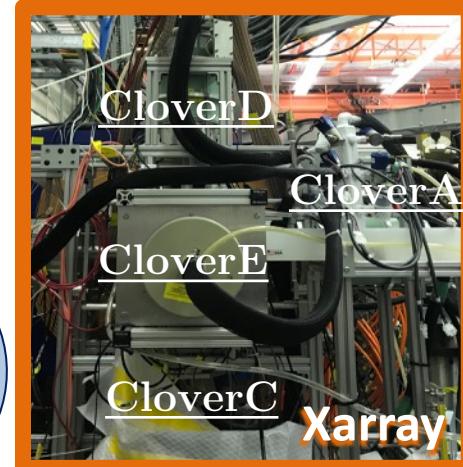
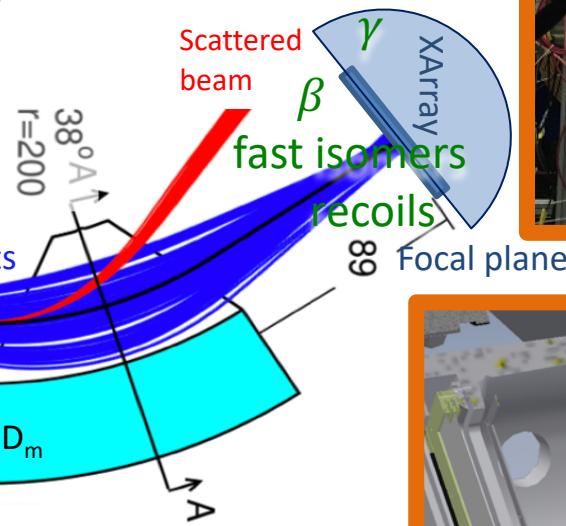
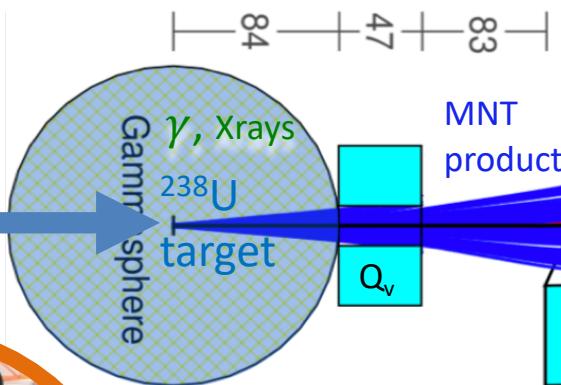


# M multinucleon transfer reactions (MNT) at Argonne

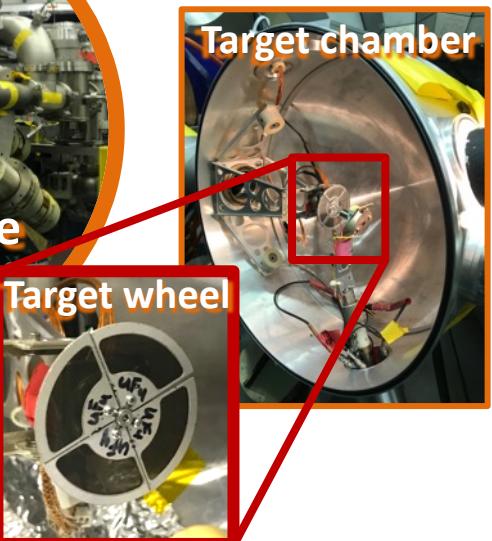
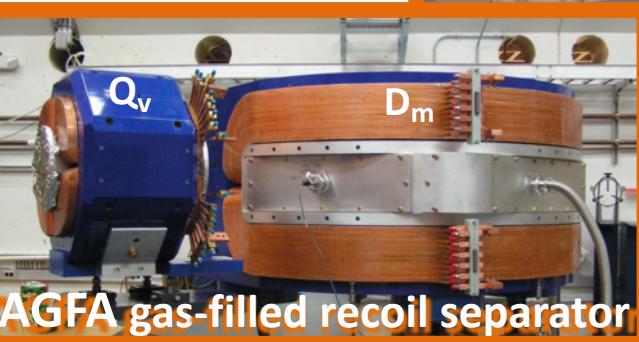
- Proof-of-principle experiment to study neutron-rich heavy nuclei using MNT reactions
- 1<sup>st</sup> MNT reaction using AGFA @ANL to produce heavy nuclei
- Beam:  $^{136}\text{Xe}$  @605, 705 and 809MeV
- Target:  $^{238}\text{U}$  ( $\text{UF}_4$  300 $\mu\text{g}/\text{cm}^2$  + C 40 $\mu\text{g}/\text{cm}^2$ )
- Innovative solutions to increase AGFA helium pressure up to 3Torr (Ti window after the target chamber)

Target-like products identification  
(coincidences)

$^{136}\text{Xe}$  beam  
from ATLAS

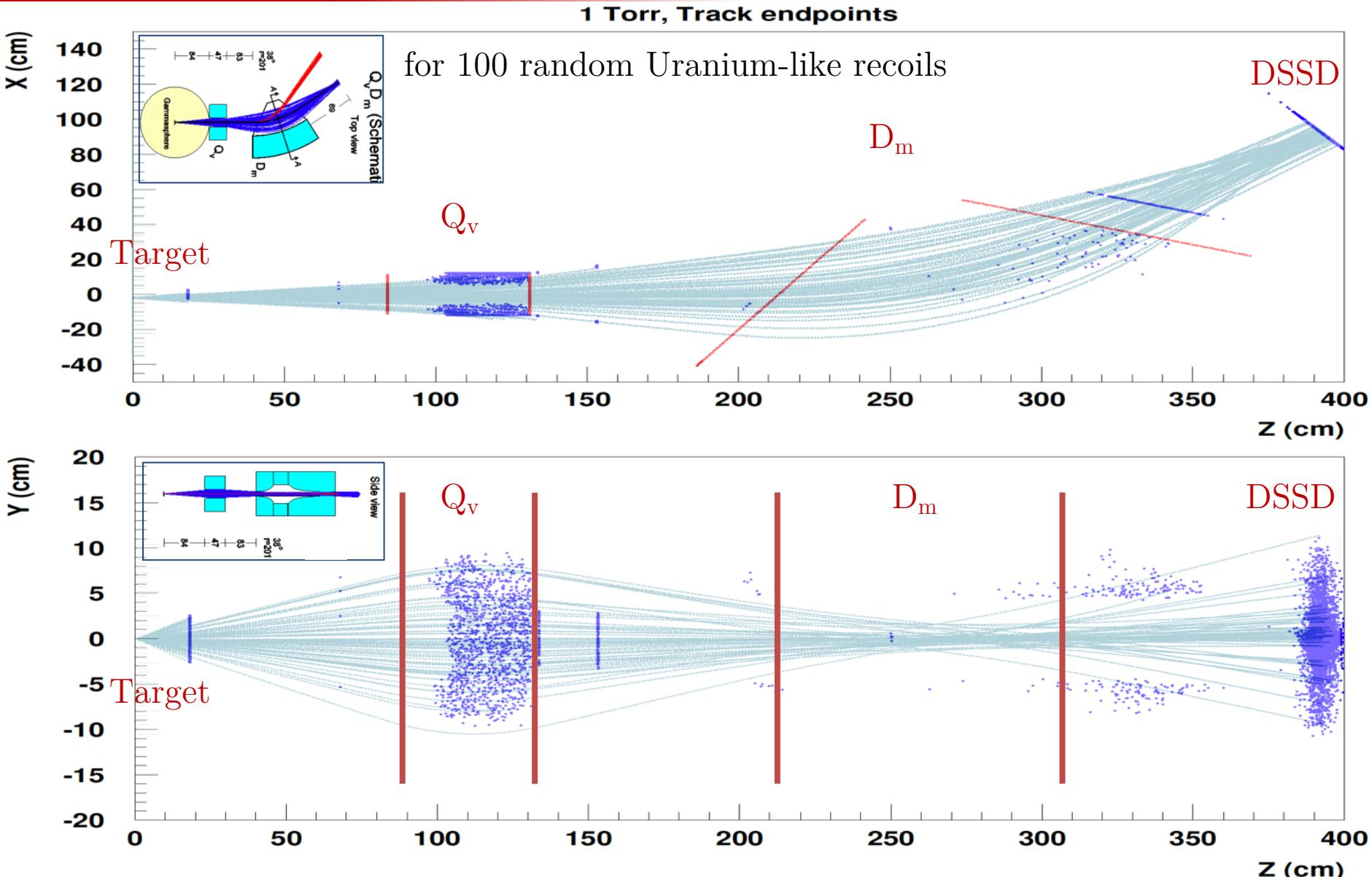


Data Analysis is on going



Target wheel

# AGFA Monte-Carlo optical simulations



# Accepted experiment #1786 @ATLAS

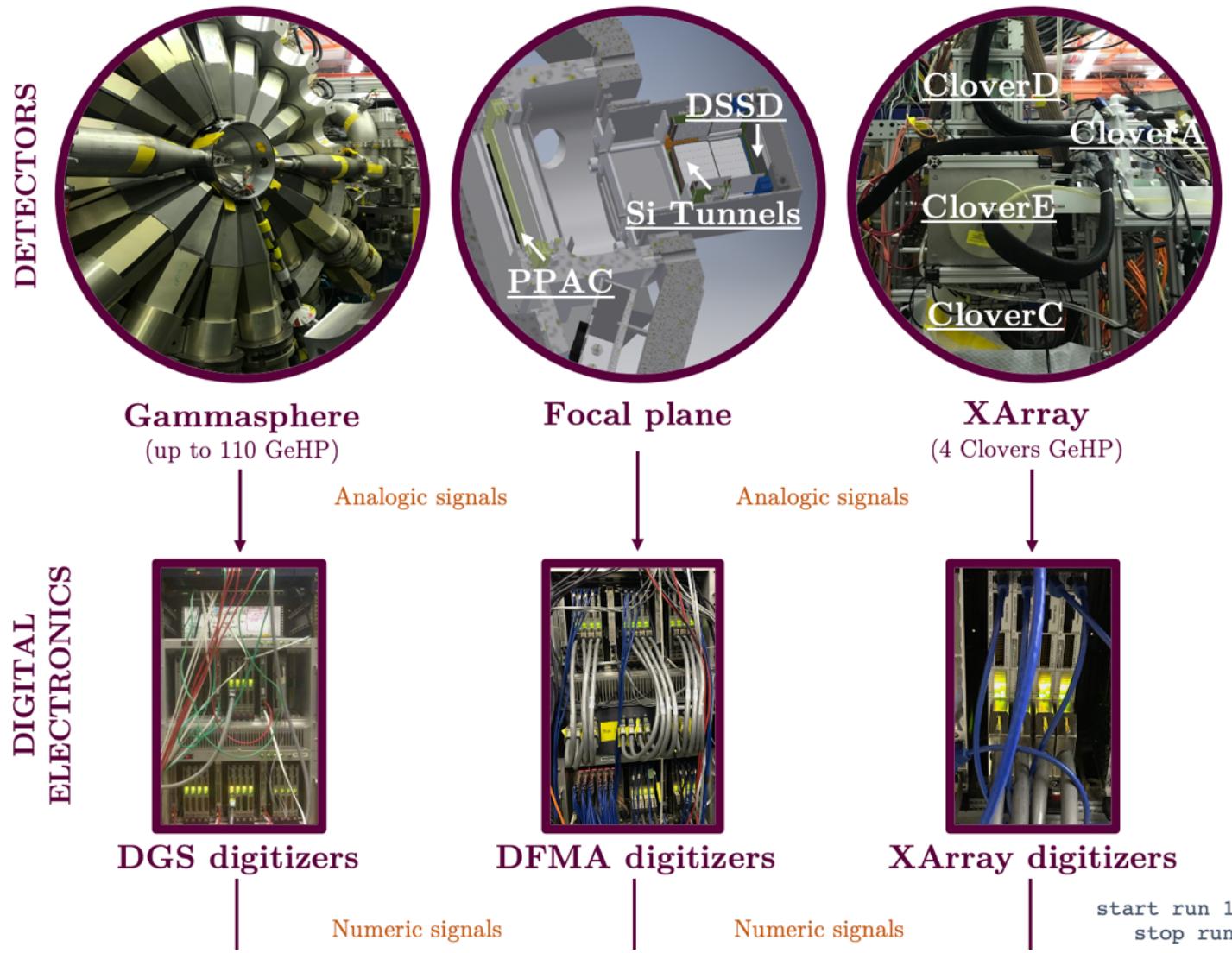
Aujourd'hui   ◀  ▶  novembre 2019   ▼

Imprimer Semaine Mois Planning

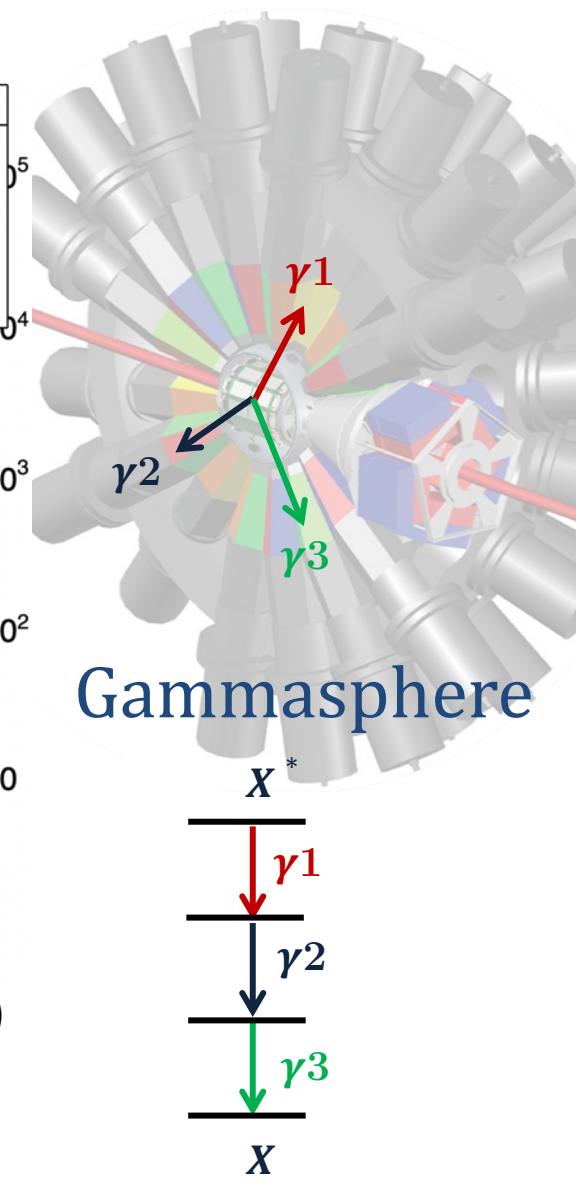
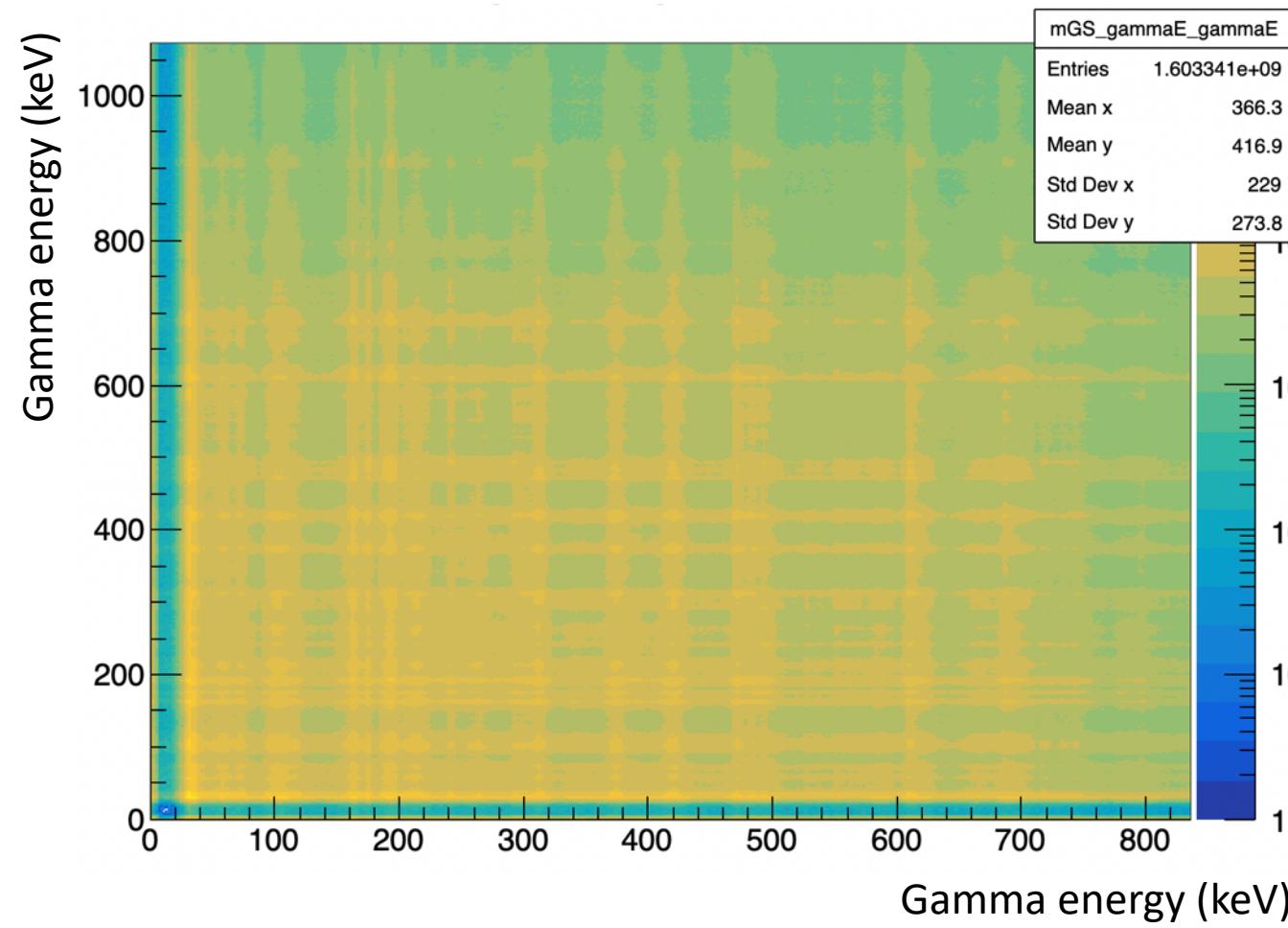
lun.	mar.	mer.	jeu.	ven.	sam.	dim.
28	29	30	31	1 nov.	2	3
1798 Tang   ECR2   15N, 13.5 MeV/u, 150 pA; in-flight 16N, 12 MeV/u, 2x10 <sup>5</sup> pps   HELIOS (A5)						
4	5	6	7	8	9	10
1824 Ong   CARIBU   106Mo, 500 MeV, 2x10 <sup>3</sup> pps, MROF   MUSIC (A8)						
1824 beam tune						
<b>136Xe+238U @3.3, 4.4 and 5.9MeV/u, 2 pA</b>						
<b>Gammasphere-AGFA-XArray</b>						
11	12	13	14	15	16	17
18	19	20	21	22	23	24
1687x Paul   ECR2   92Zr/92Mo, 81Kr (see notes); 7 MeV/u; 1 pA   AGFA (C4)						
1687x beam tune						



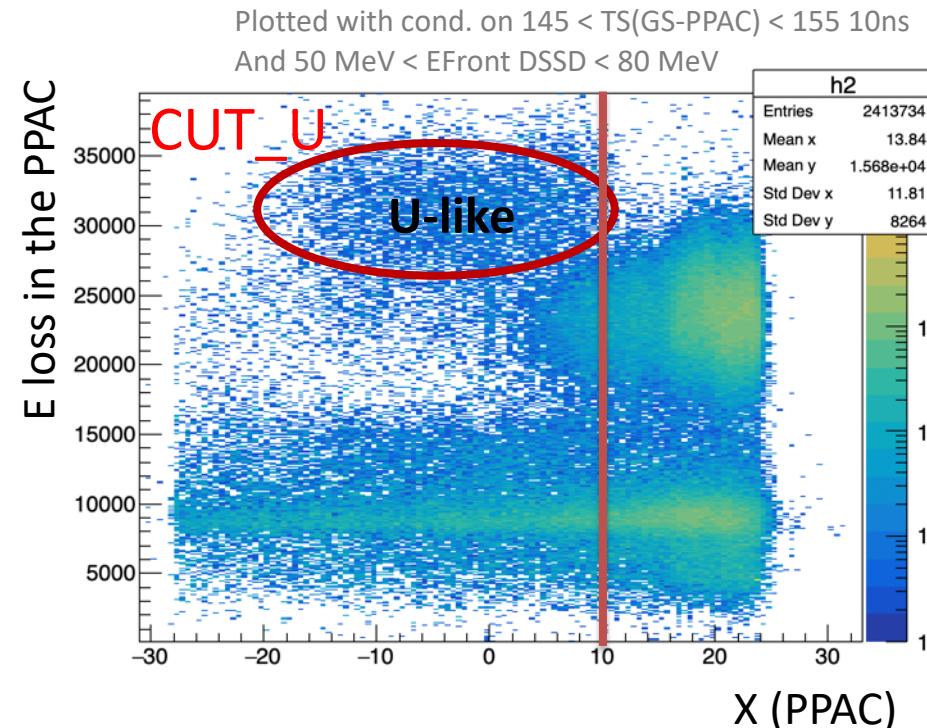
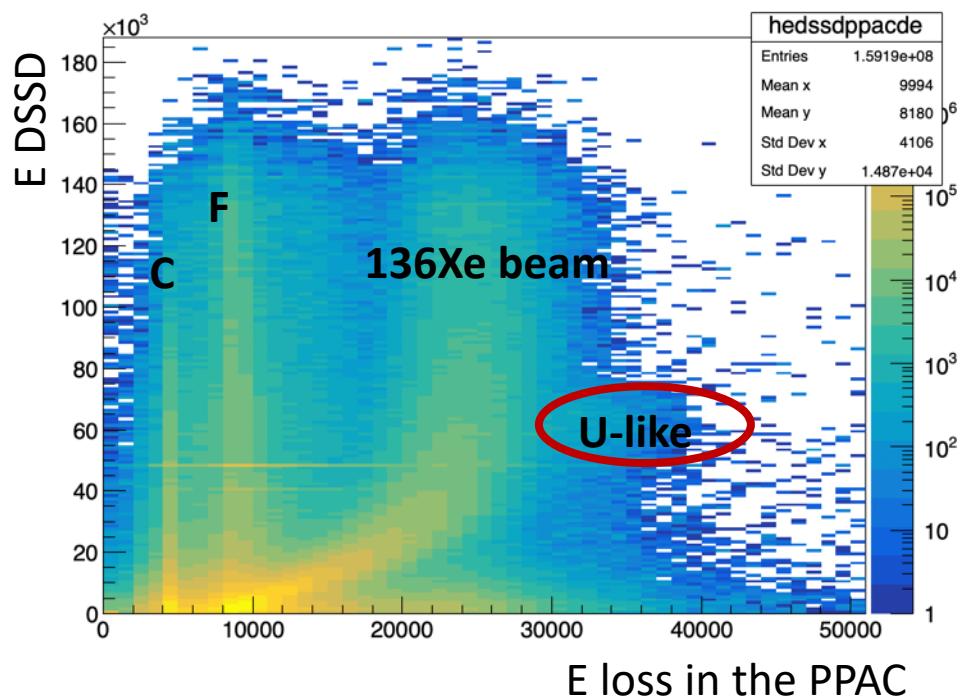
# Analysis scheme



# $\gamma$ - $\gamma$ matrix Doppler corrected and calibrated



# Data cleaning – conditions



Condition 1. Recoil U-like nuclei : CUT\_U + PPACX <10mm

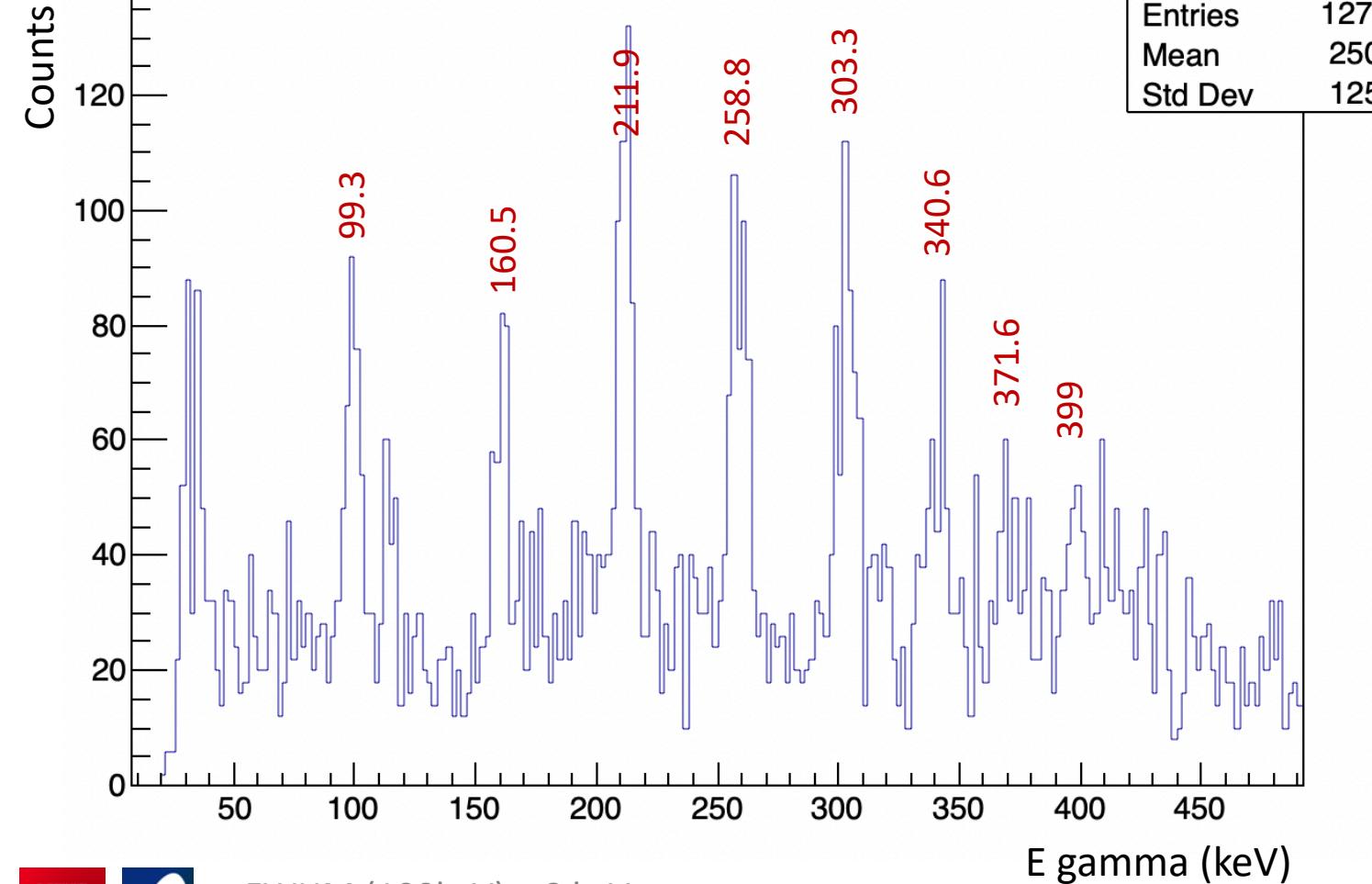
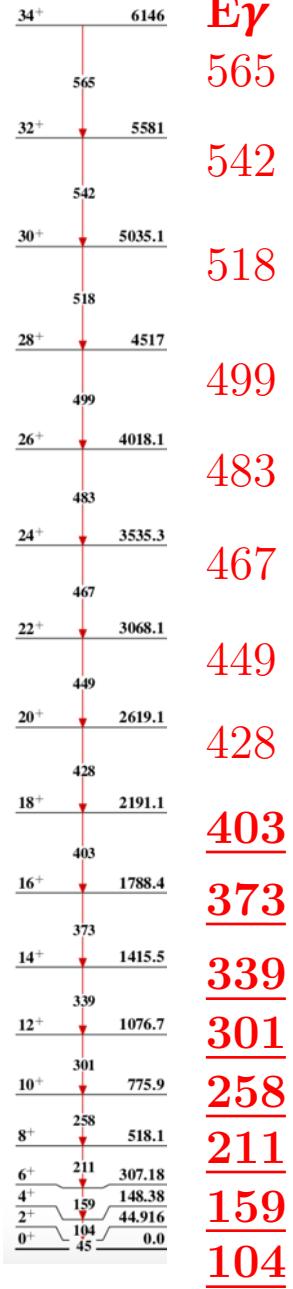


# 238U rotational band

Plotted with Condition1. Recoil U-like nuclei : CUT\_U + PPACX <10mm  
 Plotted with Condition2. Time condition env. 145 < TS(GS-PPAC) < 155

Ground state band of the  $^{238}\text{U}$

$B\rho = 1.8\text{Tm}$   
 $E = 705 \text{ MeV}$

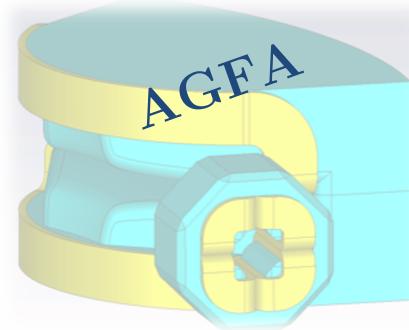


FWHM (100keV) = 8 keV

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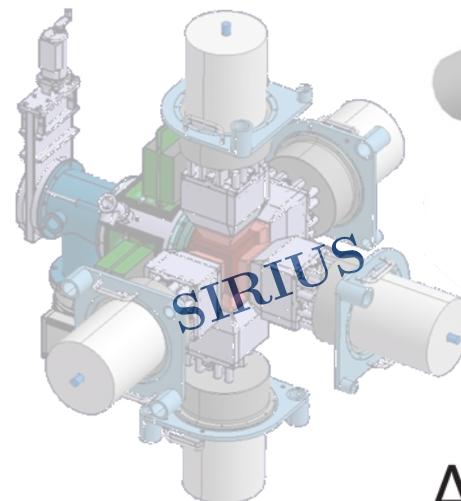
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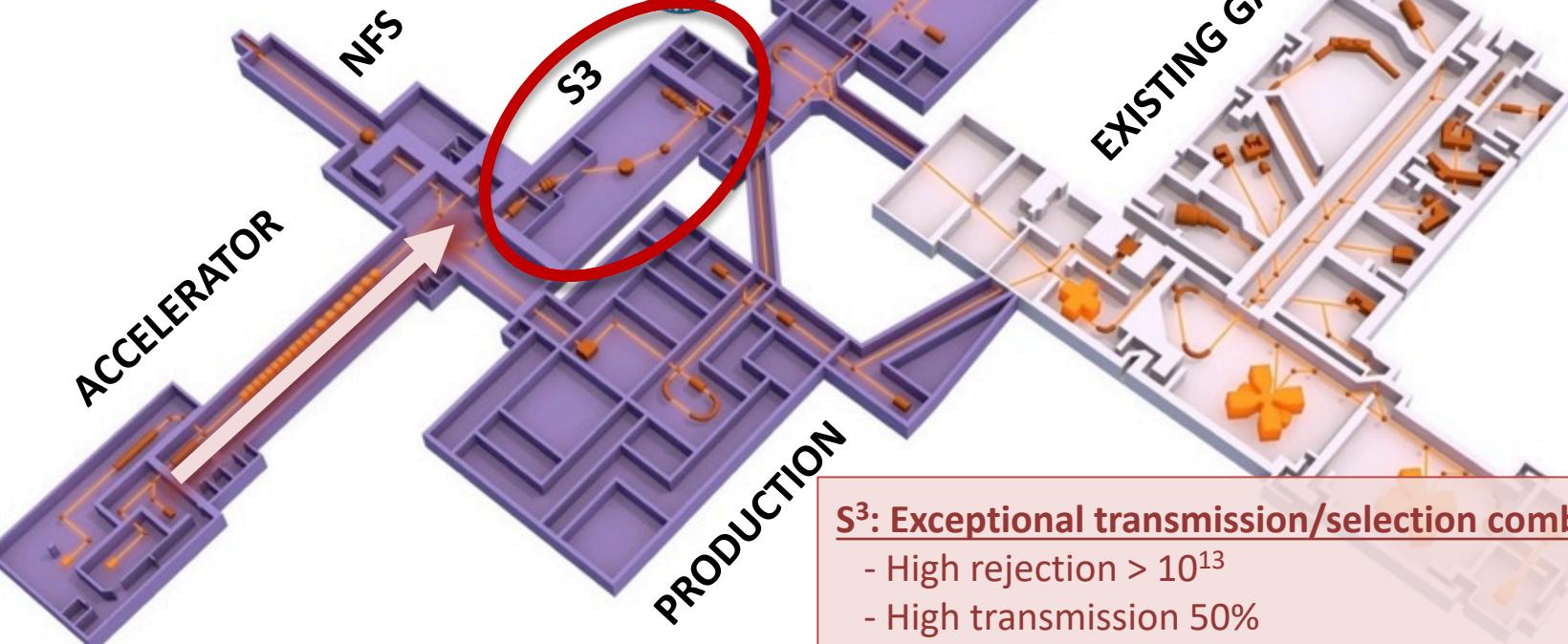
# **S<sup>3</sup>** in the SPIRAL2 project

## **Very high intensity beams (LINAG)**

- Deuterons and stable heavy beams
- $E_{beam}$  = up to 14.5 MeV/u
- Intensity  $10^{14}$  ion/s beyond 1 pμA ( $\geq 10^{13}$  pps)



DESIR



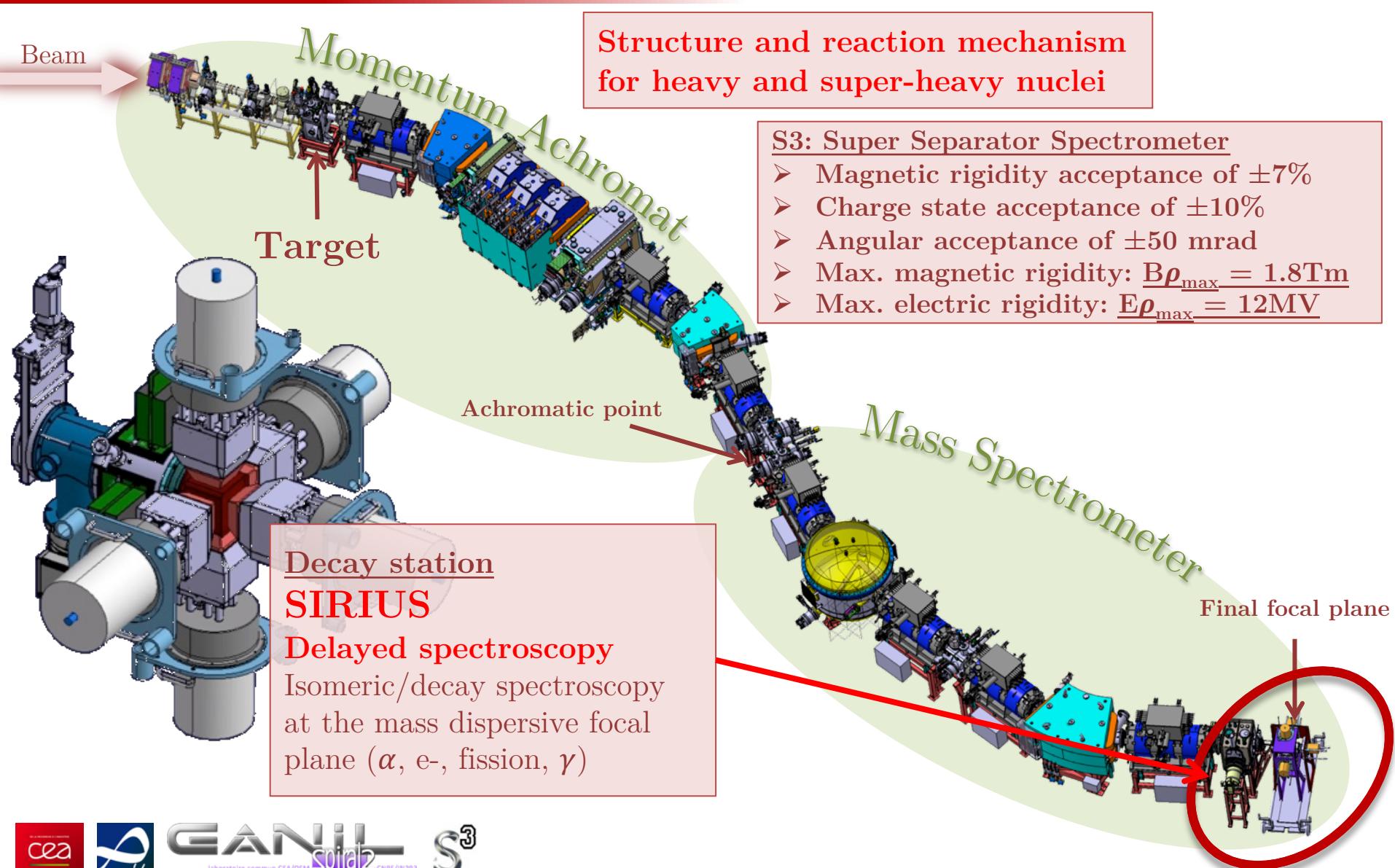
## **S<sup>3</sup>: Exceptional transmission/selection combination**

- High rejection  $> 10^{13}$
- High transmission 50%
- Mass resolution  $> 1/350$

**A cutting-edge instrumentation for S<sup>3</sup>  
(SIRIUS, LEB, FISIC...)**



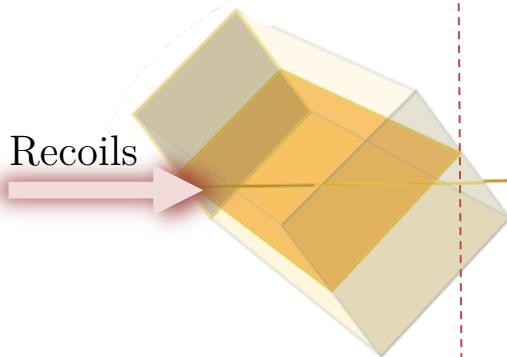
# S<sup>3</sup>: Super Separator Spectrometer



# SIRIUS decay station

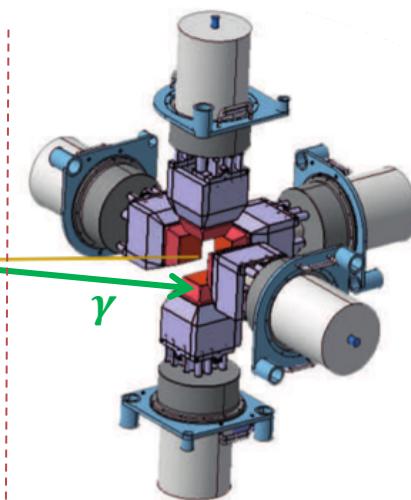
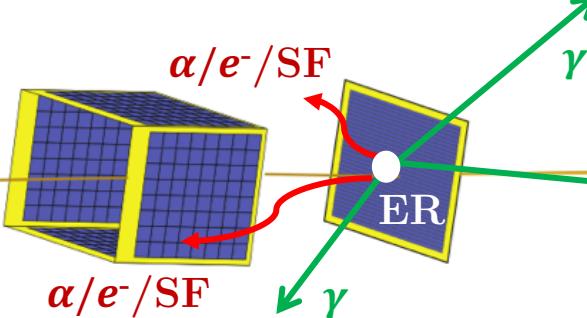
Ge-array

Tracker



Tunnel

DSSD



## Time of Flight:

- Emissive foil
  - Thin windows
  - High Time resolution
  - Mass Identification
- $A/\Delta A \sim 300$

## Silicon detectors:

- Charged particle discrimination for recoil, beta and decay alpha
- High resolution alpha and conversion electron spectroscopy
- Measurement of TKE for spontaneous fission
- Access to short decay times

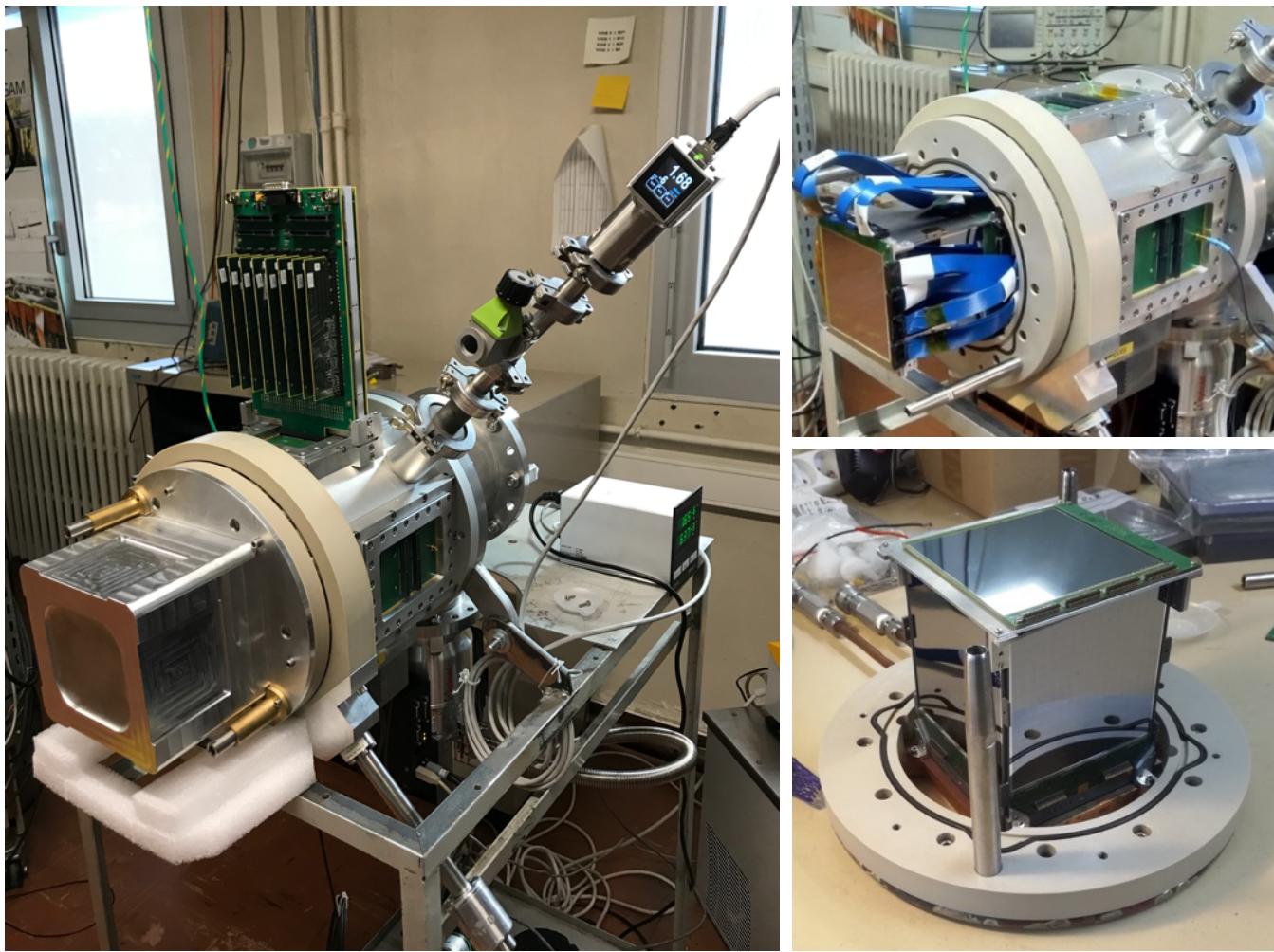
## γ-ray detection :

- 5 EXOGAM clover detectors
- Efficiency of 40% at 121 keV

## Digital electronics with PSA:

Digital signal processing

# SIRIUS decay station @CEA/Irfu

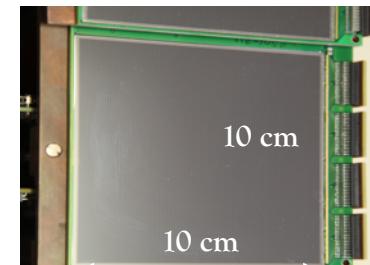


Since July 2020

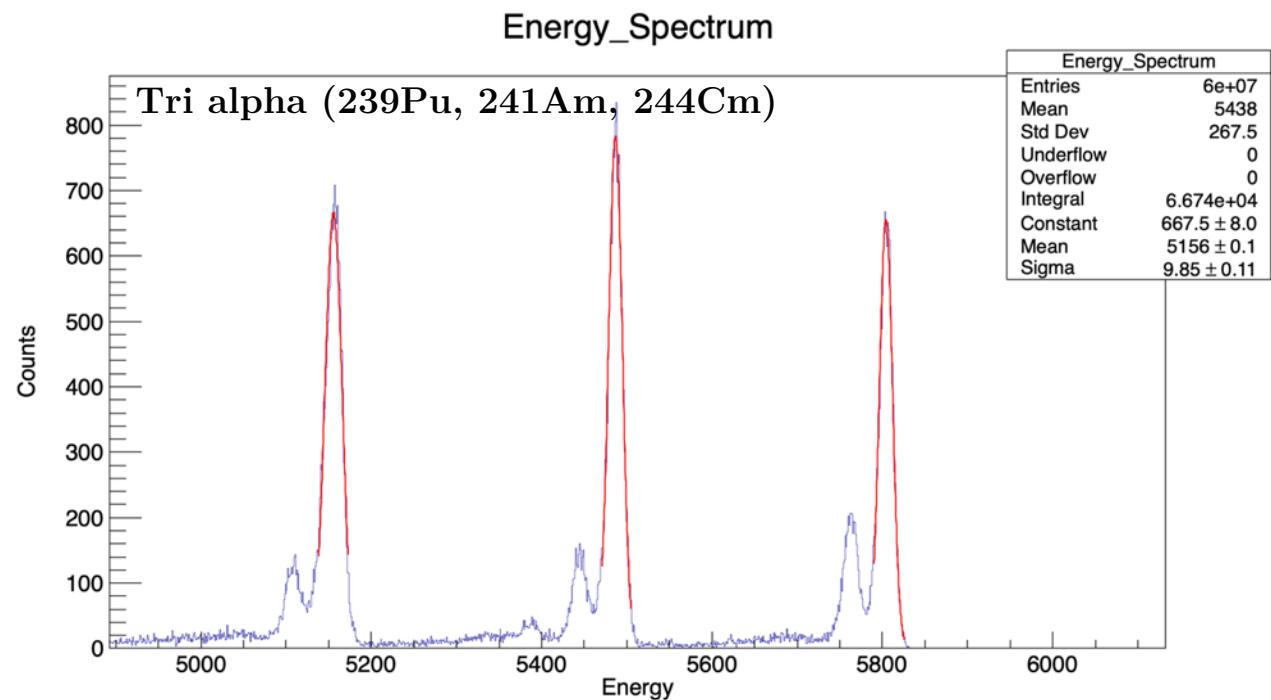
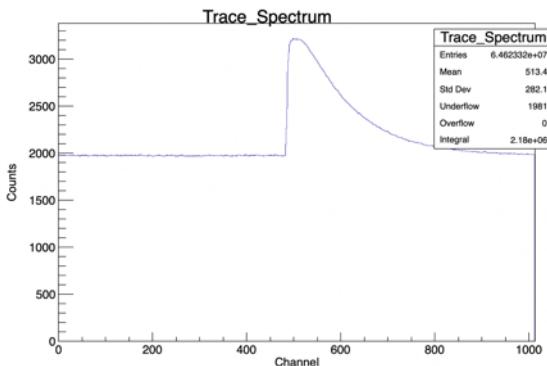
# DSSD test bench @CEA/Irfu

DSSD

128 strips x  
128 strips y



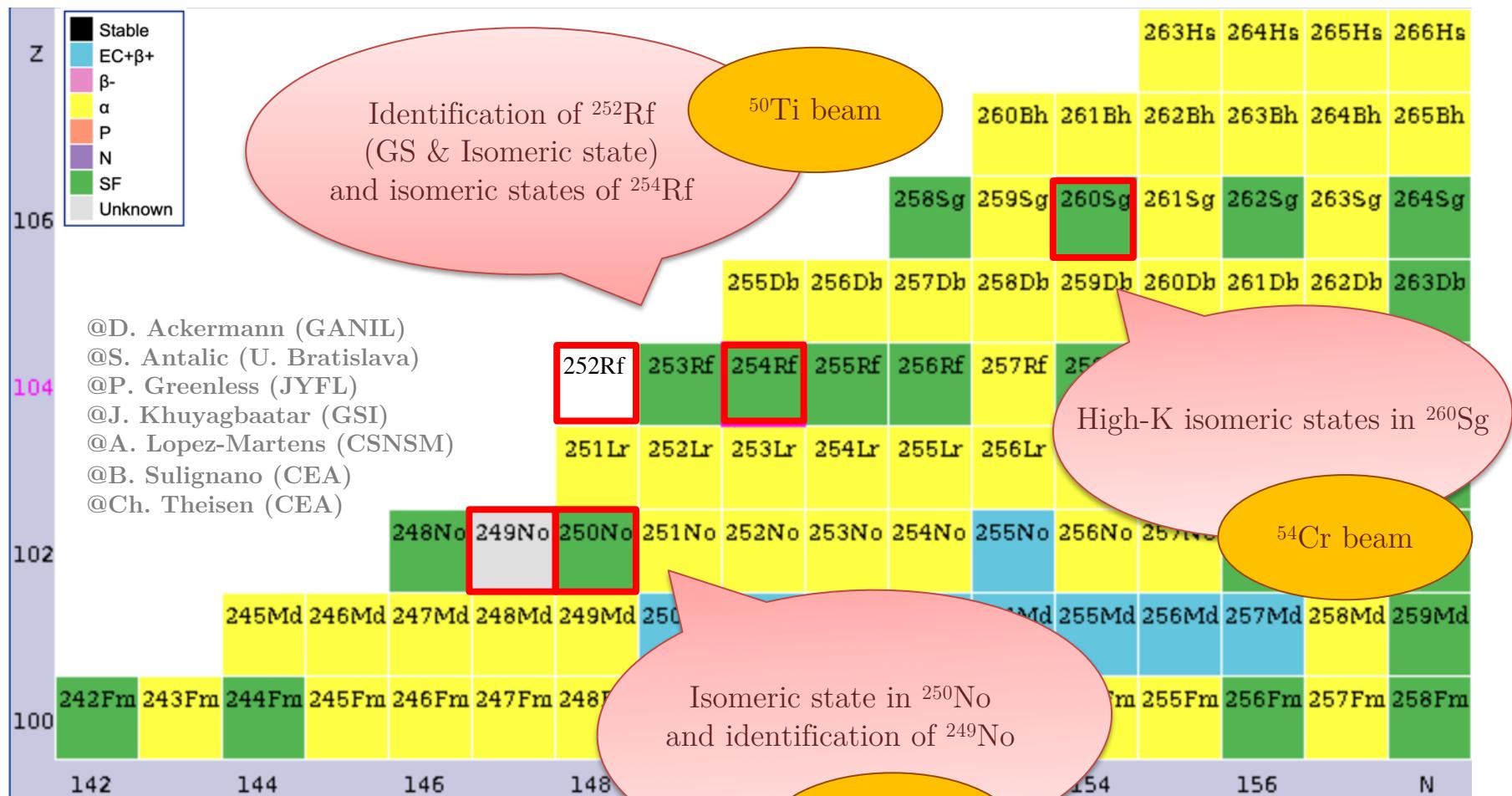
- Testing of DSSD, full electronics chain, with tri-alpha sources
- Digital Signal Processing with Pulse Shape Analysis (Jordanov Filt.)
- Characterization of the DSSD/ front-end electronics
- Write online and offline codes for data acquisition
- Different temperatures (-20, 0, +20°C)
- Test of low gain and high gain
- Use a pulse generator to simulate high energies events



16-18 keV resolution

# SIRIUS Day 1 experimental plan

The selection of day one experiments for  $S^3$  was made to determine out the list of pre-proposals with “high impact” (discovery & unique proposals for  $S^3$ ) and feasibility.



# Conclusions and perspectives

## ➤ Looking for heavy and Super Heavy Nuclei

- Detailed spectroscopy of Very and Super-Heavy Nuclei (SHN)
- Provide information on the nuclear landscape at the upper limit of the nuclear chart and on the nature of the predicted **island of stability**.

## ➤ New reaction mechanisms

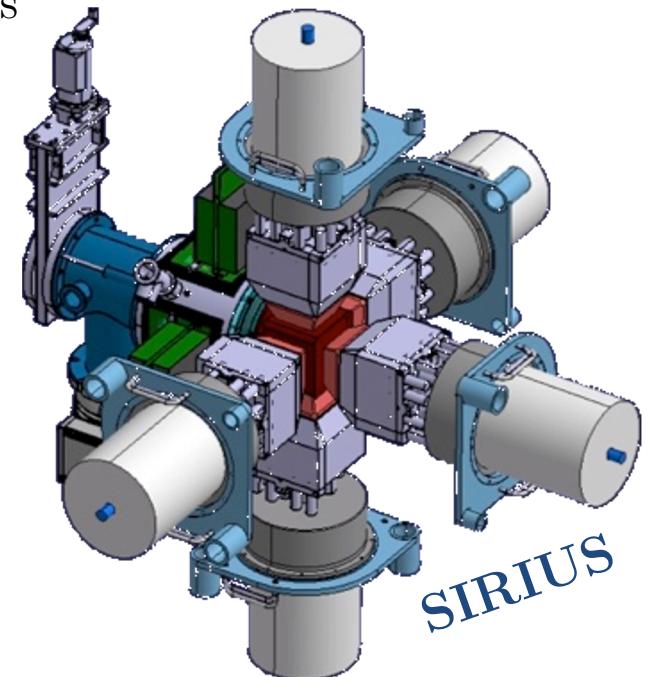
- At ANL: MNT  $^{136}\text{Xe}+^{238}\text{U}$  reaction at 3.3, 4.4 and 5.9 MeV/u (2-4pnA)
- This experiment is a proof-of-principle for MNT using the newly developed AGFA gas-filled separator.
- Less beam intensity than planned.
- Beam from @ATLAS using Gammasphere+AGFA+XArray
- Identified  $^{238}\text{U}$  GS rotational band.
- Analysis is on going with delayed and prompt coincidences to identify other heavy nuclei produced by MNT
- March 2021: new proposal to be submitted at the ATLAS PAC
- New MNT experiments at ATLAS using GS+AGFA/FMA



# Conclusions and perspectives

## ➤ Developping a cutting-edge technology

- SIRIUS in the SPIRAL2/S<sup>3</sup> framework
- SIRIUS = “Spectroscopy and Identification of Rare Isotopes Using S3”
- All the different parts of SIRIUS have been tested offline
  - @IPHC, IJClab, GANIL and IRFU test benches
- Ongoing: electronic tests @CEA/Irfu
- March 2021: first tests of SIRIUS @GANIL



# SIRIUS Collaboration

**CEA/IRFU** : M. Authier, Th. Chaminade, A. Drouart, ZF, T. Goigoux, W. Korten, M. Siciliano, B. Sulignano, Ch. Theisen, M. Vandebrouck, M. Zielinska

**GANIL** : D. Ackermann, M. Blaizot, A. Boujrad, E. Clément, S. Coudert, S. Herlant, G. Lebertre, C. Maugeais, J. Piot, F. Saillant, H. Savajols, G. Wittwer

**CSNSM** : V. Alaphilipe, L. Gibelin, K. Hauschild, N. Karkour, X. Lafay, D. Linget, A. Lopez-Martens

**IPHC** : P. Brionnet, O. Dorvaux, B. Gall, Th. Goeltzenlichter, C. Mathieu

**IPNO** : L. LeBlanc



# Proposal #1786 – MNT @ANL

**CEA/IRFU:** ZF, A. Drouart, W. Korten, M. Siciliano, B. Sulignano, Ch. Theisen, M. Vandebrouck, M. Zielinska.

**ANL:** D. Seweryniak, B.B. Back, M. Carpenter, P.A. Copp, J.P. Greene, T. Huang, T.L. Khoo, F.G. Kondev, D.H. Potterveld, T. Lauritsen, G. Savard, S. Stolze, J. Wu, W. Reviol.

**Oregon State University:** W.D. Loveland.

**GANIL:** D. Ackermann, N. Lebesne, J. Piot, H. Savajols, C. Stodel.

**CSNSM:** K. Hauschild, A. Korichi, A. Lopez-Martens.

**IPHC:** O. Dorvaux.

**JINR:** A. Karpov.

**UM Lowell:** P. Chowdhury.

**JYFL:** P. Greenlees, J. Uusitalo.

**Berkeley:** R.M. Clark, A.O. Macchiavelli, C. Morse.

**GSI:** M. Block, F. Giacoppo, S. Heinz, F.P. Hessberger, J. Khuyagbaatar.

**INFN:** A. Di Nitto.

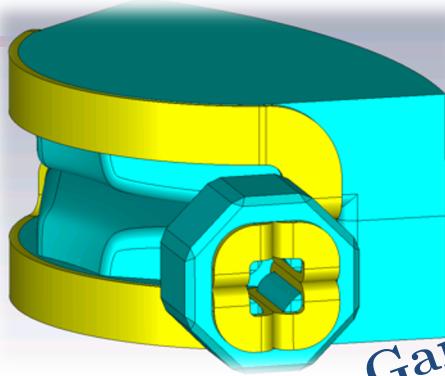
**Cologne:** P. Reiter.

**Bratislava:** S. Antalic, A. Bronis, P. Mosat.

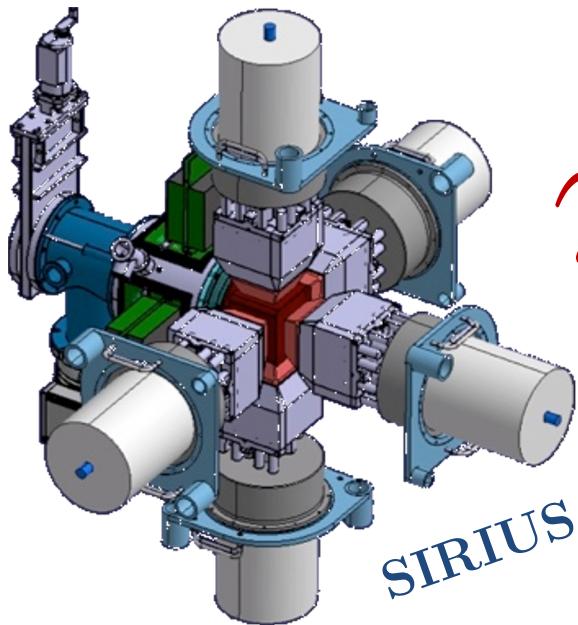
**KU Leven:** B. Andel.

**Surrey:** D. Doherty.





AGFA  
Gammasphere



SIRIUS

Thank you

