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EMMI Workshop/NUSTAR program

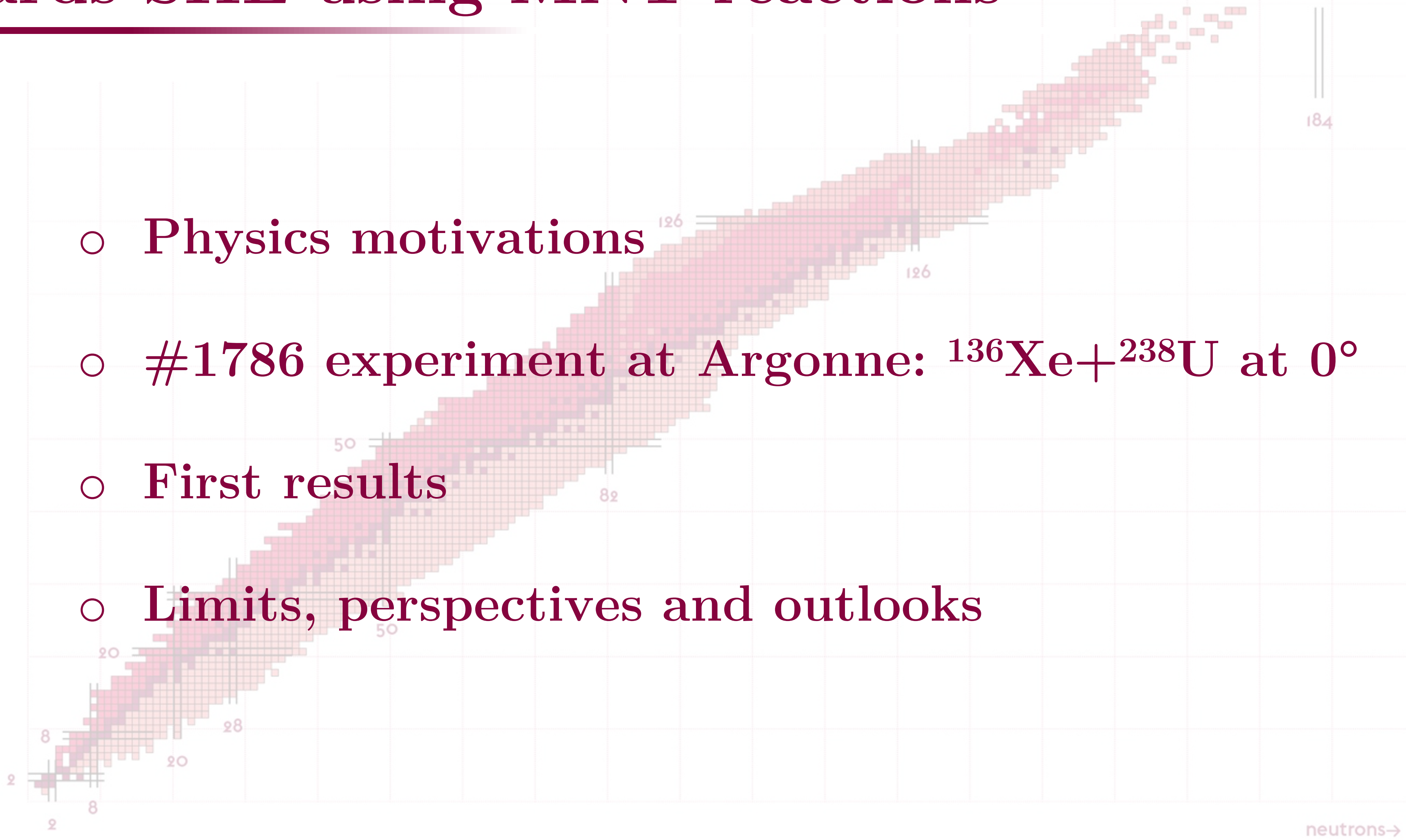
Online/GSI, September 16th 2021

Towards the superheavy elements:

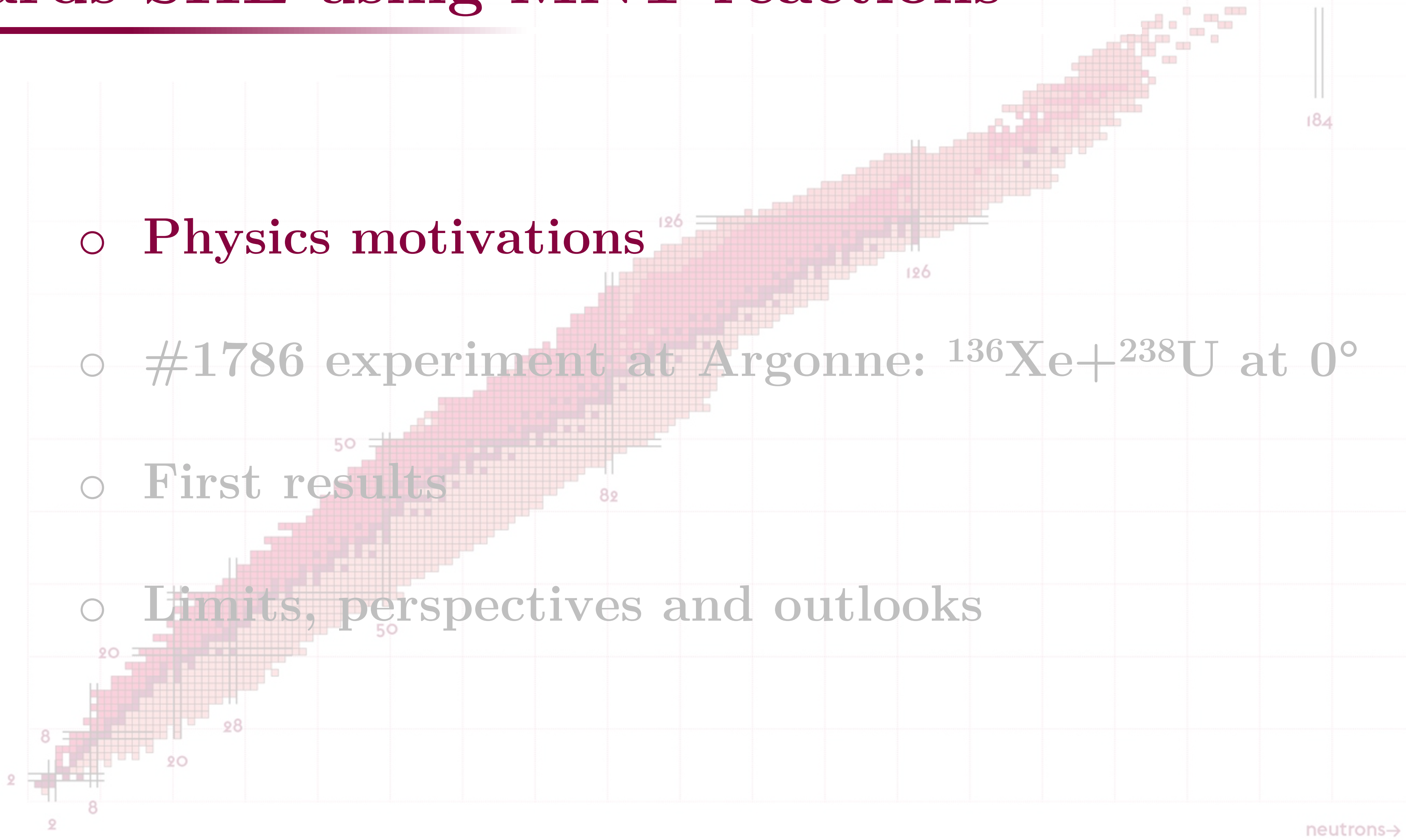
MNT experiment carried out at Argonne: $^{136}Xe+^{238}U$ at 0°

Towards SHE using MNT reactions

- Physics motivations
- #1786 experiment at Argonne: ^{136}Xe+^{238}U at 0°
- First results
- Limits, perspectives and outlooks



Towards SHE using MNT reactions



- Physics motivations
- #1786 experiment at Argonne: $^{136}Xe+^{238}U$ at 0°
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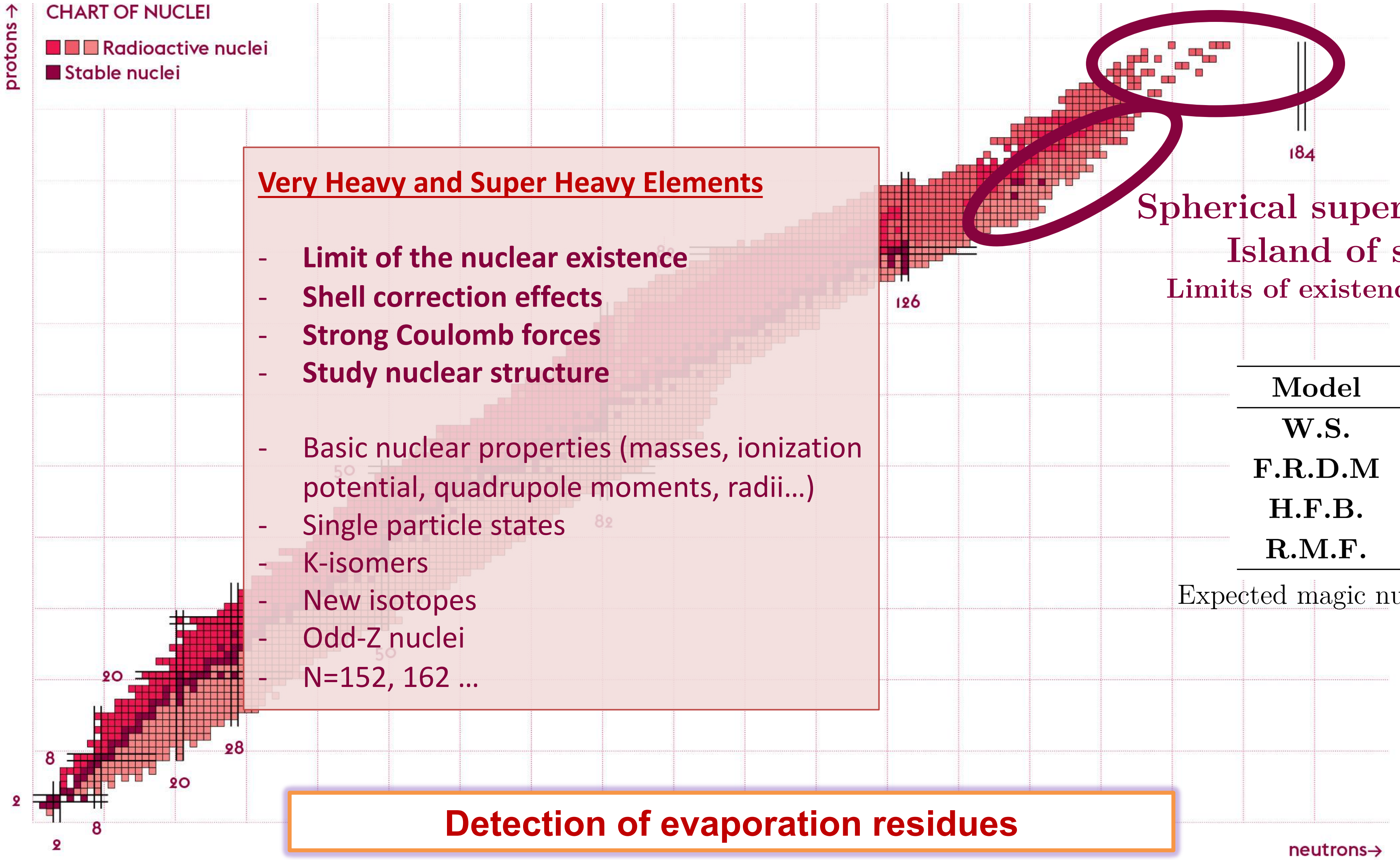
Physics objectives: SHE, a perfect laboratory



Very Heavy and Super Heavy Elements

- **Limit of the nuclear existence**
- **Shell correction effects**
- **Strong Coulomb forces**
- **Study nuclear structure**

- Basic nuclear properties (masses, ionization potential, quadrupole moments, radii…)
- Single particle states
- K-isomers
- New isotopes
- Odd-Z nuclei
- N=152, 162 …

Spherical superheavy nuclei?
Island of stability?
Limits of existence of the matter

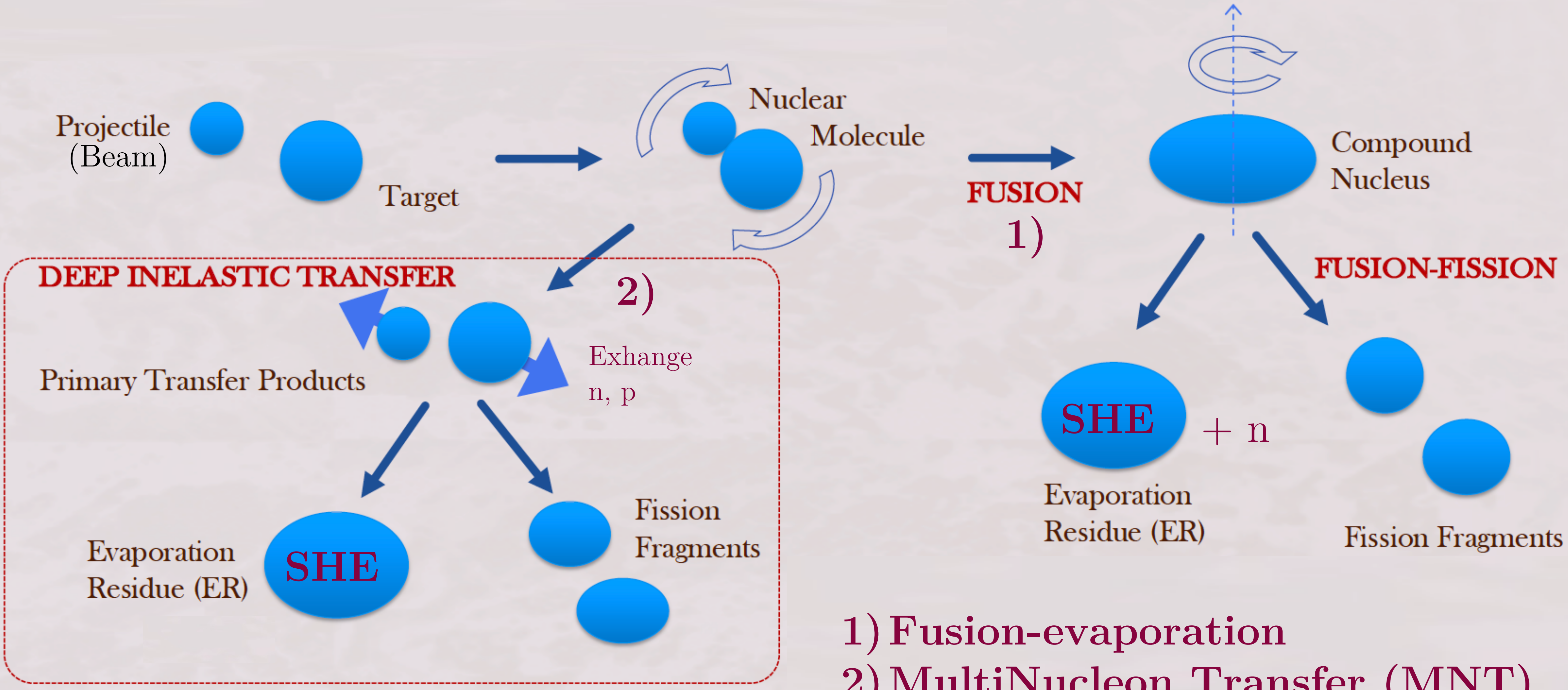
Model	Z	N
W.S.	114	184
F.R.D.M	114	178
H.F.B.	126	184
R.M.F.	120	172

Expected magic numbers for SHE

Detection of evaporation residues

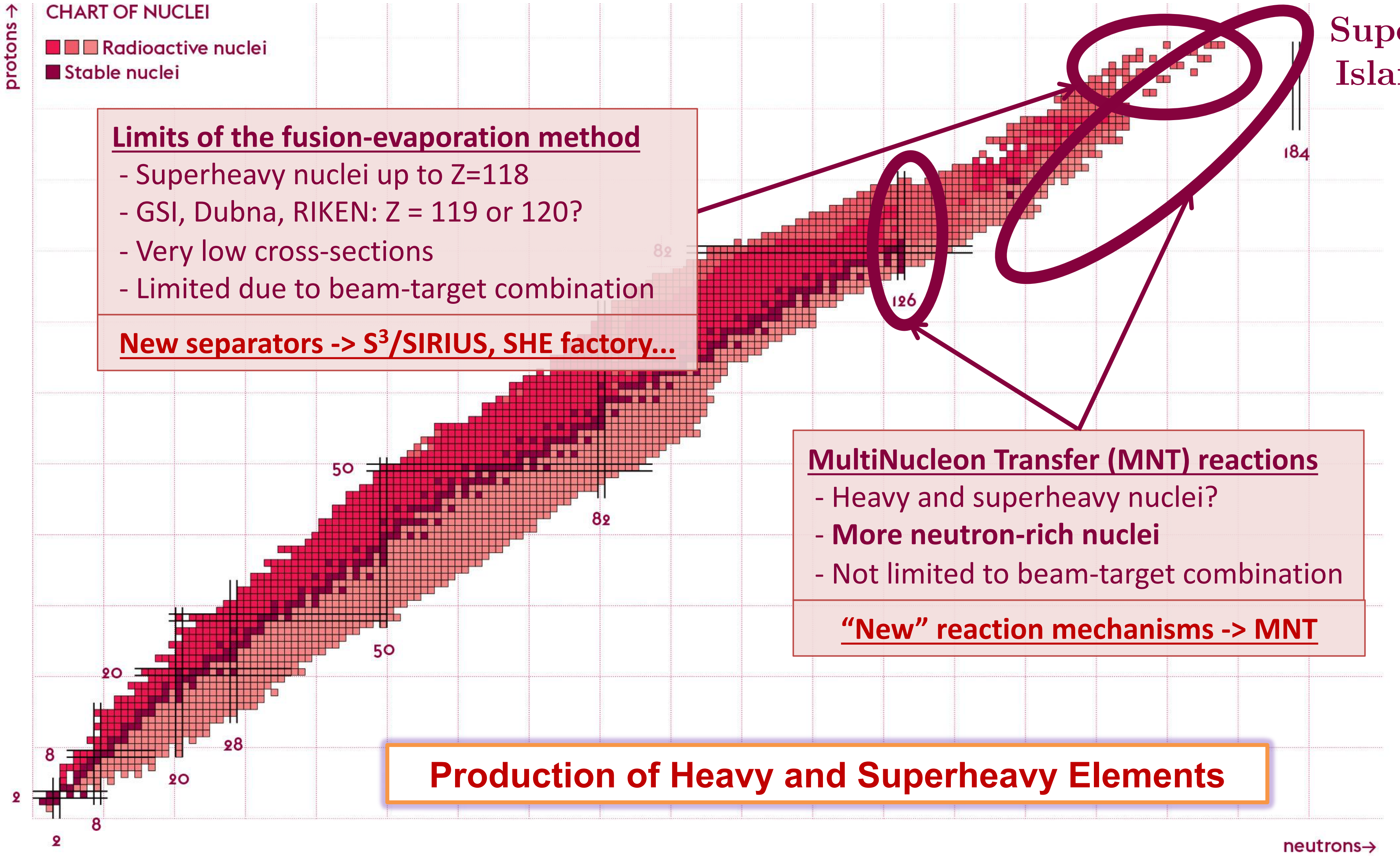
(Nuclear chart from l'Edition n°13 - June 2020)

Reaction mechanisms to produce SHE?



1) Fusion-evaporation
2) MultiNucleon Transfer (MNT)

Physics objectives: VHE and SHE



Superheavy nuclei?
Island of stability?

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 separators -> S^3/SIRIUS, SHE factory...

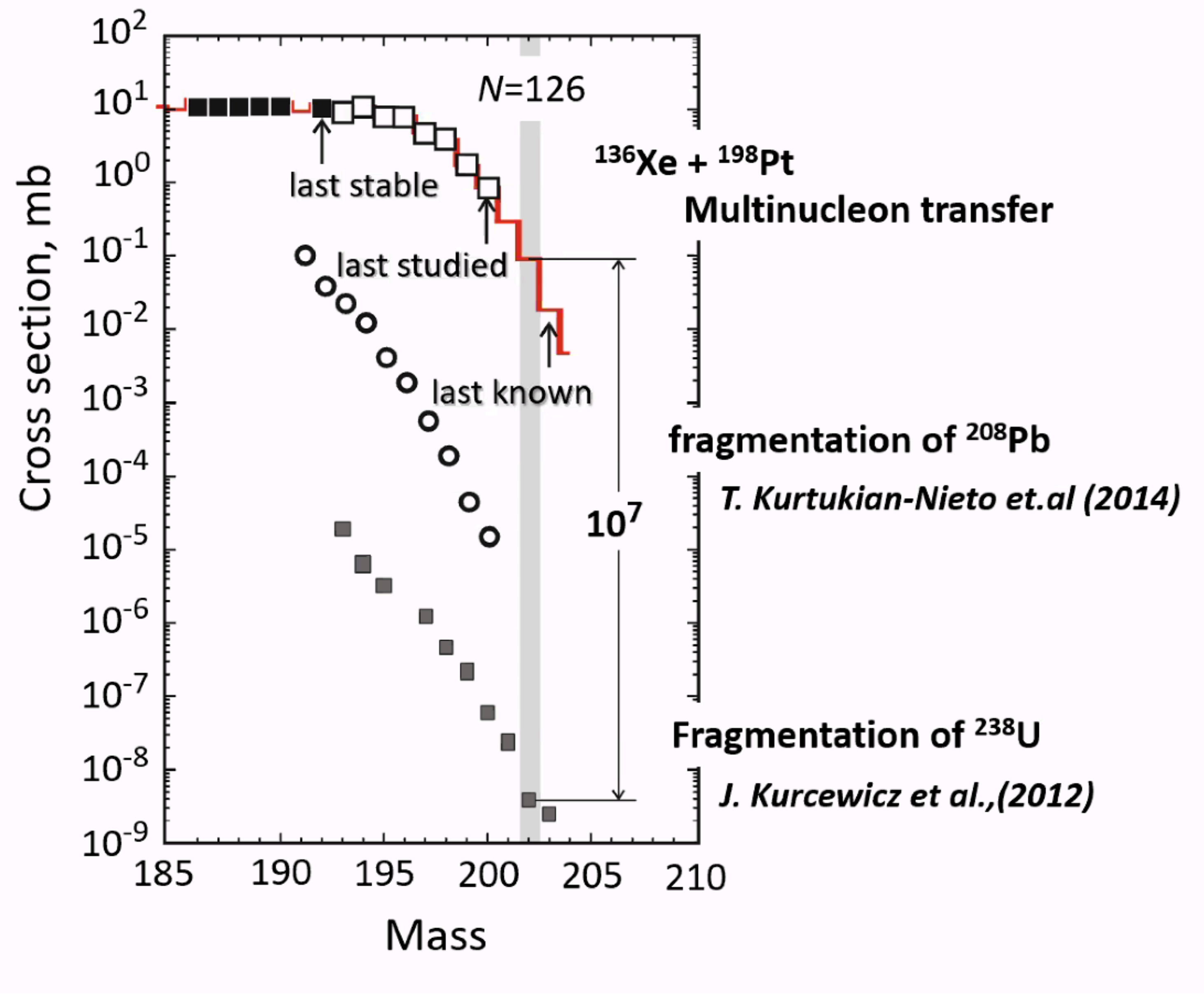
MultiNucleon Transfer (MNT) reactions
- Heavy and superheavy nuclei?
- **More neutron-rich nuclei**
- Not limited to beam-target combination

“New” reaction mechanisms -> MNT

Production of Heavy and Superheavy Elements

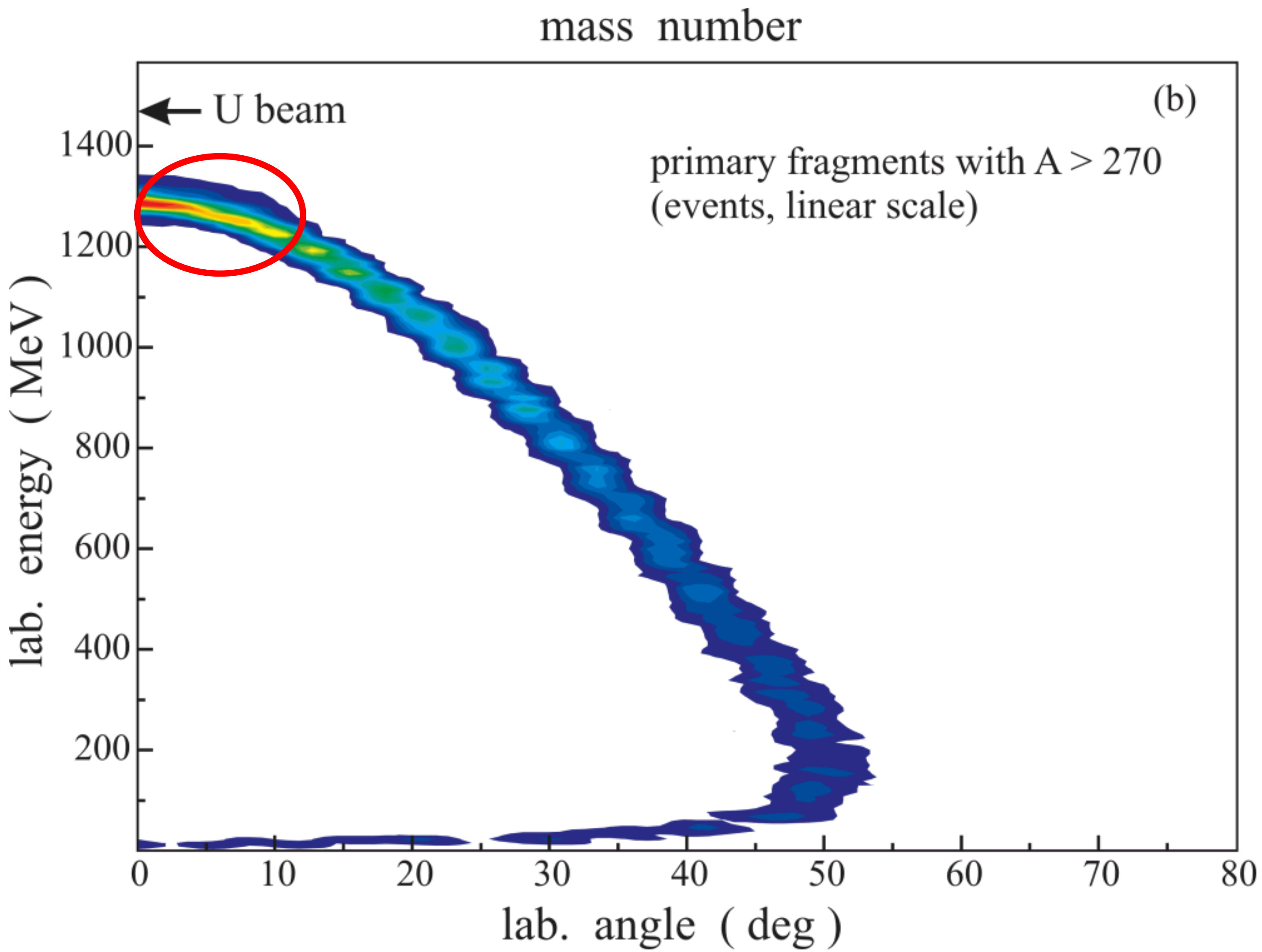
(Nuclear chart from l'Edition n°13 - June 2020)

Production of neutron-rich Os isotopes



Deep-inelastic studies at 0°

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

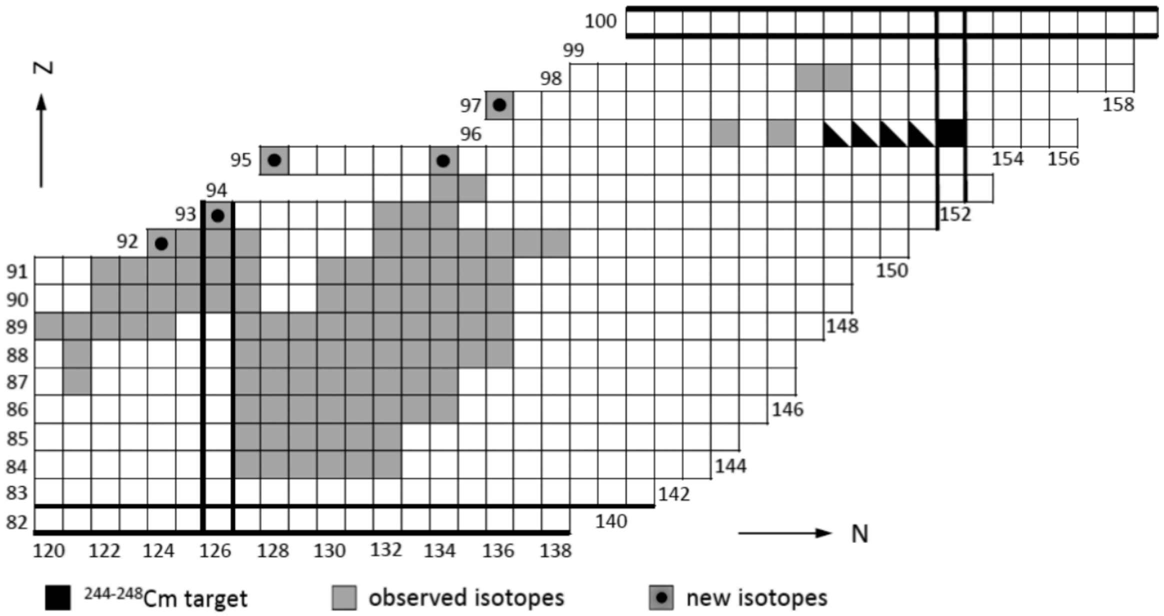


The angular distribution of the superheavy nuclei does not reveal any grazing feature, it is forward directed.

First MNT studies in the SHE region at 0°

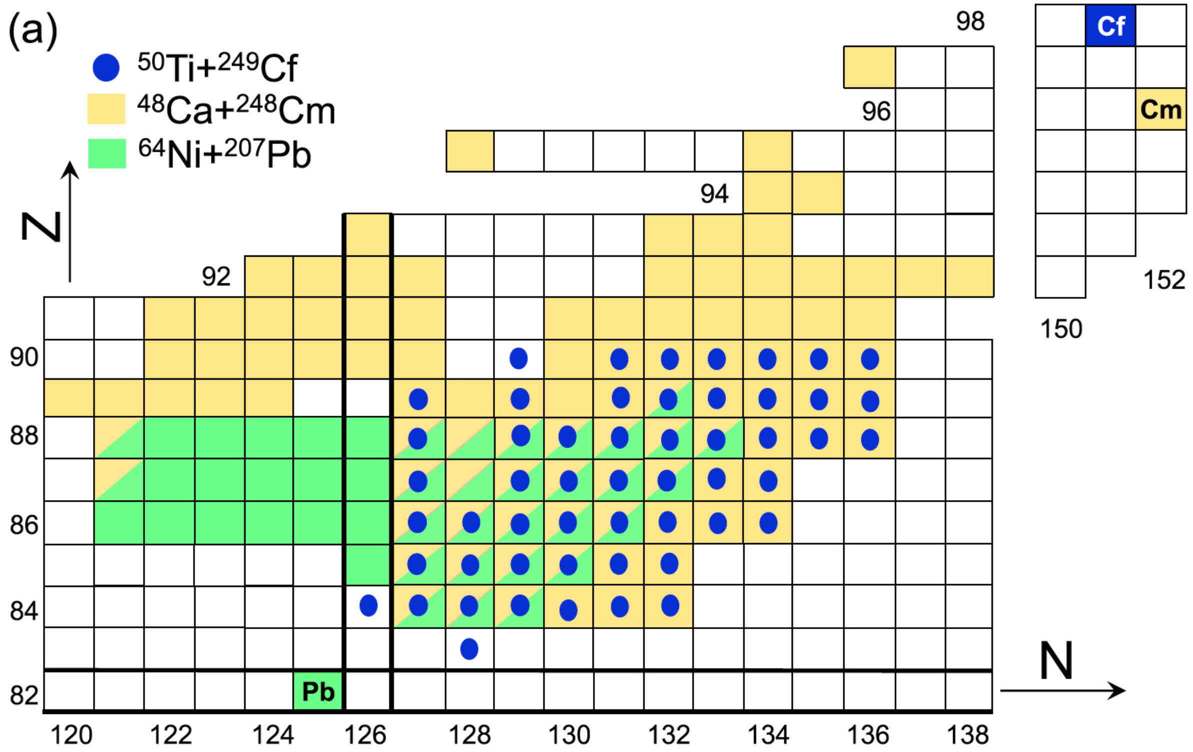
48Ca+248Cm @ (5.3 MeV/n) At SHIP (GSI) 0°

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



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

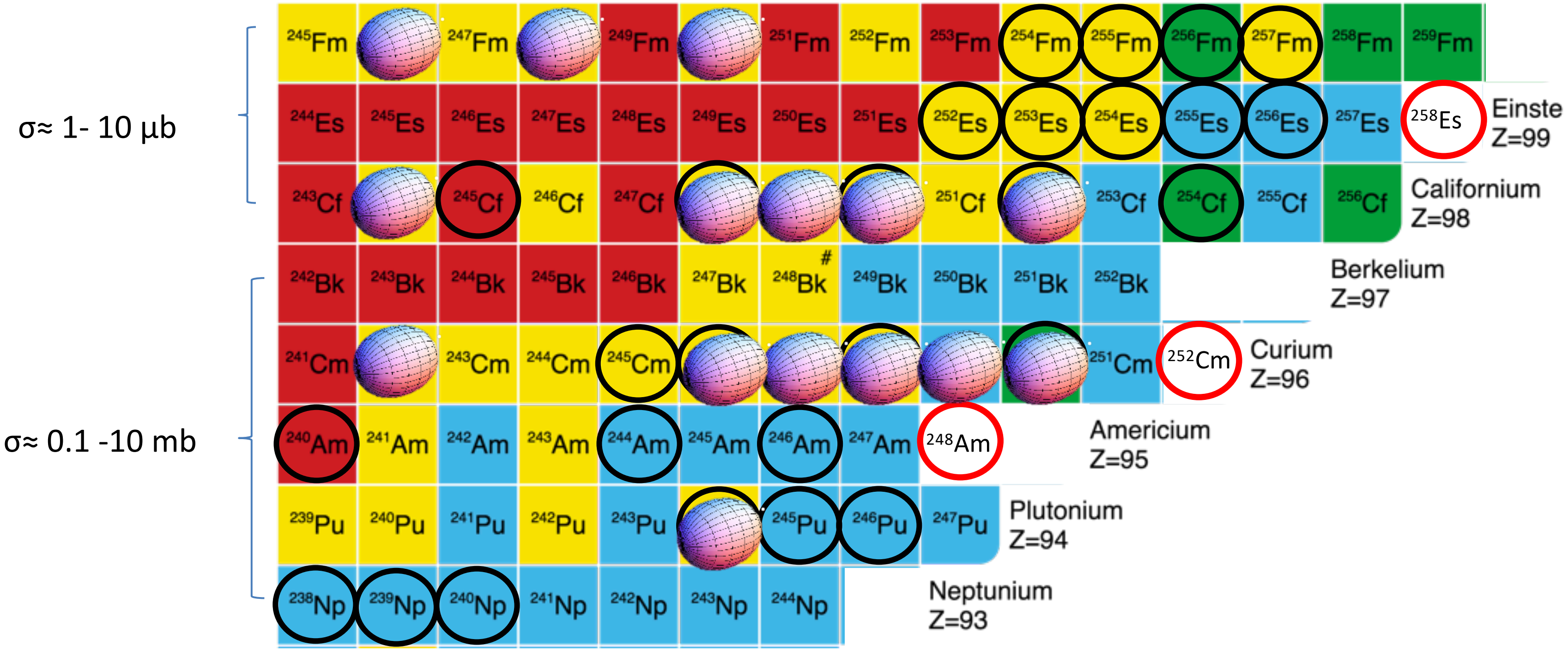
[1]A. Di Nitto, et al. PLB 784 (2018)199–205



The nuclei observed in the $^{50}Ti+^{249}Cf$ and $^{48}Ca+^{248}Cm$ reactions originate from a process where a large number of nucleons flow in the direction of the projectile nucleus with cross-sections significantly higher than the fusion-evaporation ones.[1]

Towards superheavy elements

136Xe + 248Cm @ 5 MeV/n around 0°

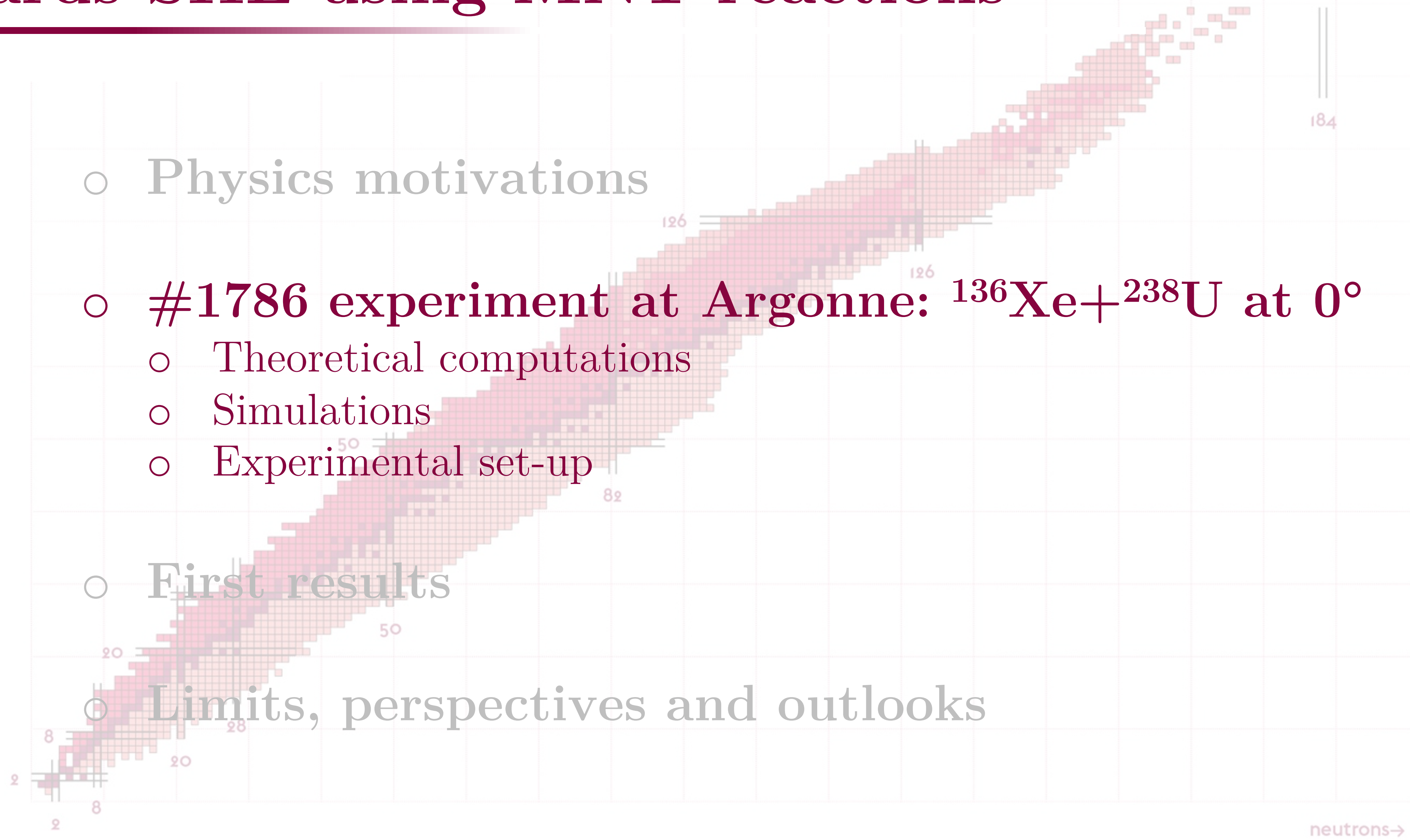


Prompt spectroscopy allows to measure:

- Highly excited states not populated via fusion-evaporation reaction
- γ-rays spectroscopy will provide crucial information for theoretical models

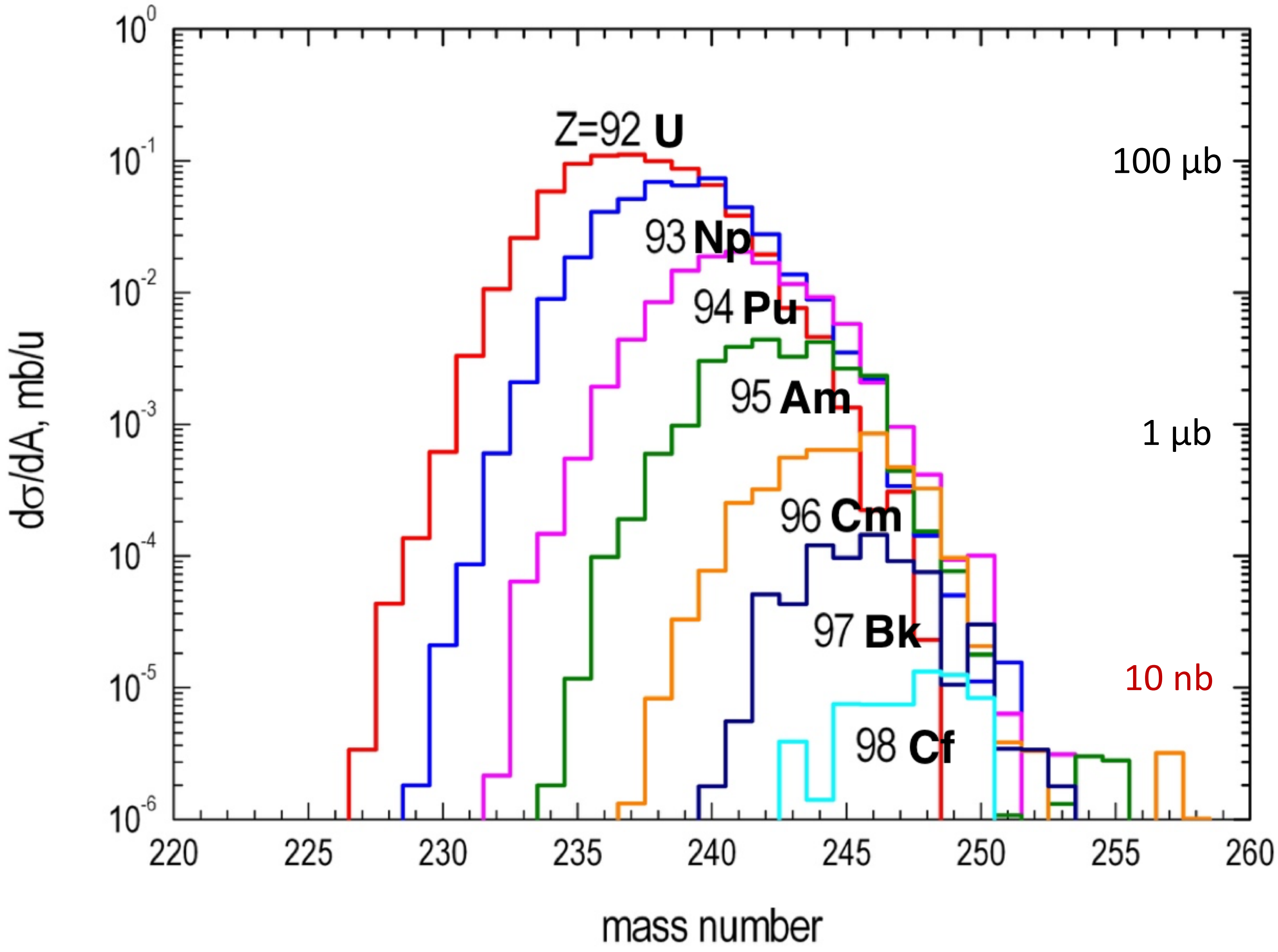
E.g.: Via measurement of excitation energy and spin distribution

Towards SHE using MNT reactions



- Physics motivations
- **#1786 experiment at Argonne: $^{136}Xe+^{238}U$ at 0°**
  - Theoretical computations
  - Simulations
  - Experimental set-up
- First results
- Limits, perspectives and outlooks

^{136}Xe+^{238}U at 0° #1786 ATLAS PAC2019



The experiment:

ZF, D. Seweryniak et al:

« Synthesis of heavy and superheavy neutron-rich nuclei in multinucleon transfer reactions close to 0° »

The reaction:

^{136}Xe+^{238}U at 0°

*@**3.6, 4.4 and 5.9MeV/u,** 20 pnA*

Gammasphere-AGFA-XArray

← **Courtesy of A. Karpov**

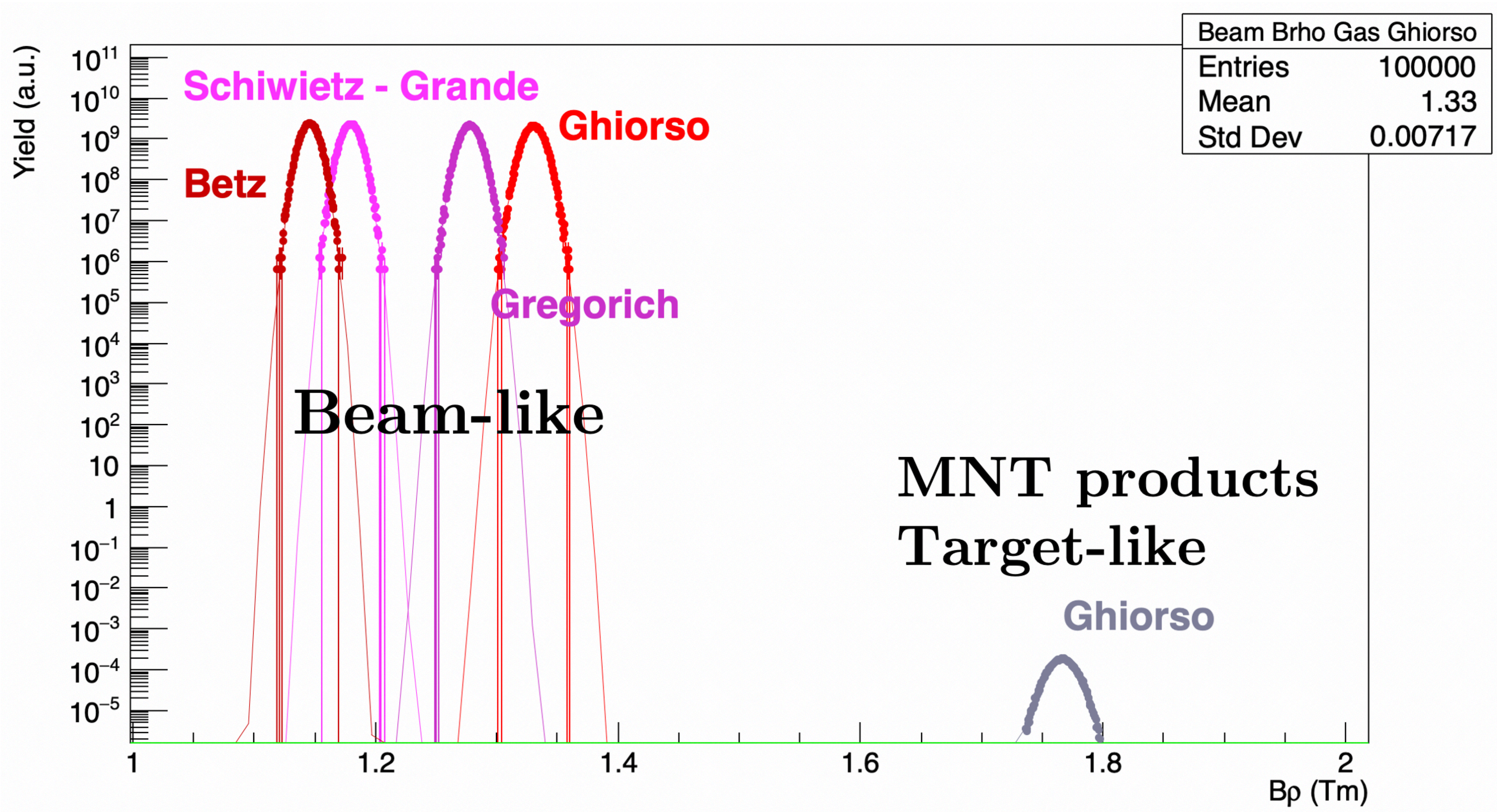
(using the Langevin's model)

E_{cm} = ~490 MeV

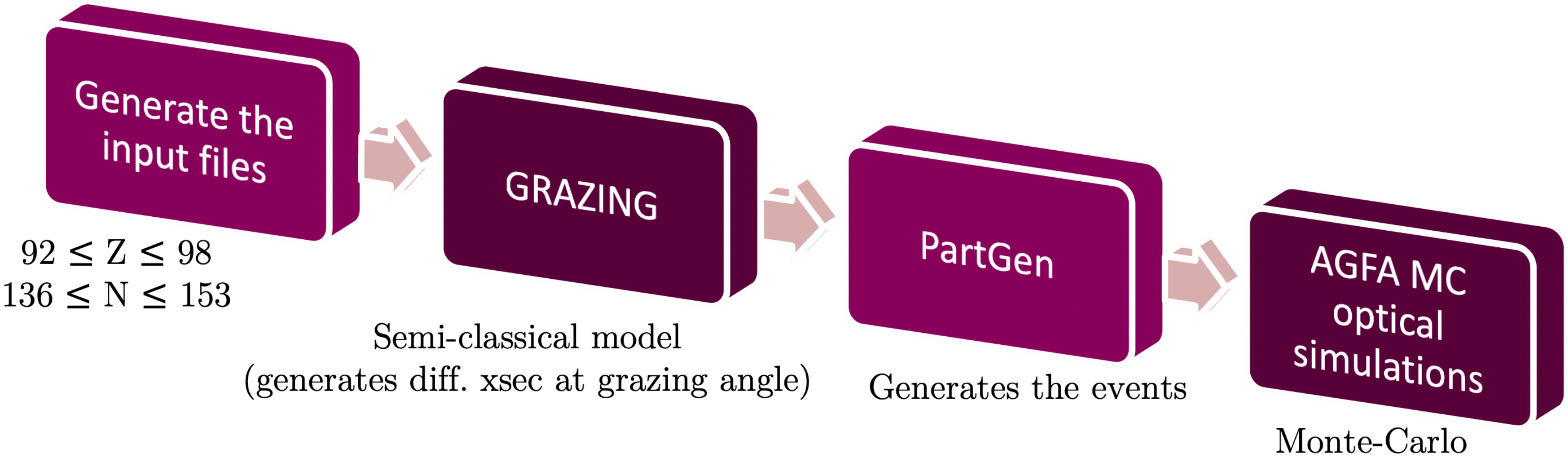
Integrated between 0-5°

Kinetic simulations (VGS code)

Developed by Ch. Theisen



Optical simulations (transmission of AGFA)



➢ **GRAZING Code:** (greetings to M. Siciliano)

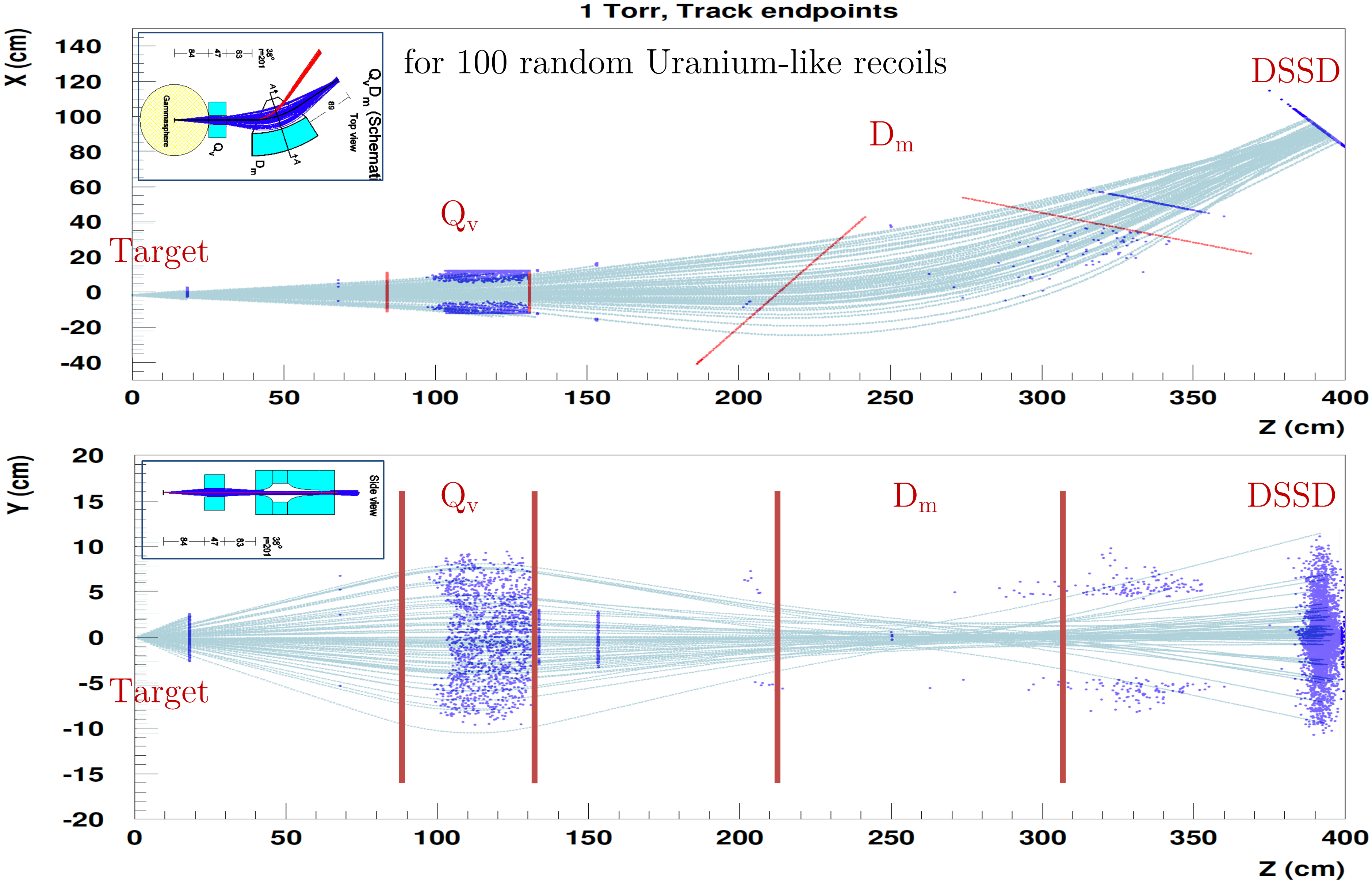
- **Aim: to produce an event generator to feed the AGFA MC simulation**
- Estimates the Q-value (with ame2012.cal)
- Generates the output files of the event generator

$$\mathbf{Z} \quad \boldsymbol{A} \quad \boldsymbol{Q} \quad \bar{\boldsymbol{Q}} \quad \mathbf{E} \quad \vec{\boldsymbol{x}} \quad \frac{\vec{\boldsymbol{p}}}{\|\vec{\boldsymbol{p}}\|} \quad \mathrm{B}\boldsymbol{\rho}$$

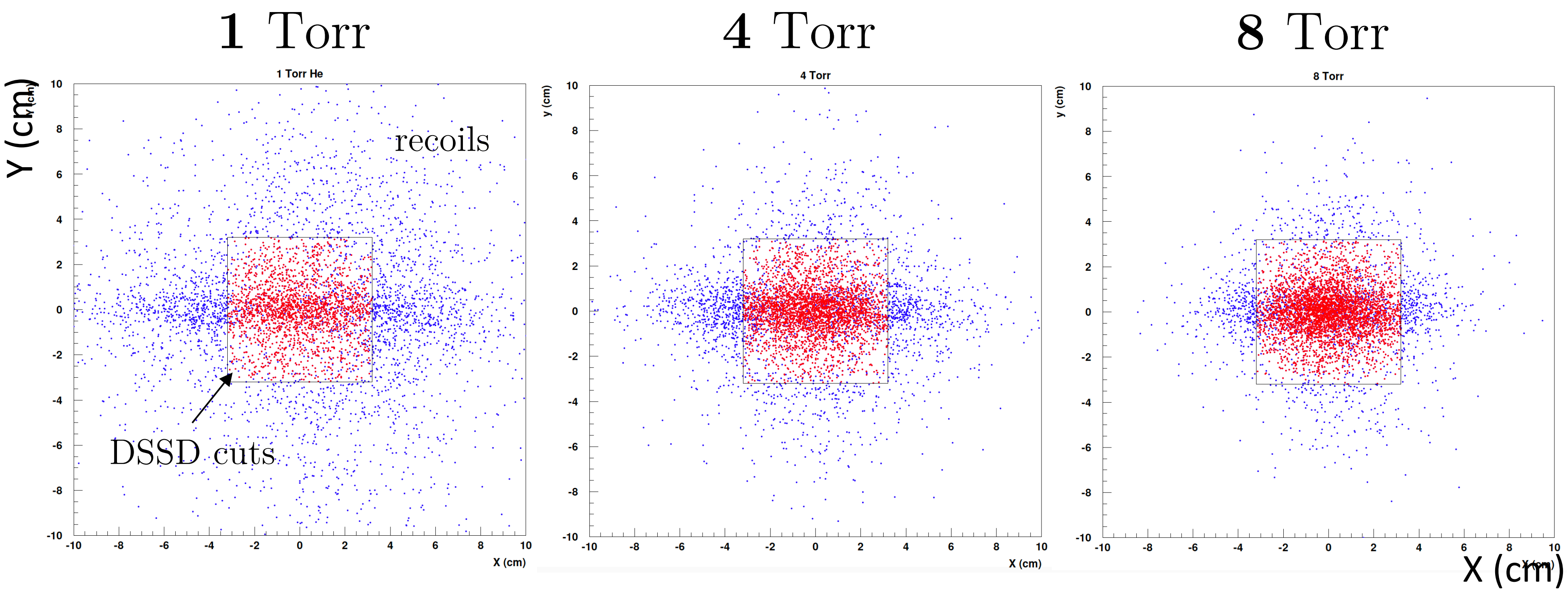
➢ **AGFA Monte-Carlo simulation:** (greetings to D.H. Potterveld)

- Charge state model: A. Ghiorso et al. NIM in PRA 269 (1988) 192-201
- Optical simulations of AGFA

AGFA Monte-Carlo simulations



AGFA Monte-Carlo simulations



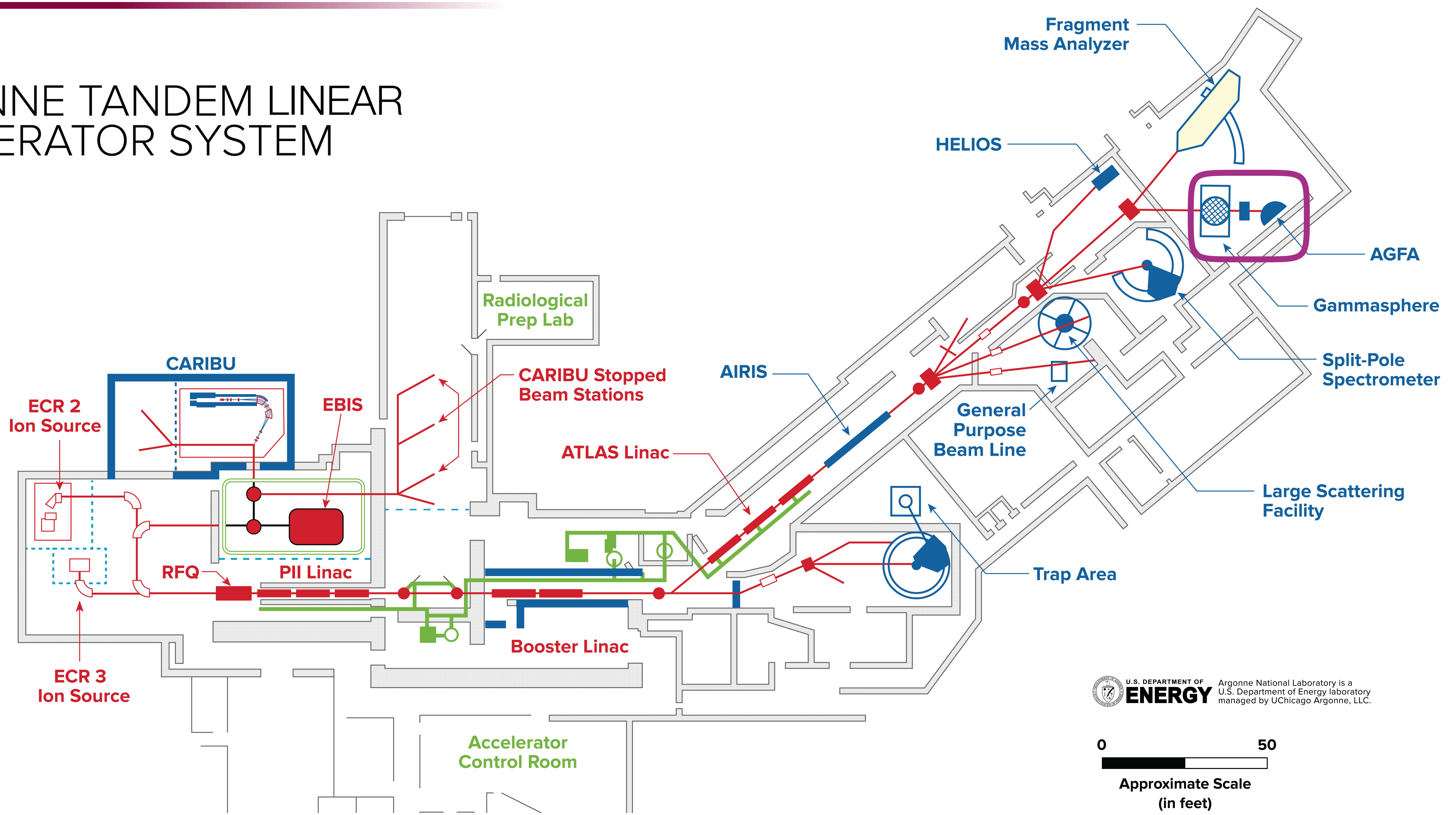
Pressure (Torr)	N_{AGFA}	N_{DSSD}	Transmission to the DSSD (%)
0.44	4735	1275	13.6
1.0	5159	1936	20.7
2.0	5215	2229	23.8
4.0	5384	3106	33.2
8.0	5114	3827	40.9

~28% at 3 Torr

ATLAS at Argonne

Argonne NATIONAL LABORATORY

ATLAS
ARGONNE TANDEM LINEAR ACCELERATOR SYSTEM



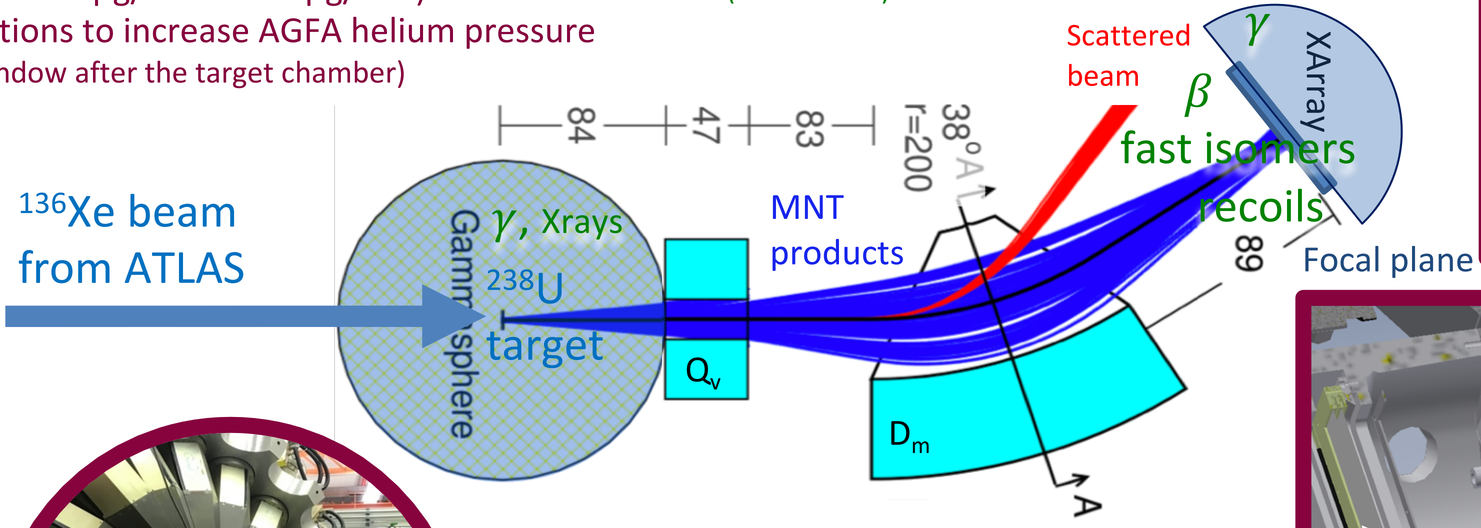
U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

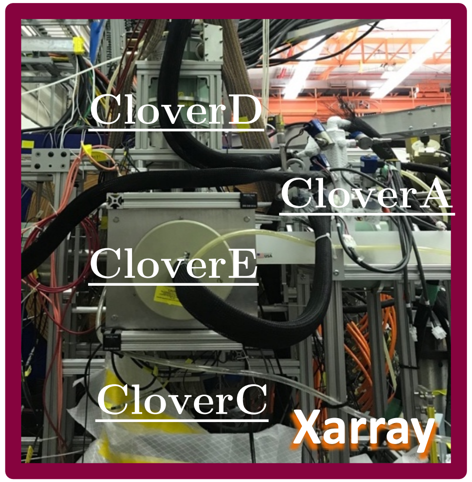
Multinucleon transfer reactions (MNT) at Argonne

- **Proof-of-principle experiment to study neutron-rich heavy nuclei using MNT reactions**
- 1st MNT reaction using AGFA @ANL to produce heavy nuclei
- **Beam**: ^{136}**Xe** @605, 705 and 809MeV
- **Target**: ^{238}**U** (UF4 300µg/cm^2 + C 40µg/cm^2)
- Innovative solutions to increase AGFA helium pressure up to 3Torr (Ti window after the target chamber)

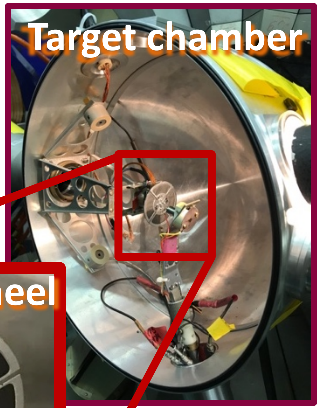
Target-like products identification

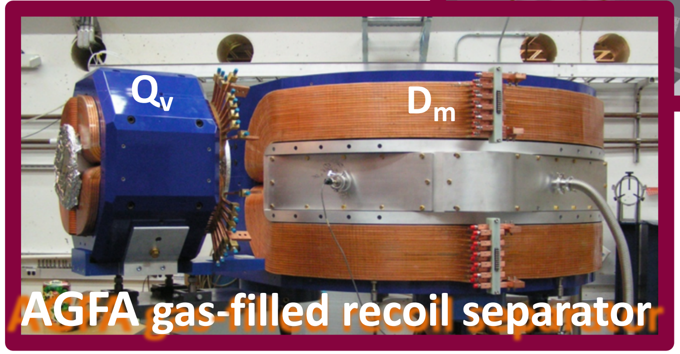
(coincidences)





Decay spectroscopy





Prompt spectroscopy

Argonne NATIONAL LABORATORY

Experimental conditions

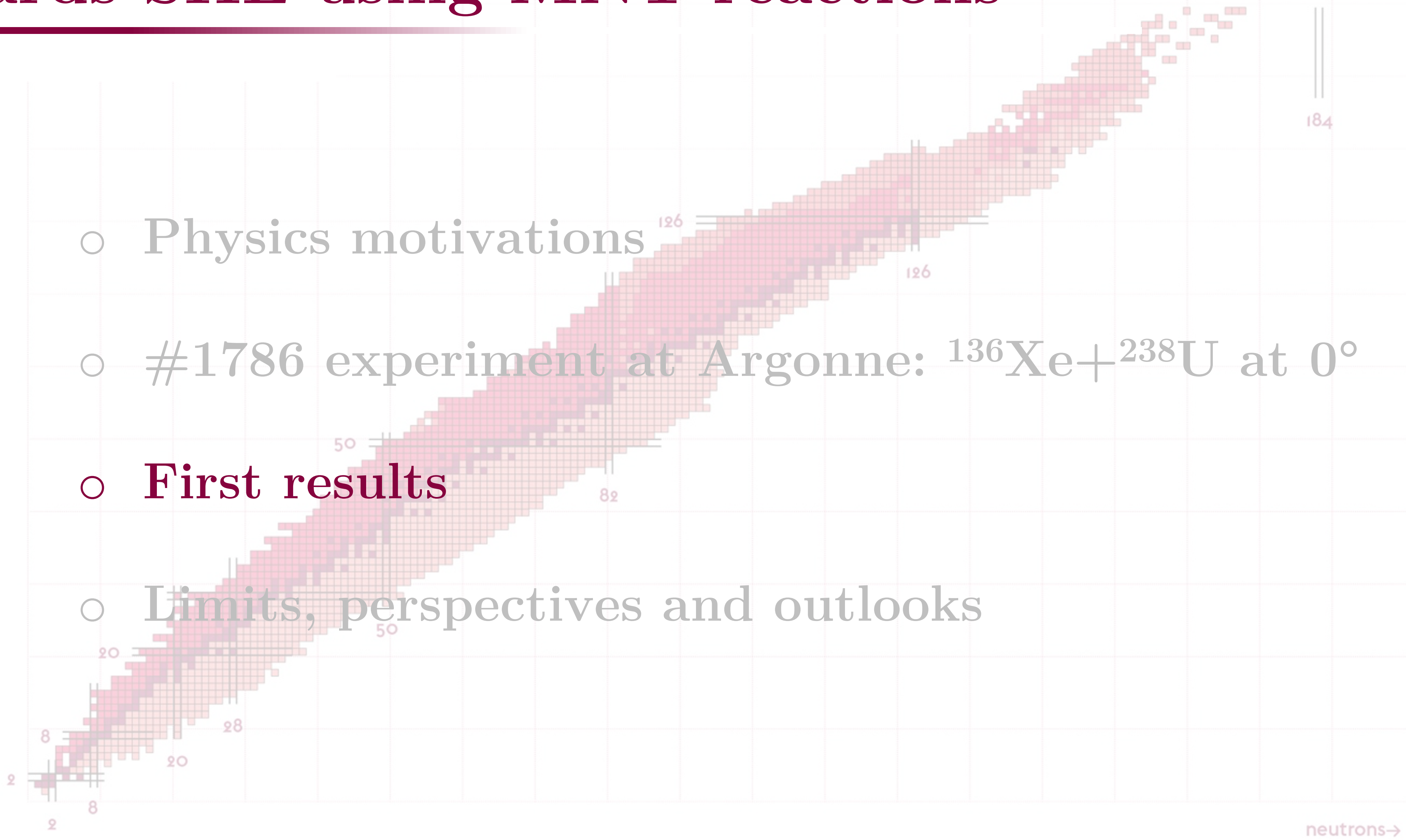
3 energies

Beam energy (MeV)	Run numbers	Theor. β=v/c (%)
No beam	1->19 ans 117->129	0
605	20->50	6.91
705	**73->116**	**7.55**
809	51->72	8.16

5 Bρ

Beam energy (MeV)	Run numbers	Bρ (Tm)
605	20	2.4
	21->27	1.8
	28	2.0
	29	2.2
	30	2.4
	21->50	1.8
705	**73->116**	**1.8**
809	51->66	1.8
	67->72	1.9

Towards SHE using MNT reactions



- Physics motivations
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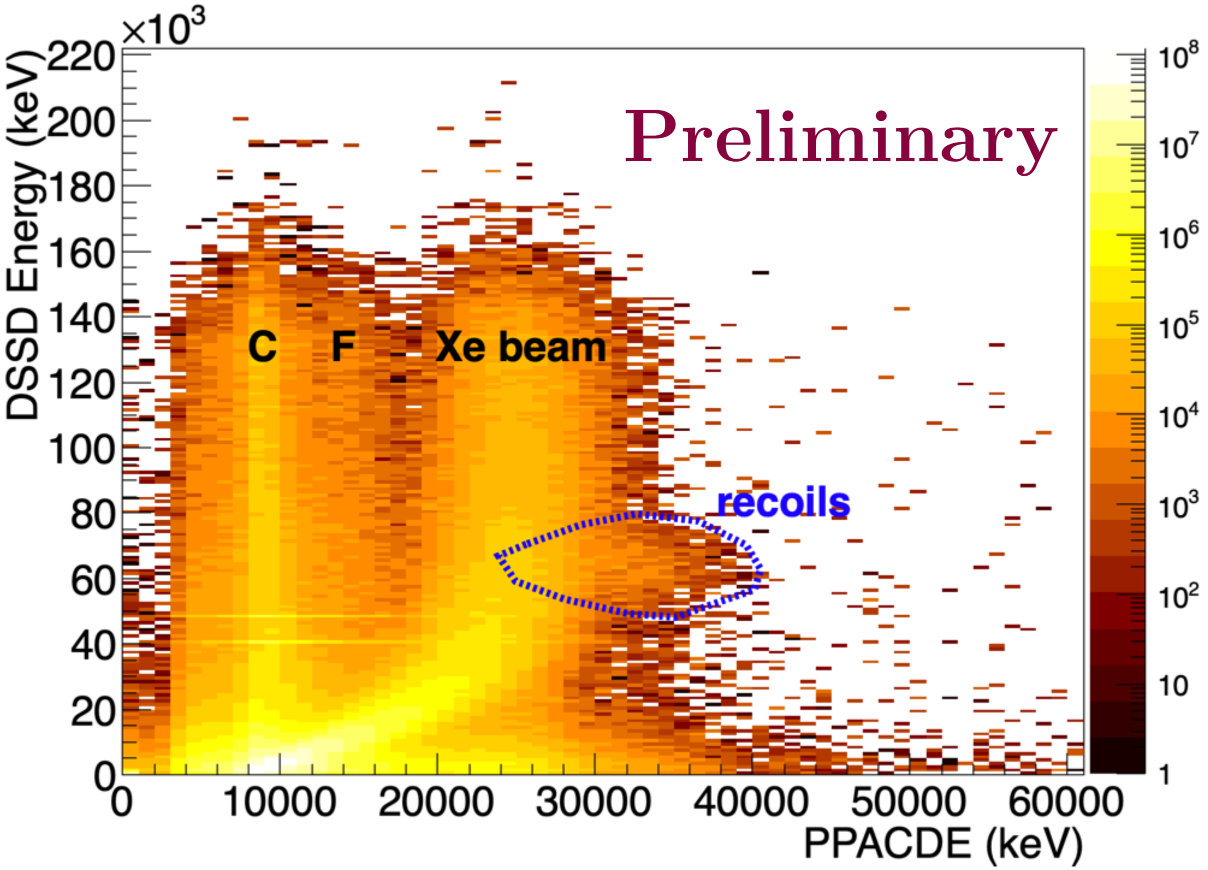
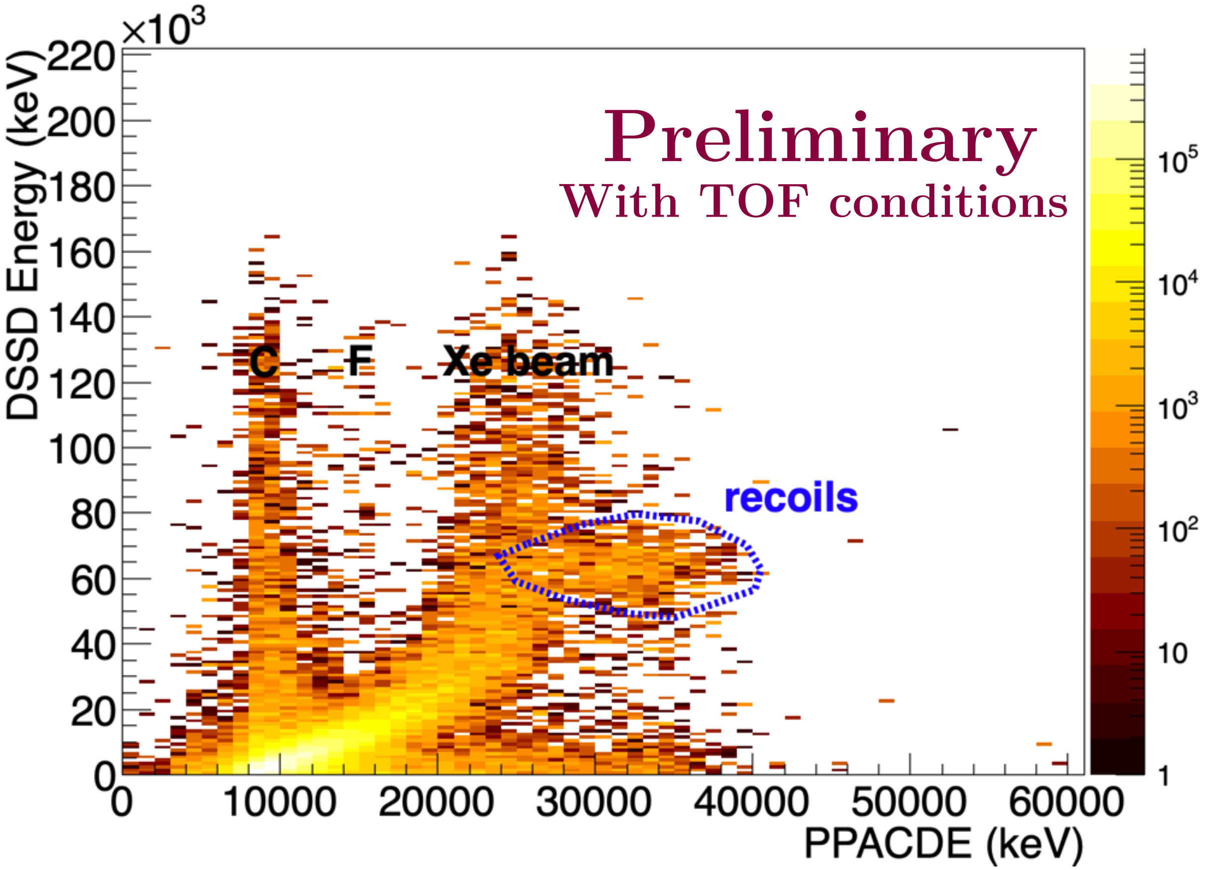
- **First results**
- Limits, perspectives and outlooks

Identification of neutron-rich nuclei (recoils)





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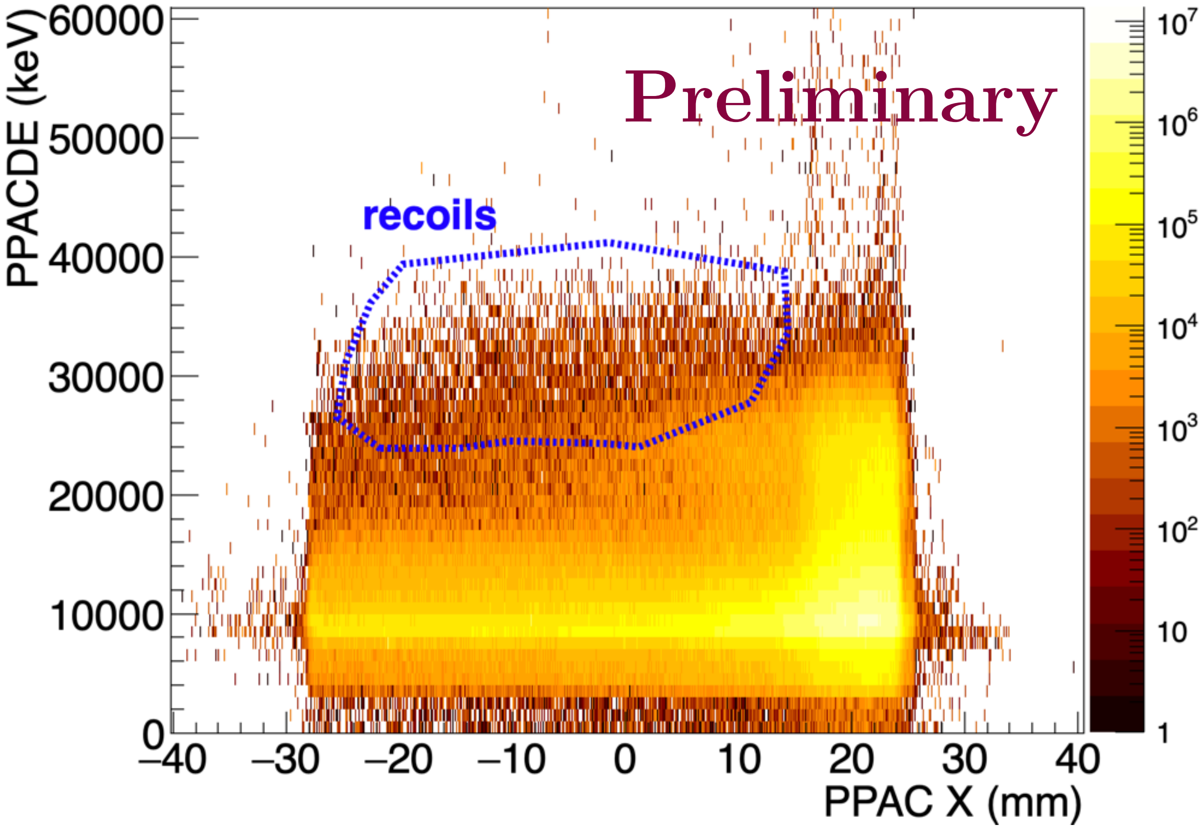

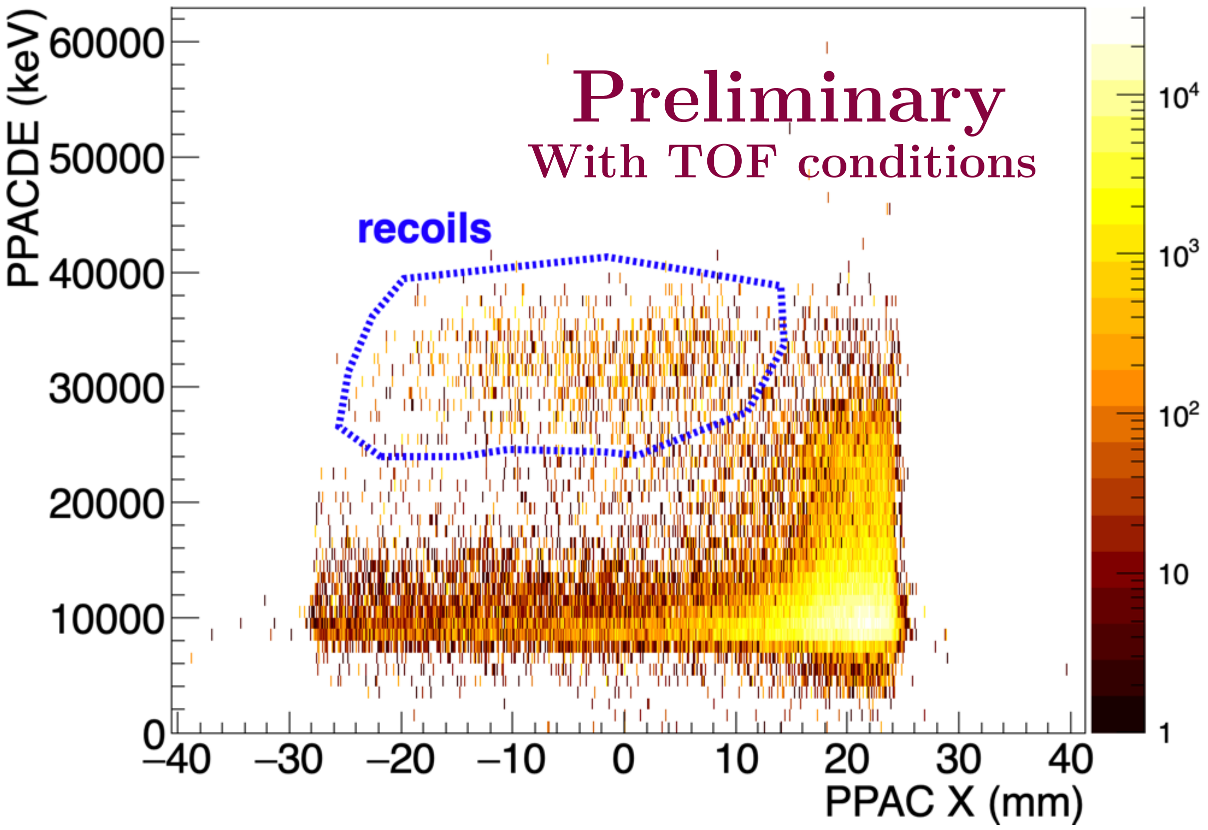

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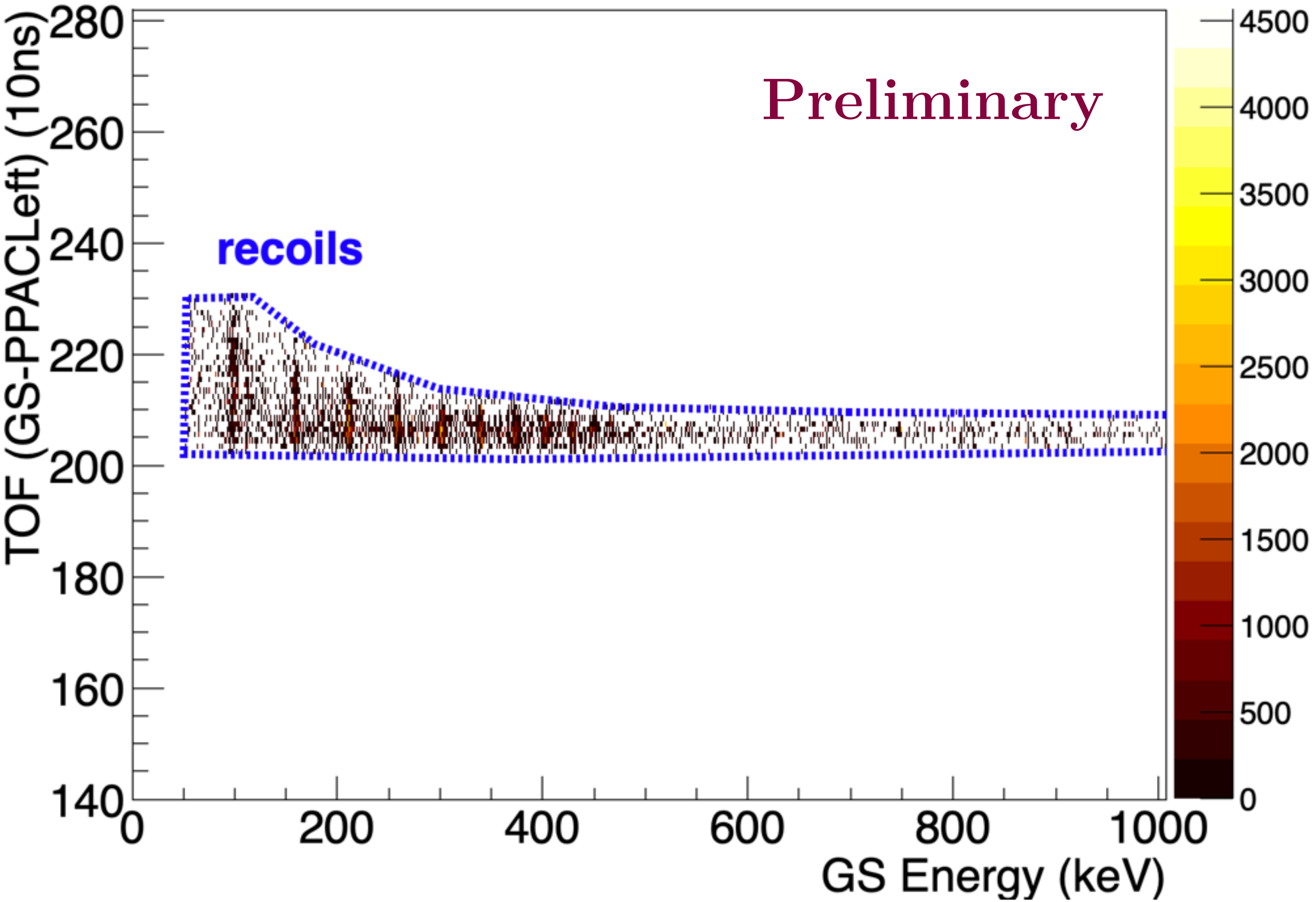
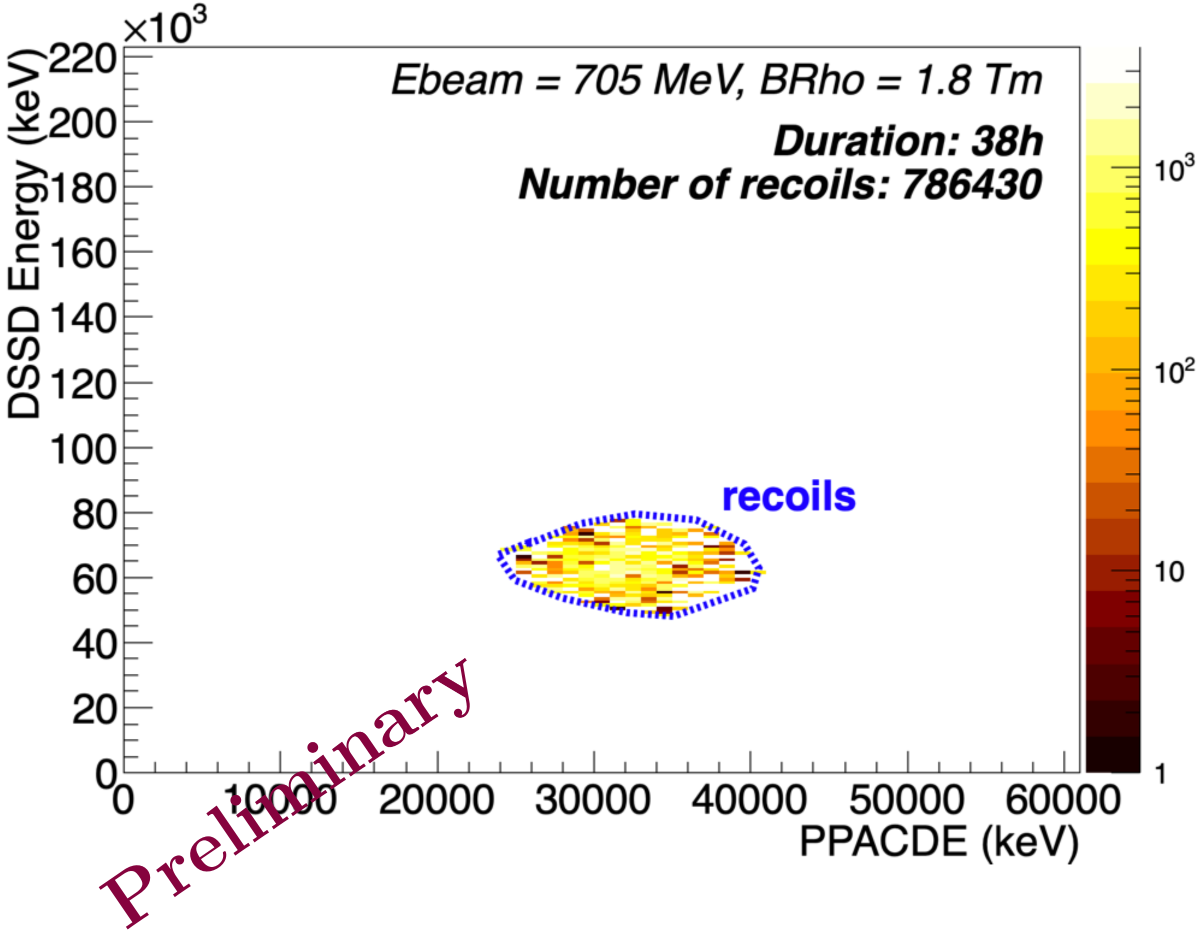
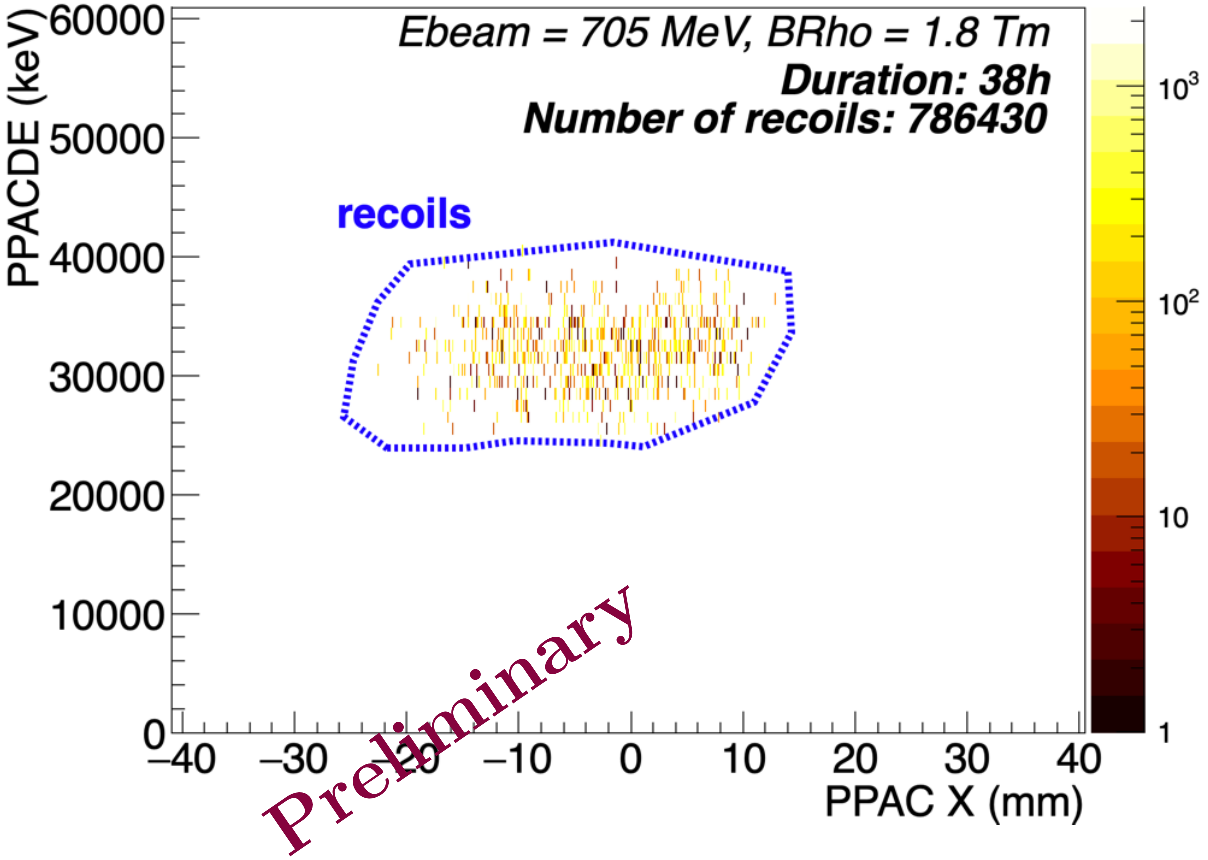


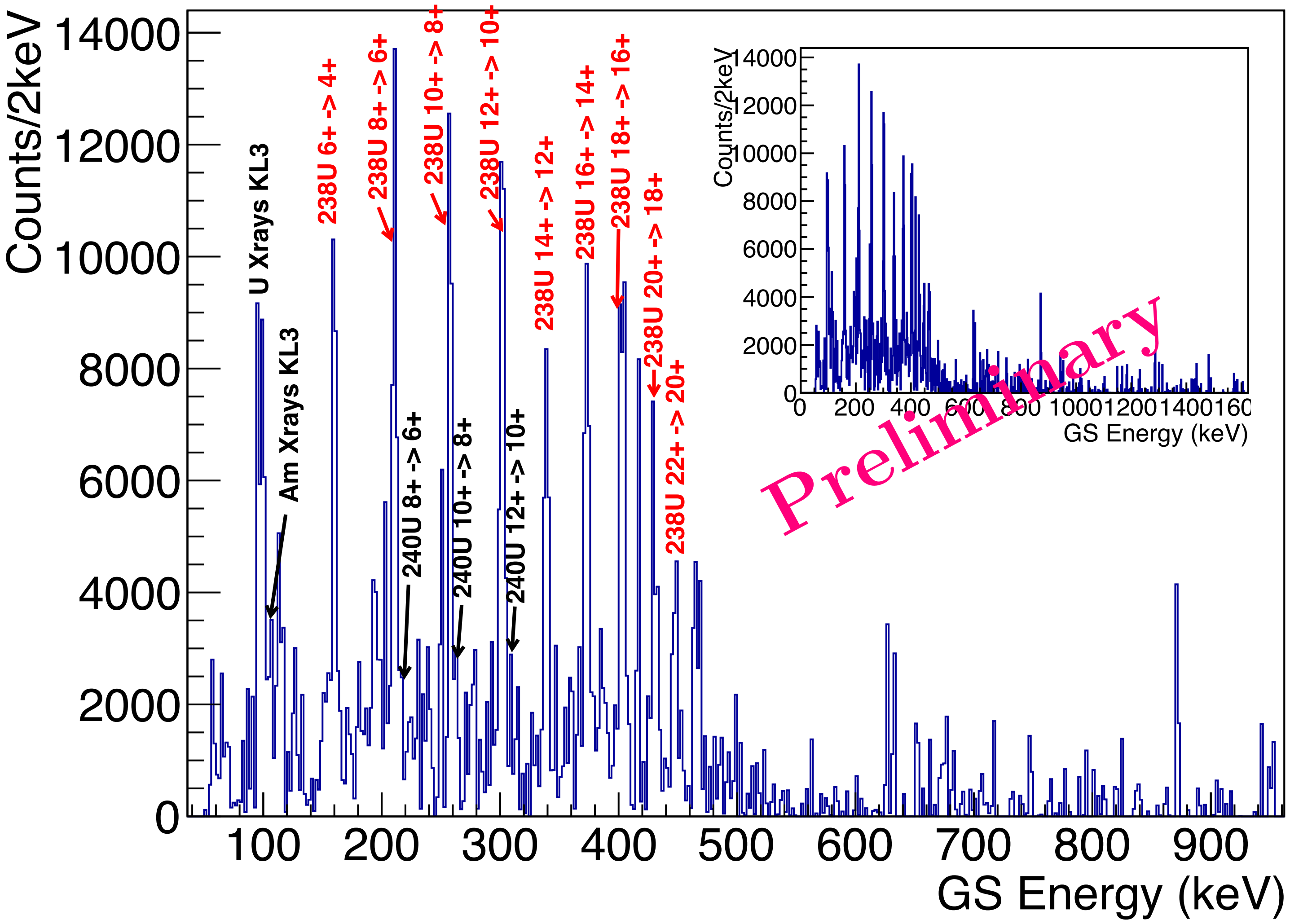
Identification of neutron-rich nuclei (recoils)

Correlations in time and position





Identification of neutron-rich nuclei (recoils)

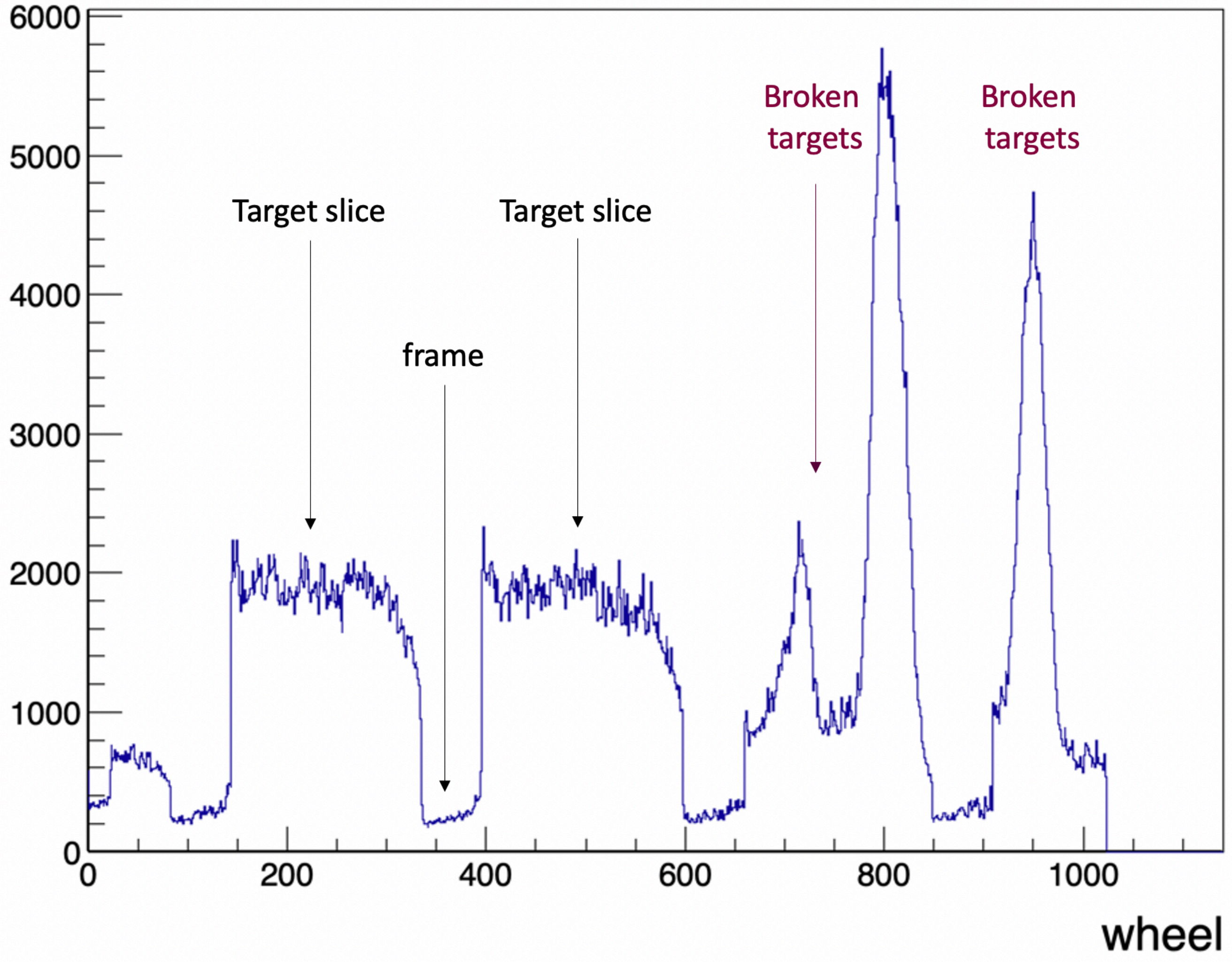


- $\gamma - \gamma$ correlations
- Transfer of 2n (^{240}U)
- Xrays of Am, Np, U (transfer of 1p, 3p)?
- Correlations with GS and XArray
- New accepted experiment at PAC2021 to get more statistics!

Towards SHE using MNT reactions

- Physics motivations
- #1786 experiment at Argonne: $^{136}Xe+^{238}U$ at 0°
- First results
- **Limits, perspectives and outlooks**

Main limits of the #1786 experiment



Lack of statistics

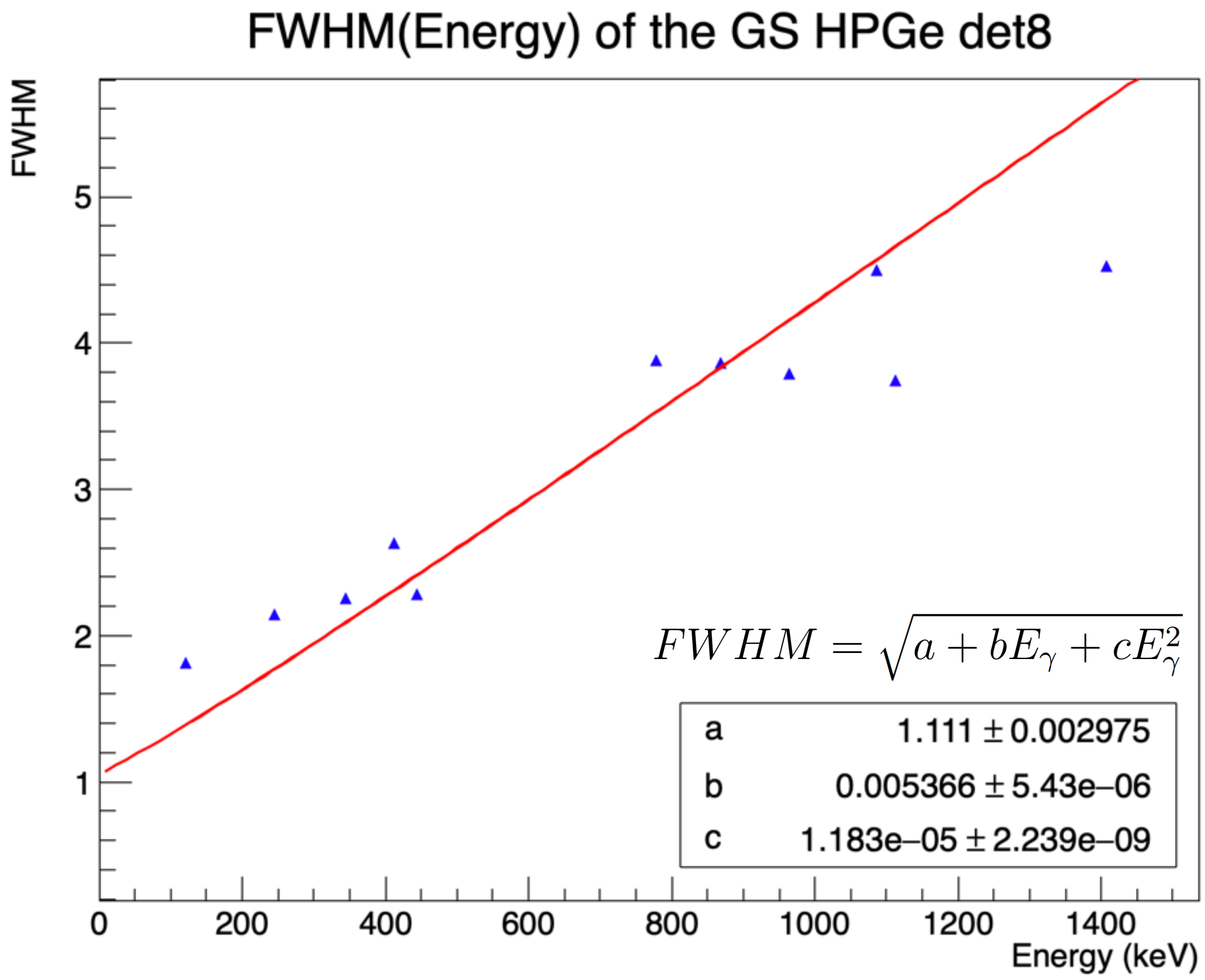
6.5 Shift losses due to:

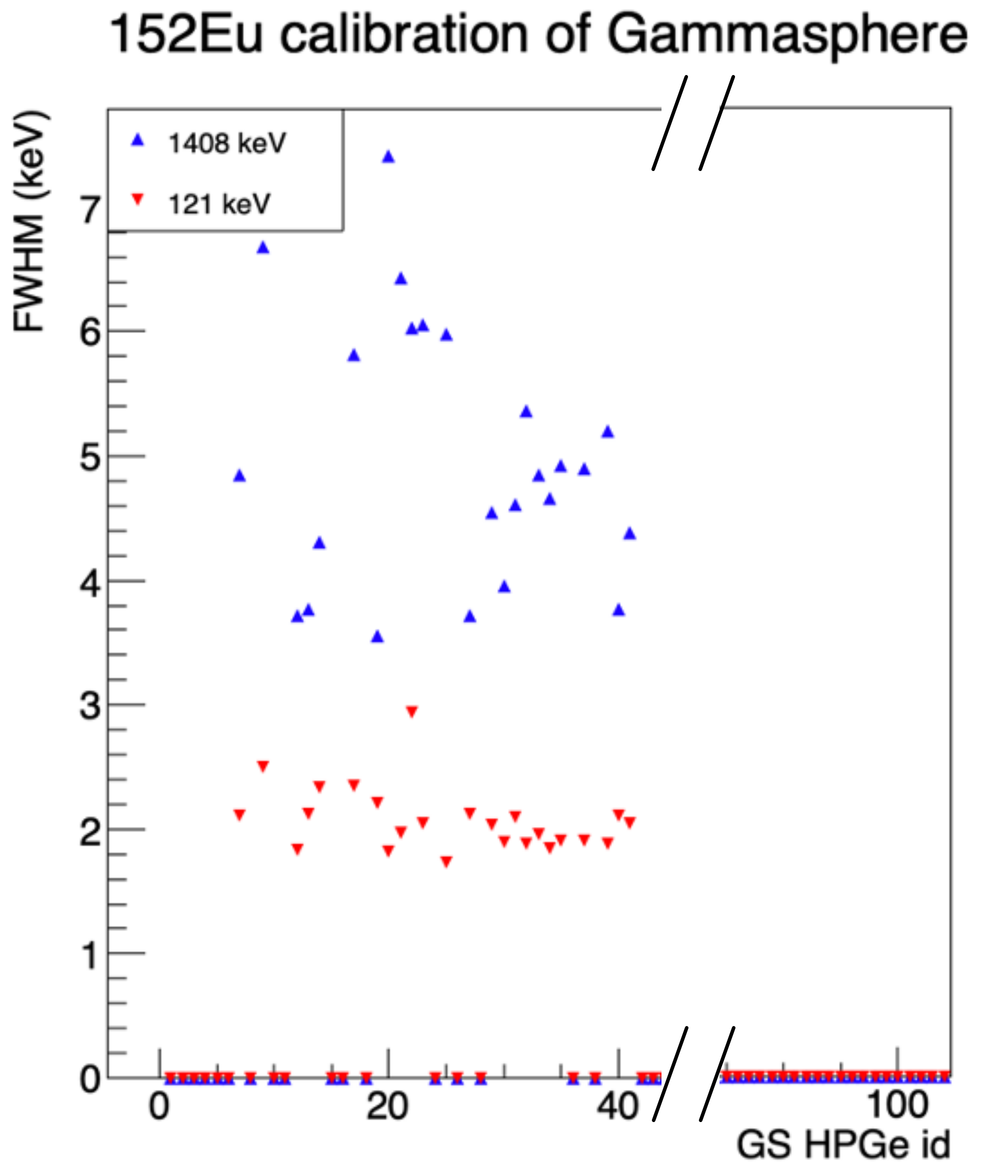
- DAQ issues (reboot IOTs)
- broken targets (mechanical constraints) had to vent, open the target chamber...

Limitations :

- APEX UF_4 targets, lots of fission events... had to decrease the beam intensity
- Frequency in the GS crystals
- 70/110 working detectors of GS
- bad resolution of the GS crystals
- can not rely on alphas
- no mass identification

GS Calibration with a ^{152}Eu source





New #1930 experiment accepted PAC 2021

- **$^{136}Xe+^{238}U$ at 0°**
- **New metallic targets manufactured at GSI**
  (thanks to B. Lomel, B. Kindler, and their team)
  Not the old APEC UF_4 ones
- **Annealing of some GS detectors: 70 → 110?**
- **More beam intensity (from 2.25 to 20pnA)**
- **More gas pressure from 3 to 5 Torr in AGFA**

- **PAC2019 (#1786) For the E_{beam}=705 MeV:**
  We collected 786 430 recoils, within 38h at 2.25pnA
  i.e a rate of 20755 recoils/h
  These recoils emitted 4.7 10^7 single-gammas.

- **PAC 2021 (#1930) For the E_{beam}=705 MeV:**
  Running at 20 pnA with the same beam for 110 working detectors in Gammasphere (instead of 70), during 4 days (96 hours)
  we expect 1.7 10^7 recoils **(gain of factor 20)**
  emitting 1.7 10^8 single-gammas **(gain of factor 35).**

Conclusions and perspectives

- Simulations and particle generator
  - Kinetic and optical simulations
  - Helped us predict the separation power of AGFA for MNT reactions

- MNT at Argonne
  - First proof-of-principle experiment of MNT using AGFA
  - Good separaton of the BLFs and TLFs with AGFA
  - First transfers observed to be confirmed with the new experiment (PAC2021)

- MNT at GSI/FAIR
  - First experiments with TASCA and SHIP for SHE with MNT
  - See the talk of Timo Dickel

- MNT for VHE and SHE
  - A new path for neutron-rich VHE and SHE
  - Towards the “Island of Stability”? Mass identifications with gas-cells?

A few words on SIRIUS/S³/SPIRAL2

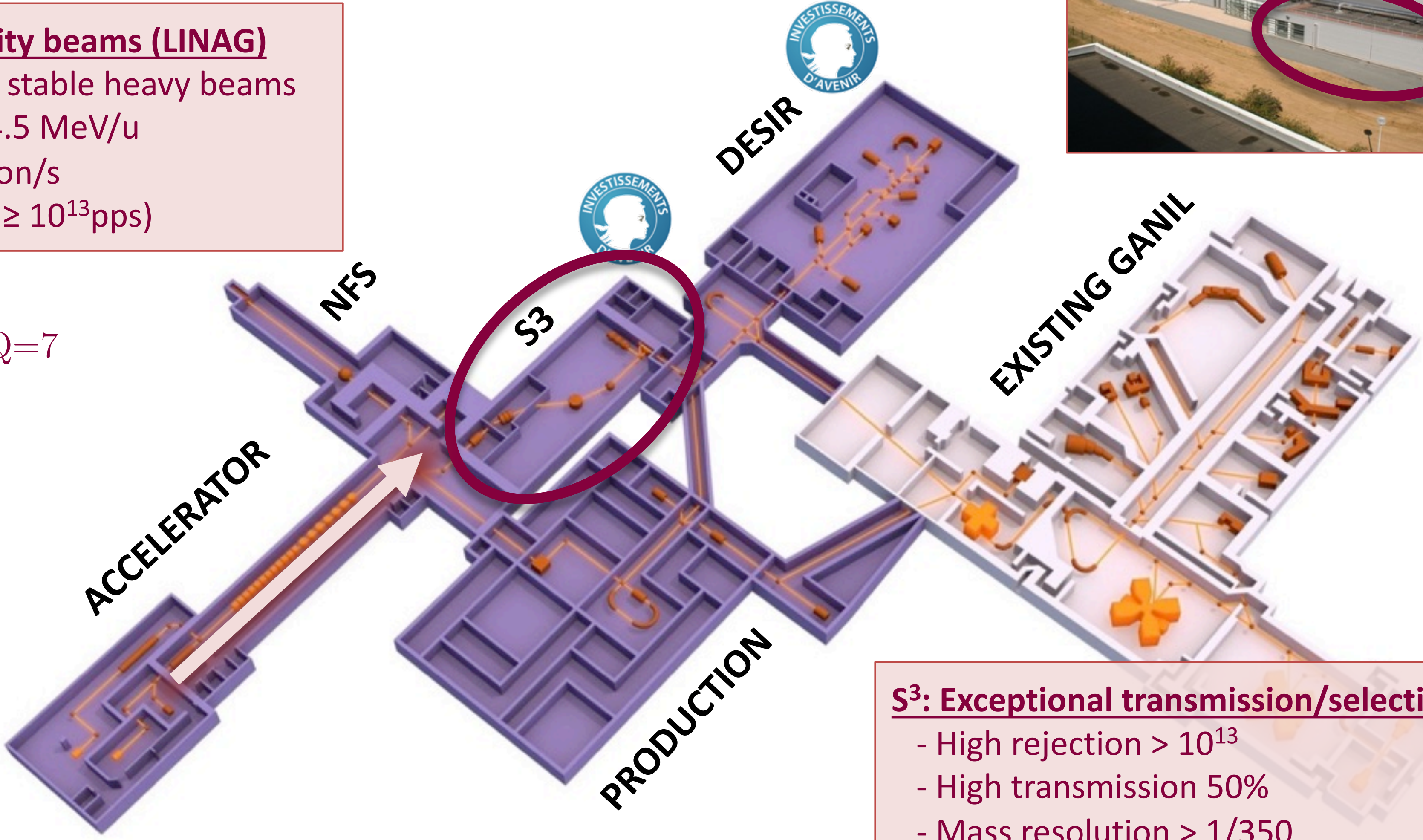
At GANIL

S^3 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 1pμA (≥ 10^{13}pps)

A/Q=3
NEWGAIN A/Q=7

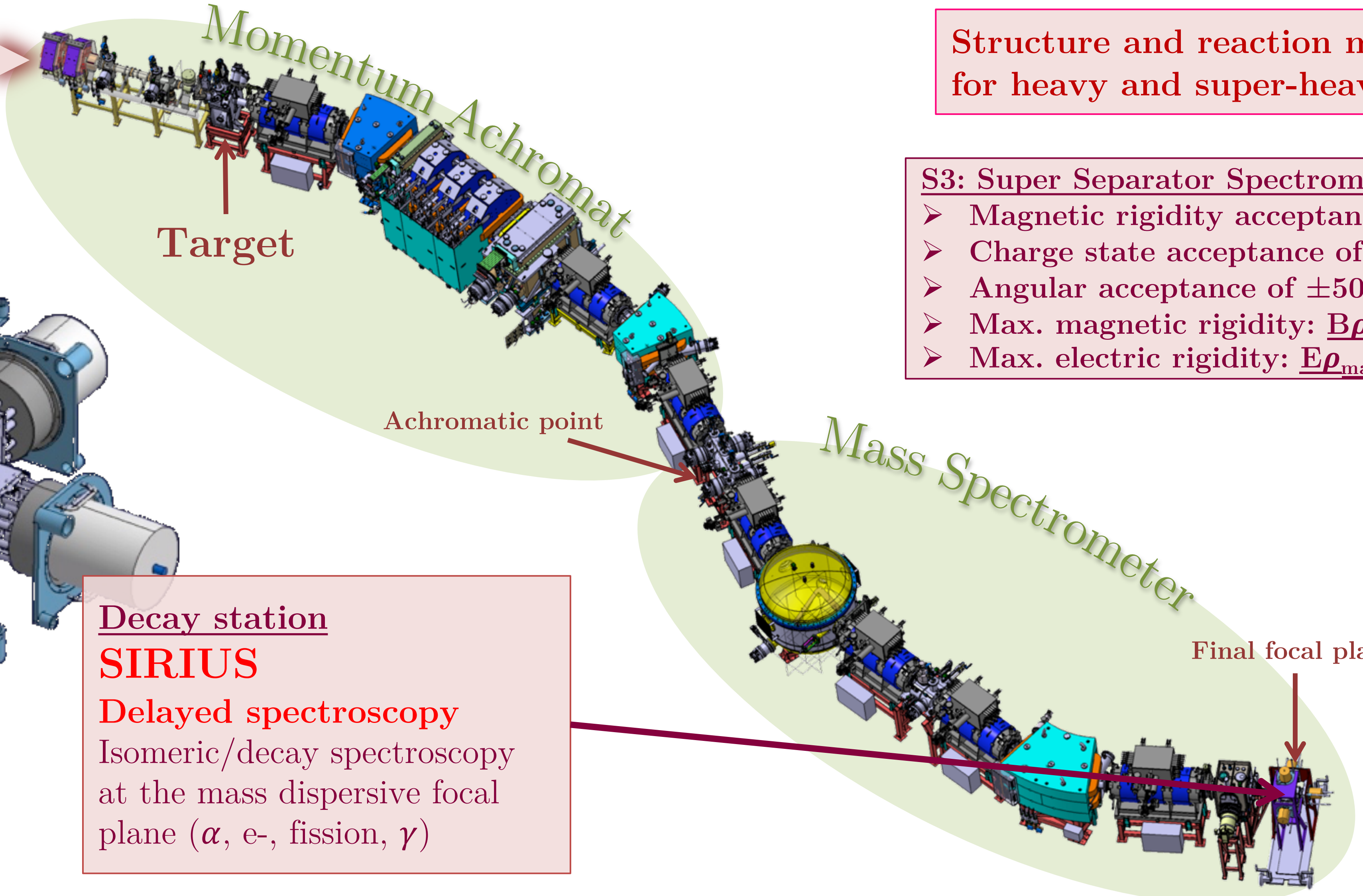


S^3: Exceptional transmission/selection combination

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

A cutting-edge instrumentation for S^3
(SIRIUS, LEB, FISIC…)

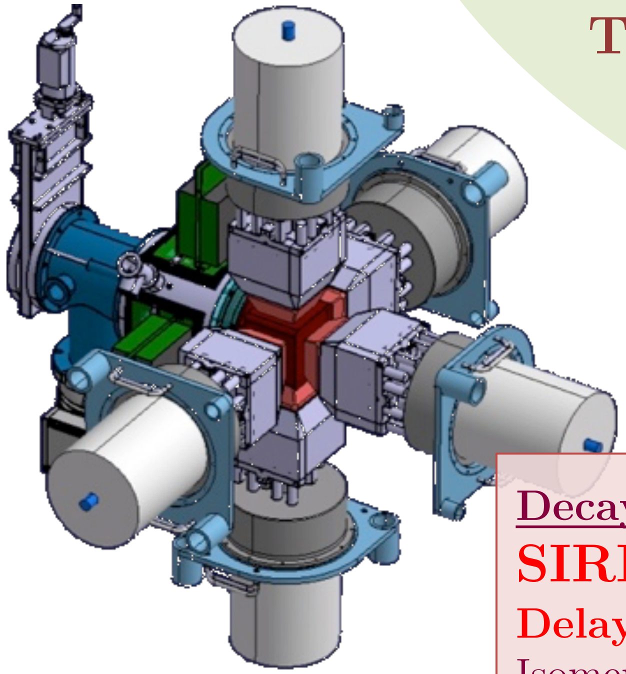
S^3: Super Separator Spectrometer



Structure and reaction mechanism for heavy and super-heavy nuclei

S3: Super Separator Spectrometer

- Magnetic rigidity acceptance of ±7%
- Charge state acceptance of ±10%
- Angular acceptance of ±50 mrad
- Max. magnetic rigidity: $B\rho_{max} = 1.8Tm$
- Max. electric rigidity: $E\rho_{max} = 12MV$



Decay station

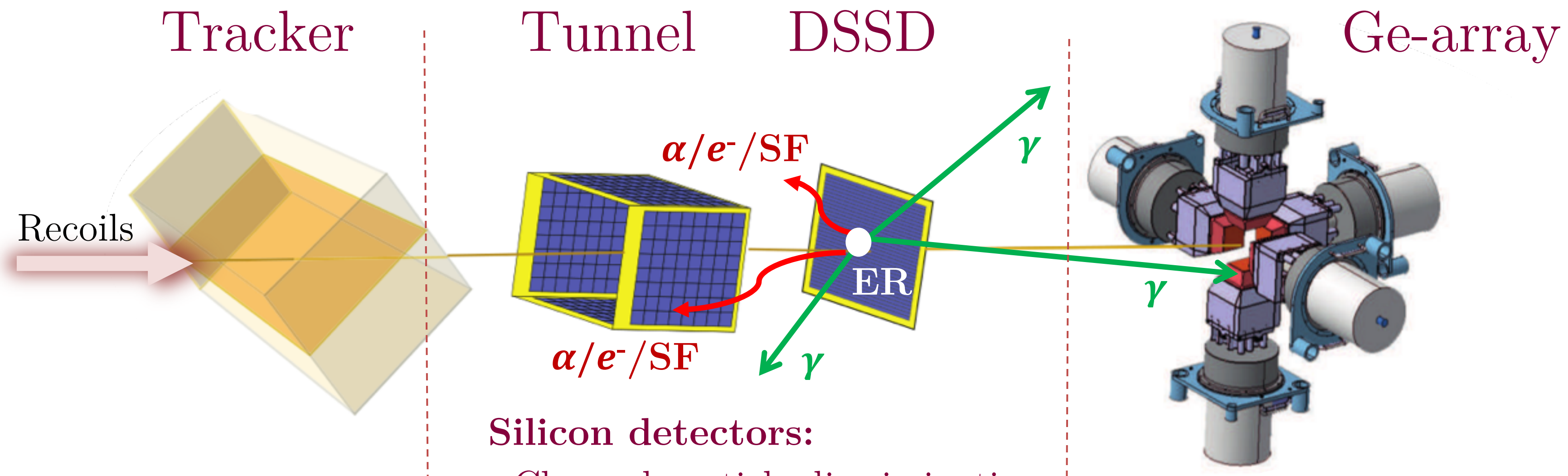
SIRIUS

Delayed spectroscopy

Isomeric/decay spectroscopy at the mass dispersive focal plane (α, e-, fission, γ)

SIRIUS decay station

SIRIUS: System for the Investigation of Recoiling Ions Using S3



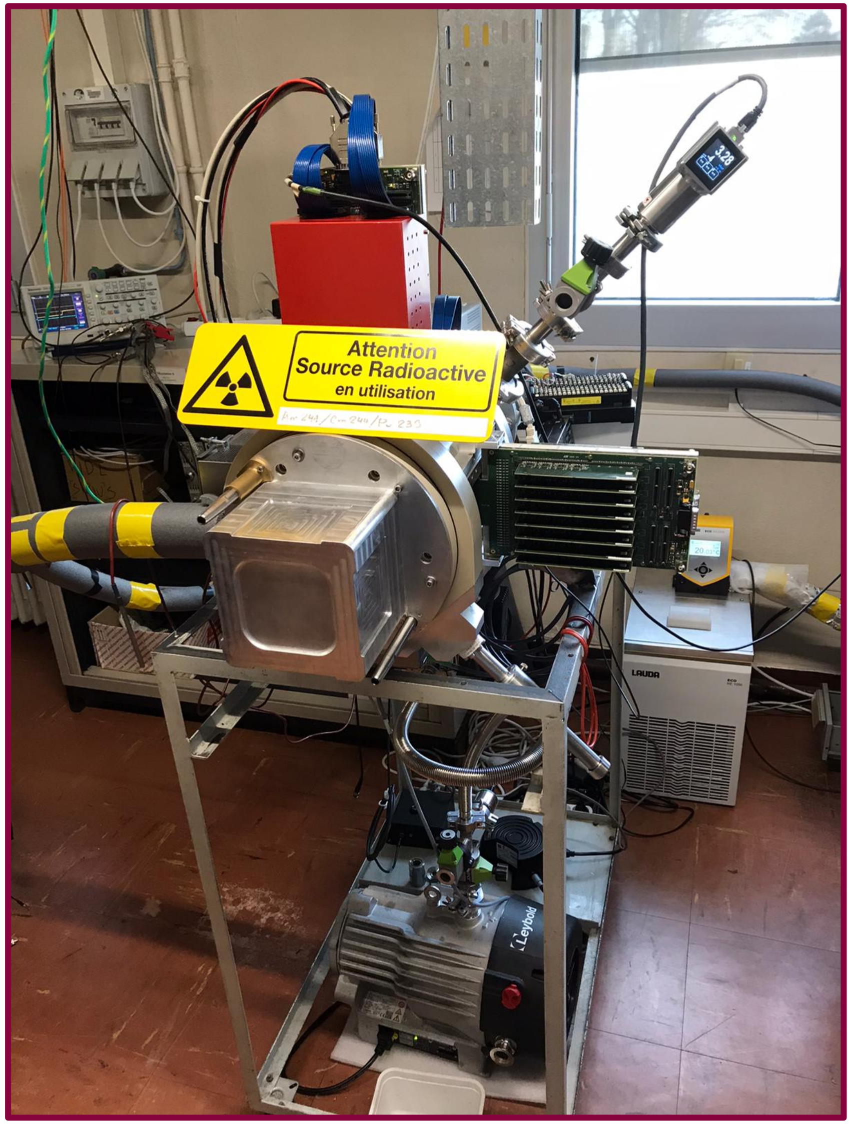
Time of Flight:
- Emissive foil
- Thin windows
- High Time resolution
- Mass Identification $A/\Delta A$ ~300

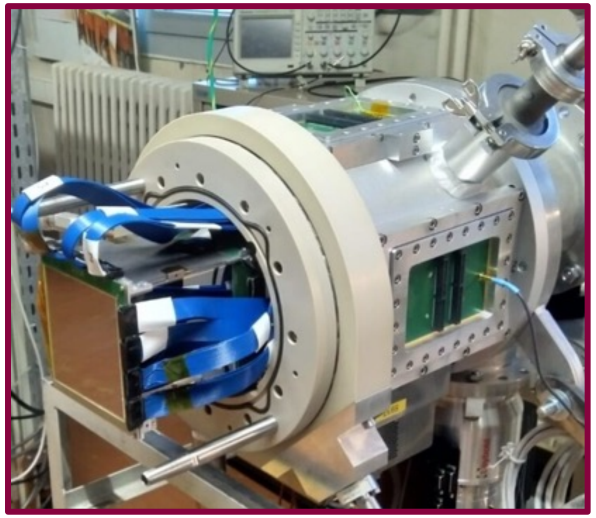
Silicon detectors:
- Charged particle discrimination for recoil, beta and decay alpha
- High resolution alpha and conversion electron spectroscopy
- Measurement of TKE for spontaneous fission
- Access to short decay times

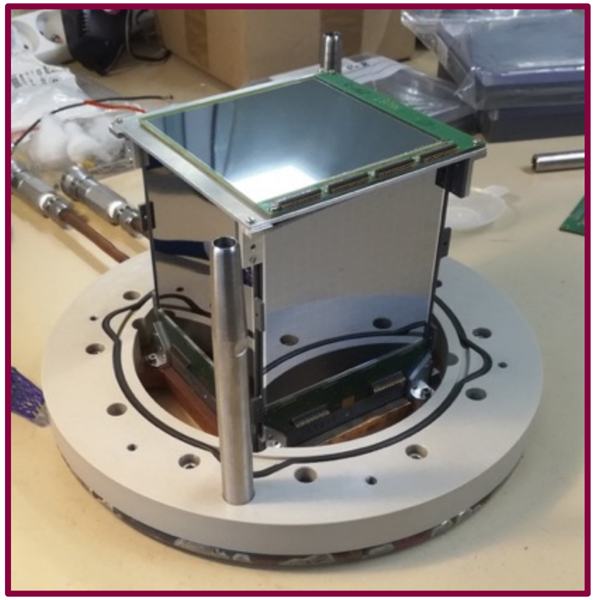
γ-ray detection :
- 5 EXOGAM clover detectors
- Efficiency of 40% at 121 keV

Digital electronics:
Digital signal processing

SIRIUS detectors







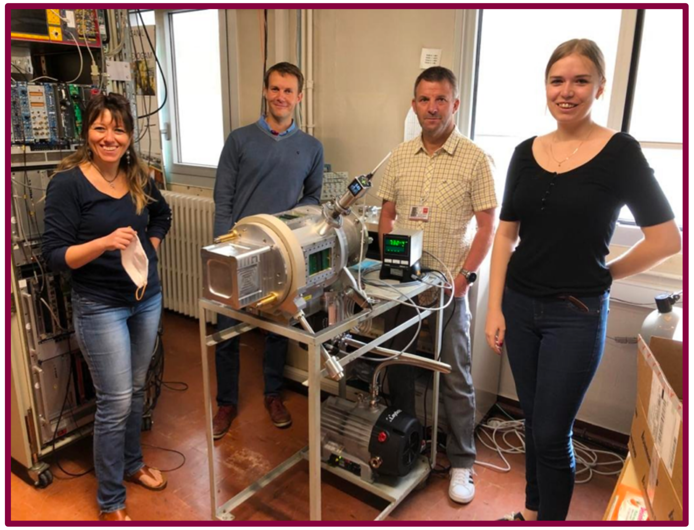
Decay station

SIRIUS

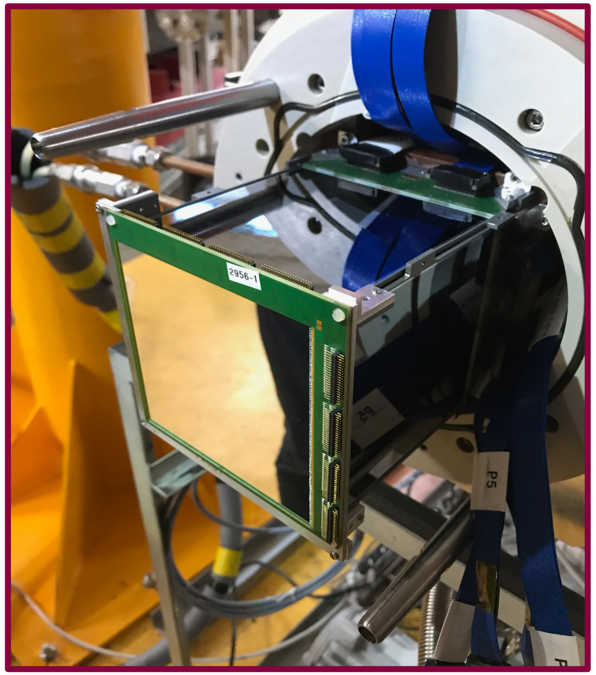
Delayed spectroscopy

Since July 2020 at **CEA/Irfu**

Complete chamber from Strasbourg.
Tunnels from IJClab.
DSSD and electroncs from CEA/Irfu.
Offline commissioning (sources α, β^-)



SIRIUS detectors



Decay station

SIRIUS

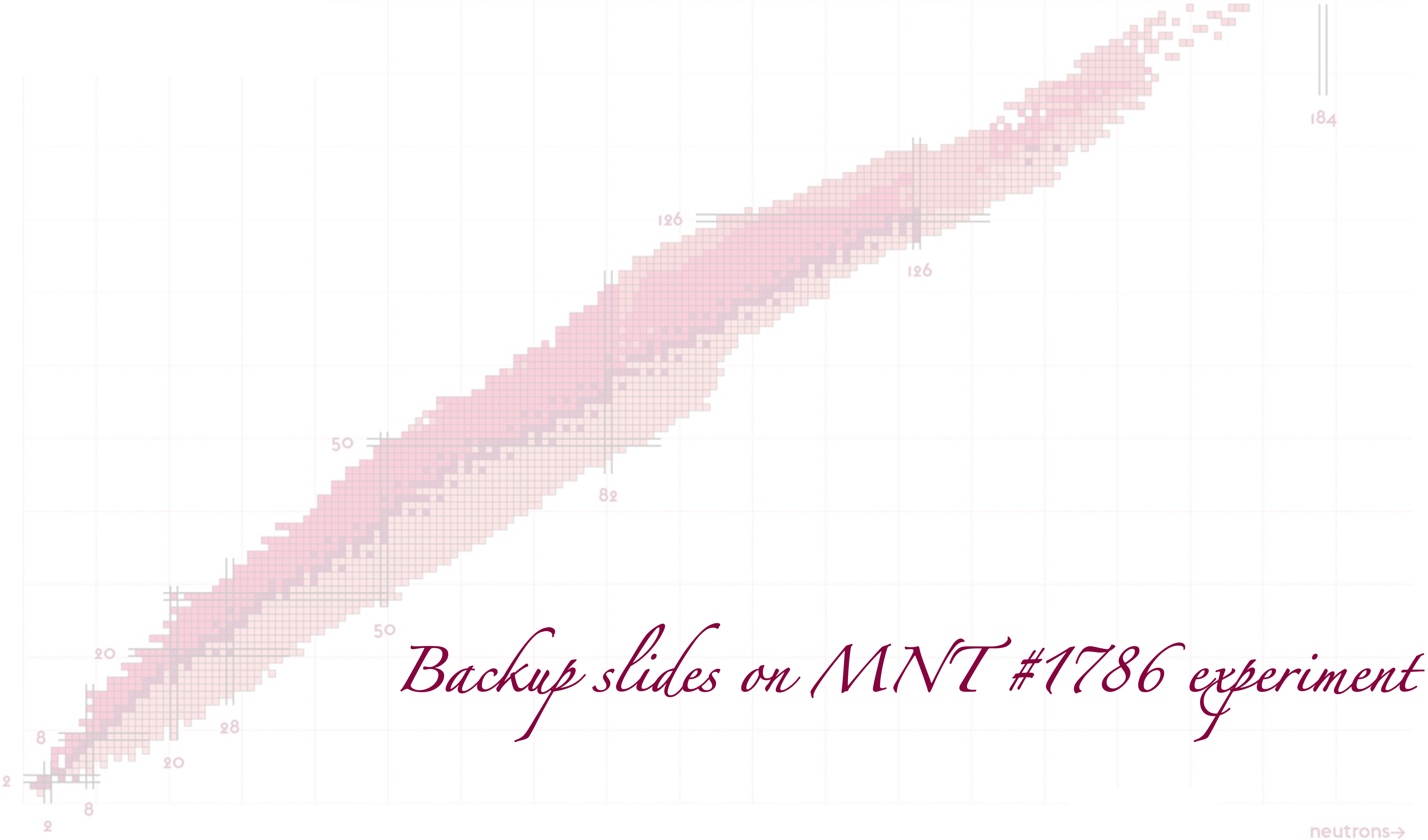
Delayed spectroscopy

Since March 2021 at **GANIL**

Complete chamber from Strasbourg.
Tunnels from IJClab.
DSSD and electroncs from CEA/Irfu.
Offline commissioning (sources α, β^-)

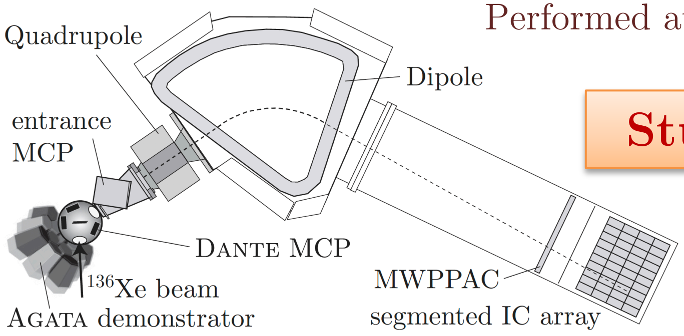
Thank you

for your kind attention



Backup slides on MNT #1786 experiment

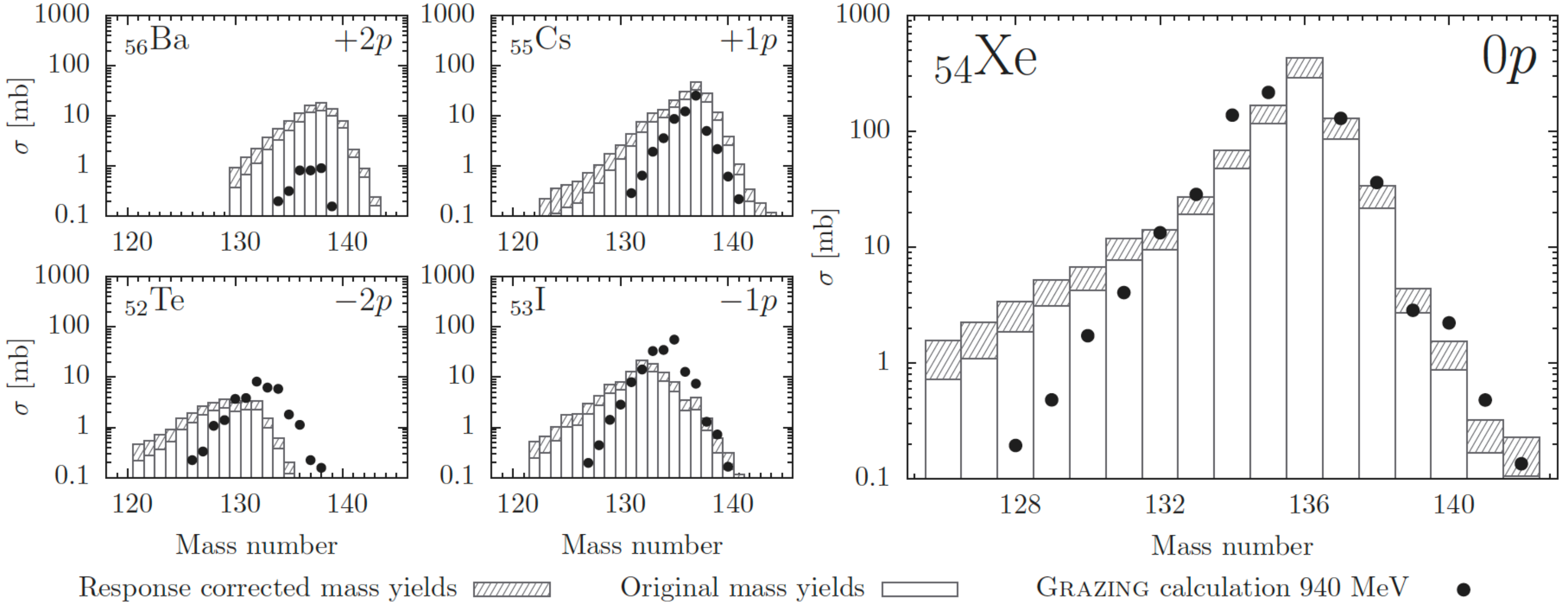
MNT 136Xe+238U at 1GeV and θlab~50°

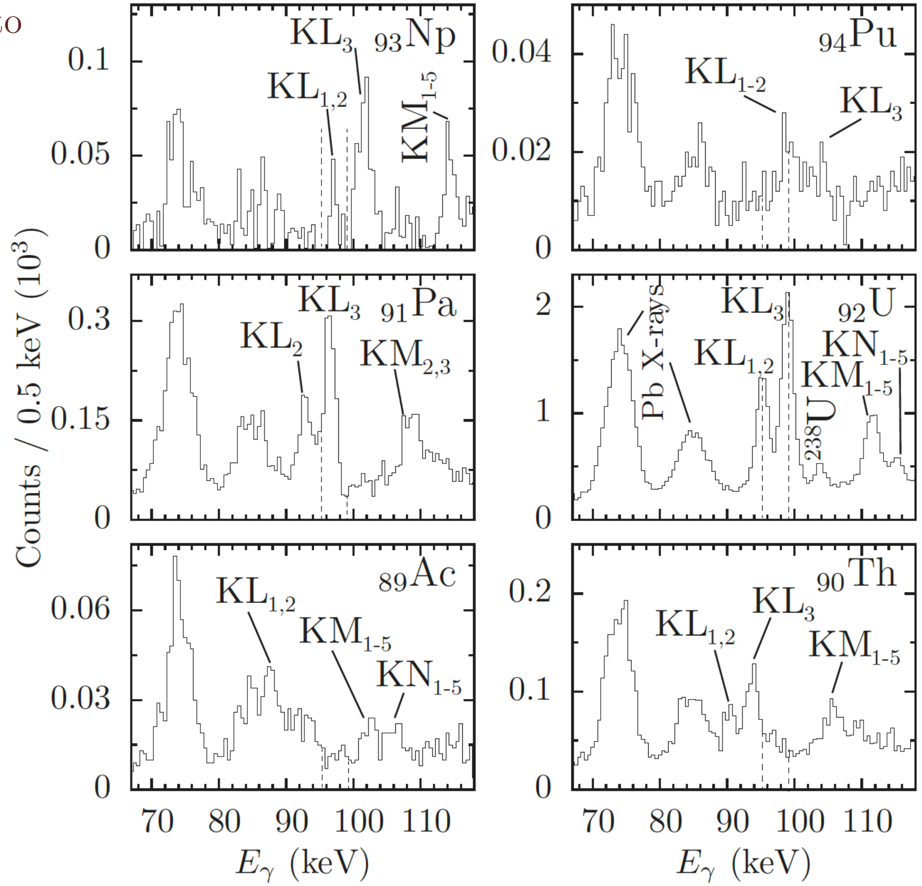


Performed at INFN LNL

Study of the beam-like (light fragments) and target-like (heavy fragments)

Cross sections of GRAZING calculations and experimental yields (histogram bars) normalized to the calculated cross section of the +1 channel of ^{137}Xe.

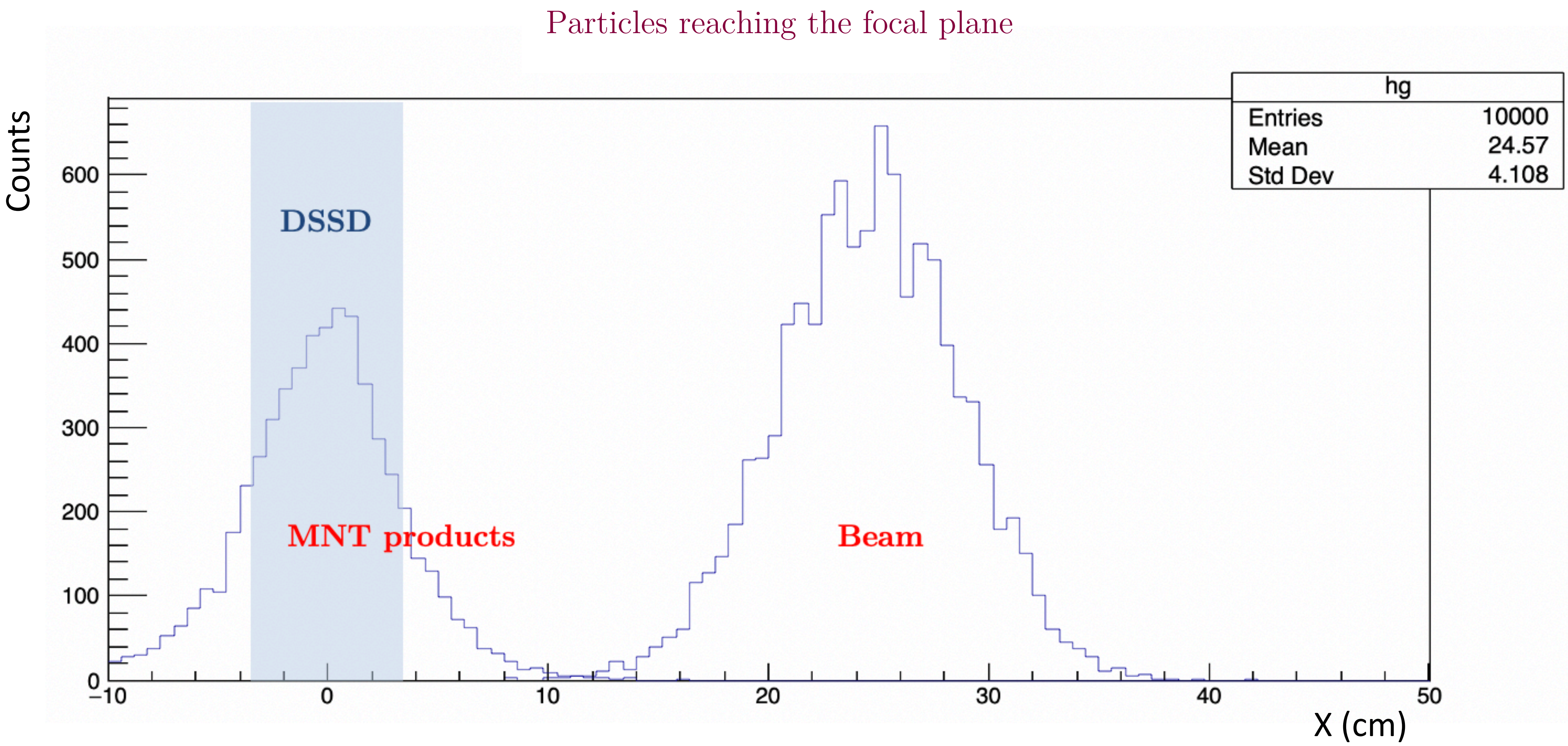




A. Vogt, et al. PRC 92, 024619 (2015)

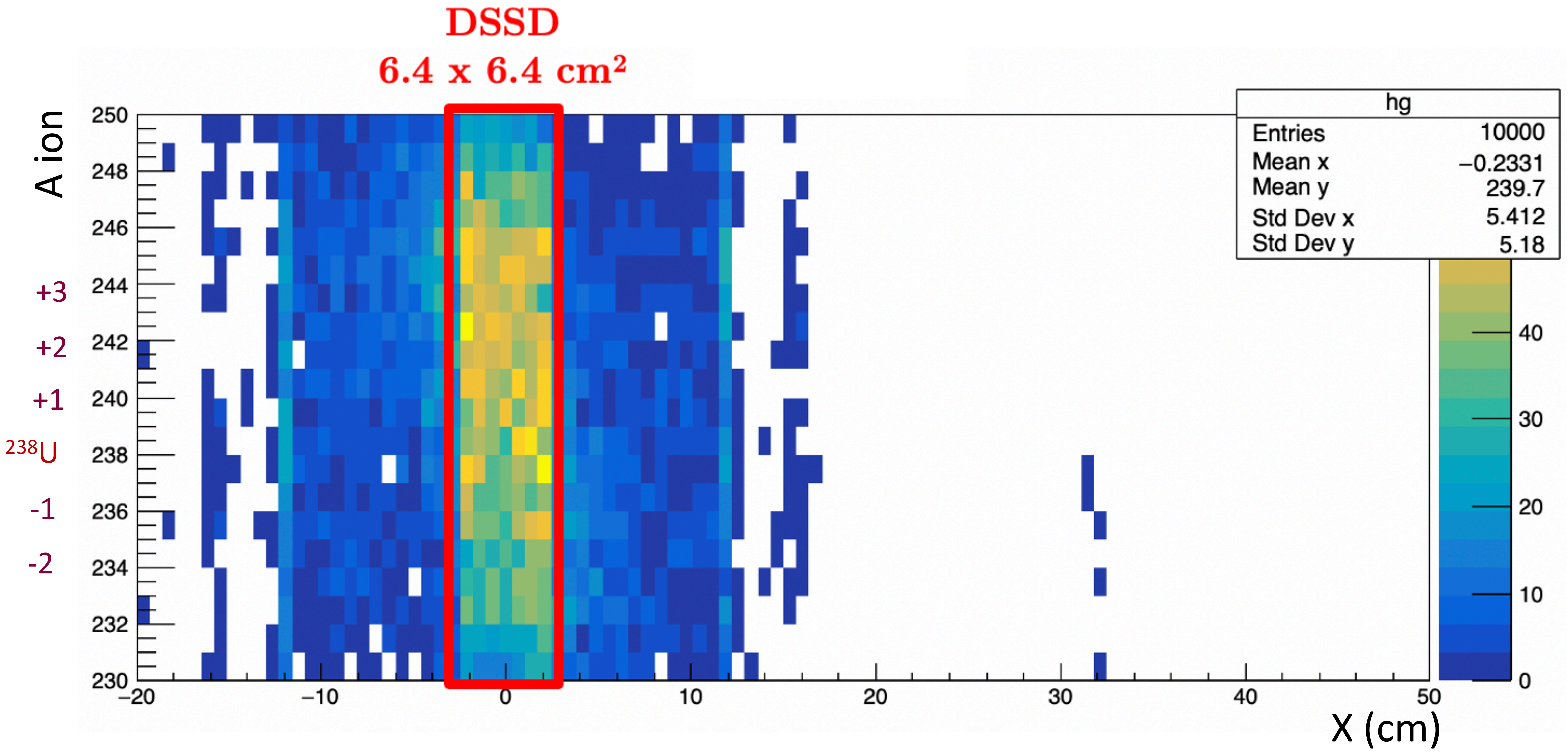
AGFA Monte-Carlo simulations

At 2 Torr

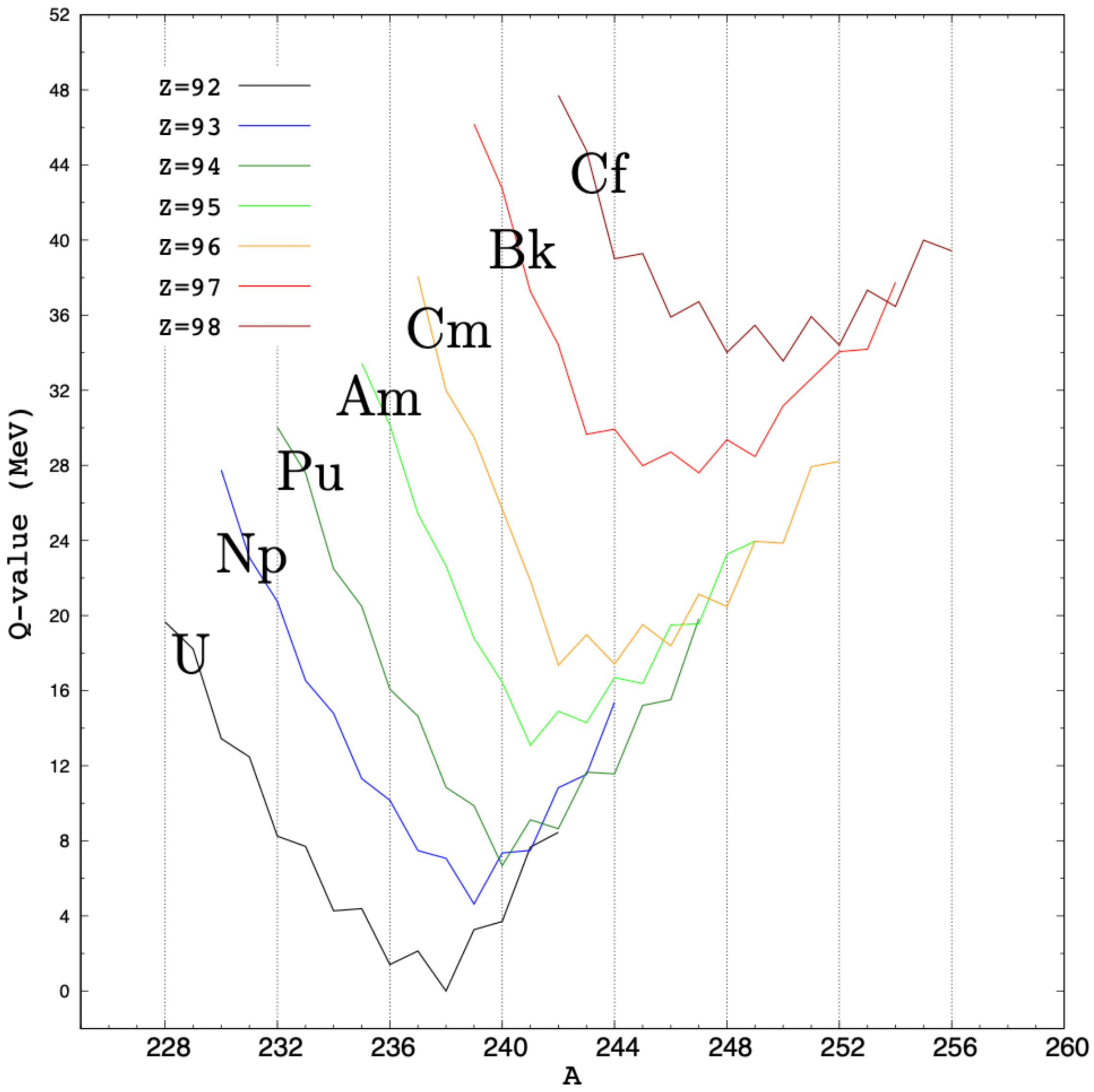


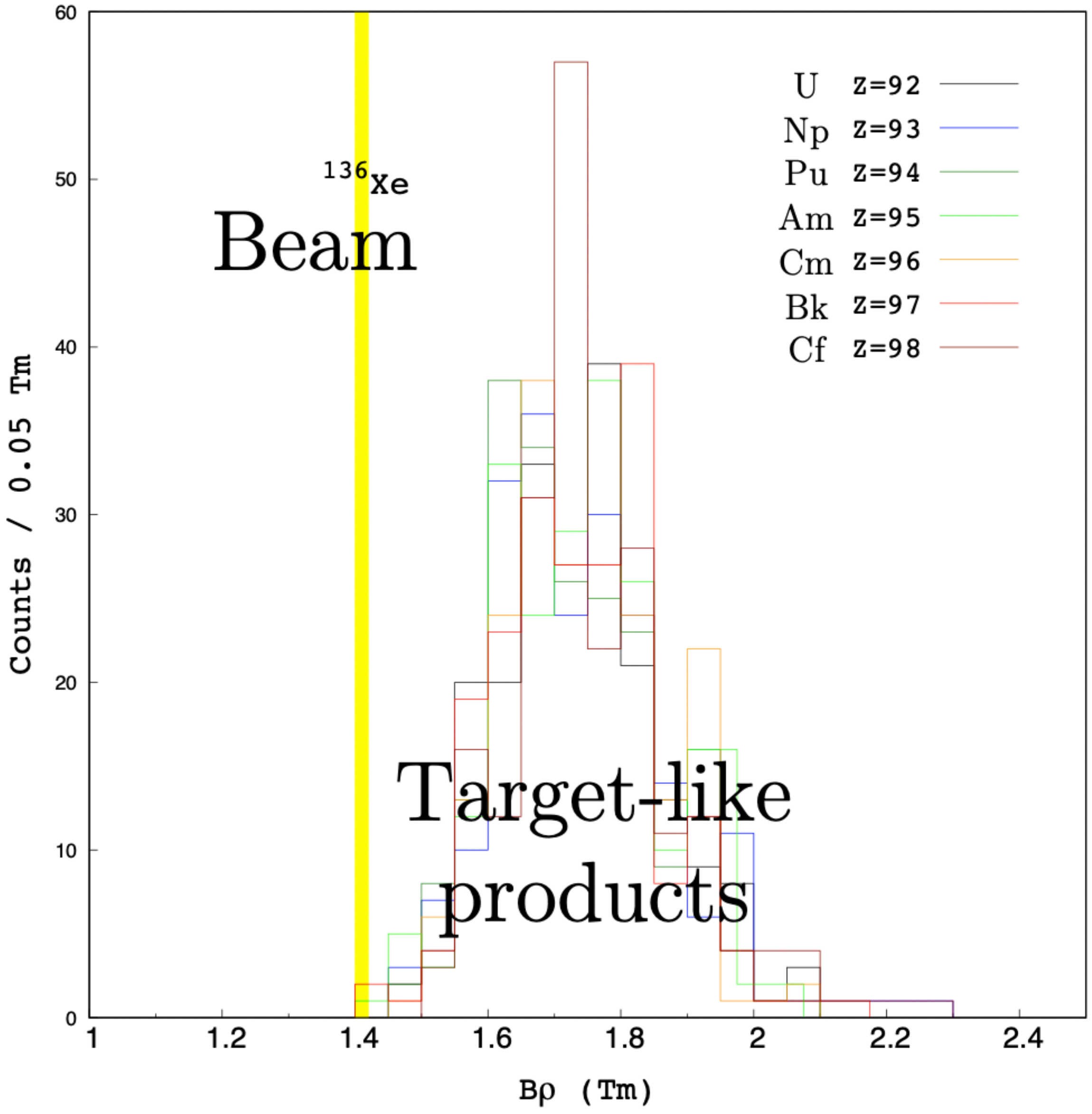
AGFA Monte-Carlo simulations

At 2 Torr

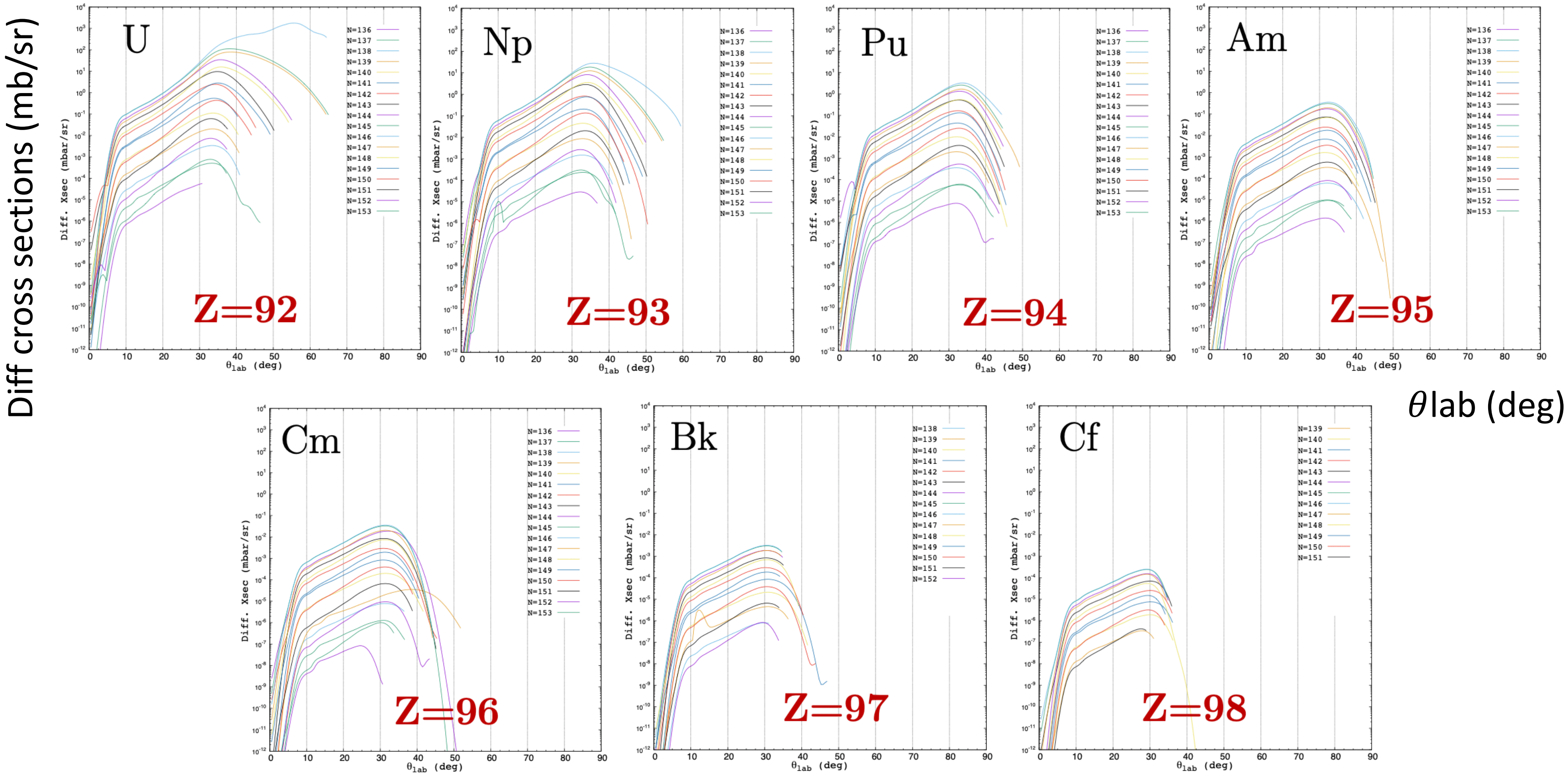


From the particle generator





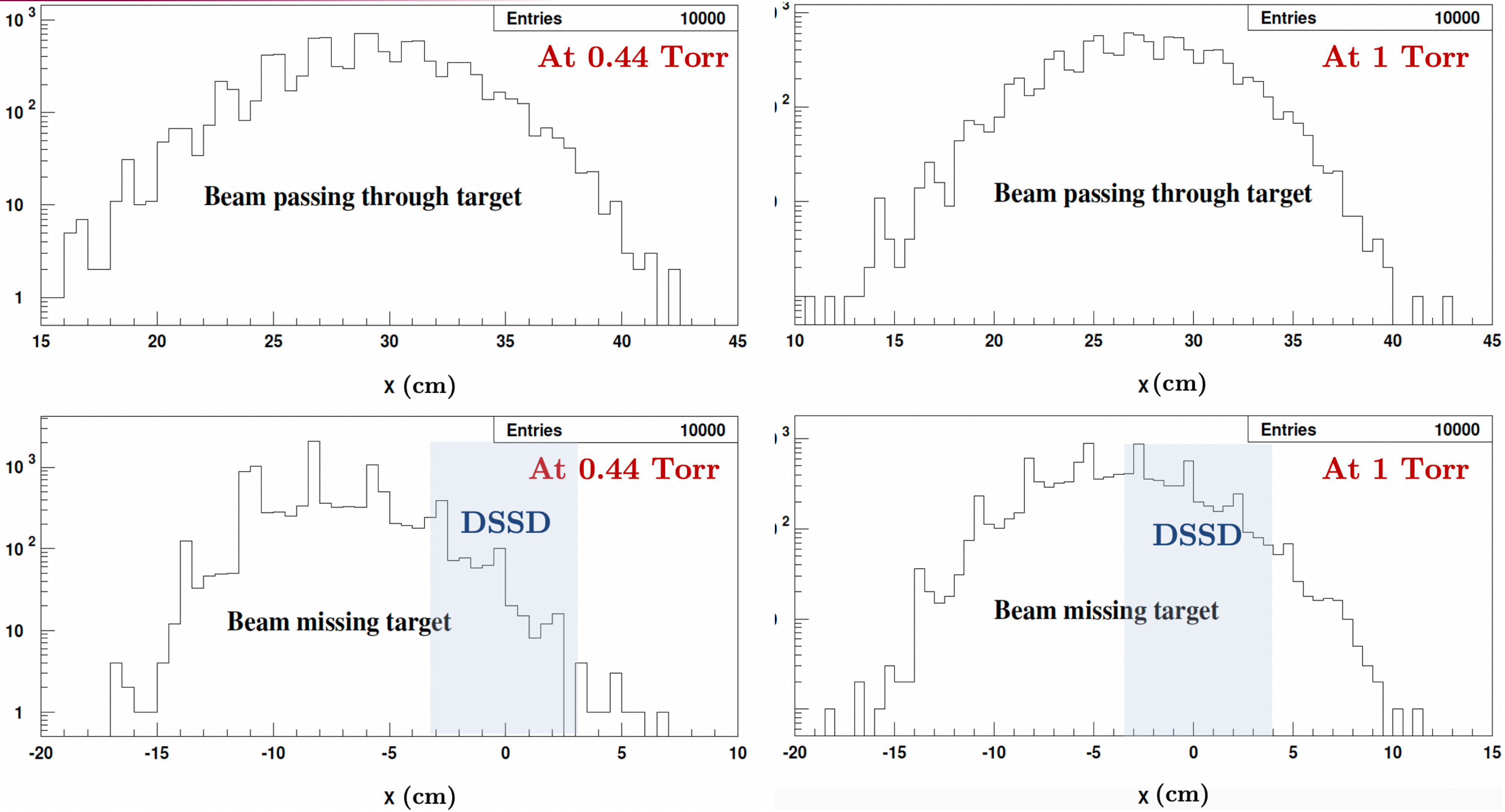
GRAZING: angular distributions



Angular distribution θ_{lab} (deg) of the differential cross-sections (mbar/sr) of the target-like nuclei generated by GRAZING.

At the grazing angle, GRAZING is giving the nice reproduction of the reactions but between 0 and 5° we are above the limits of the model.

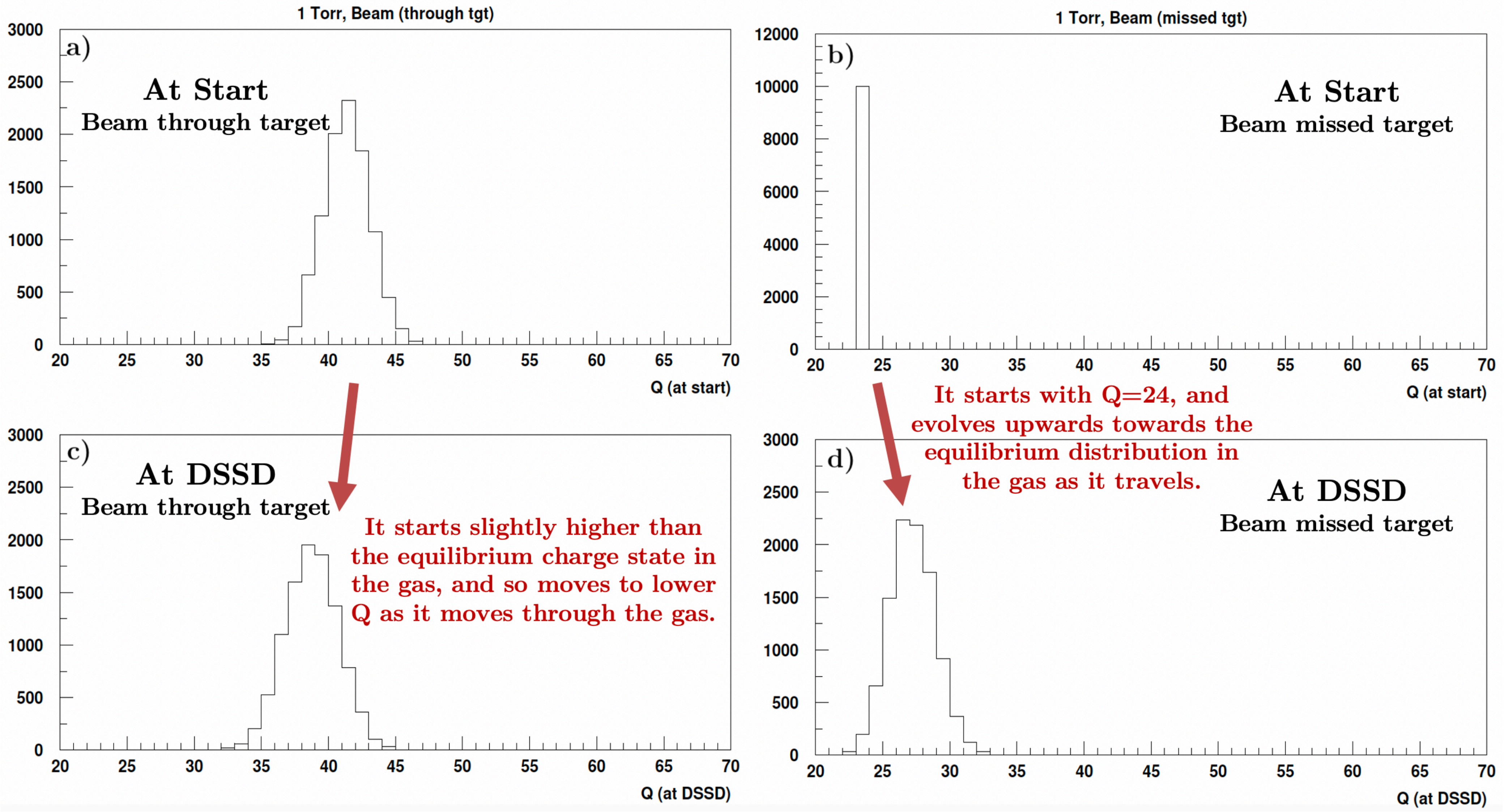
Monte-Carlo AGFA simulations



X (at the DSSD, in cm) of the 136Xe beam

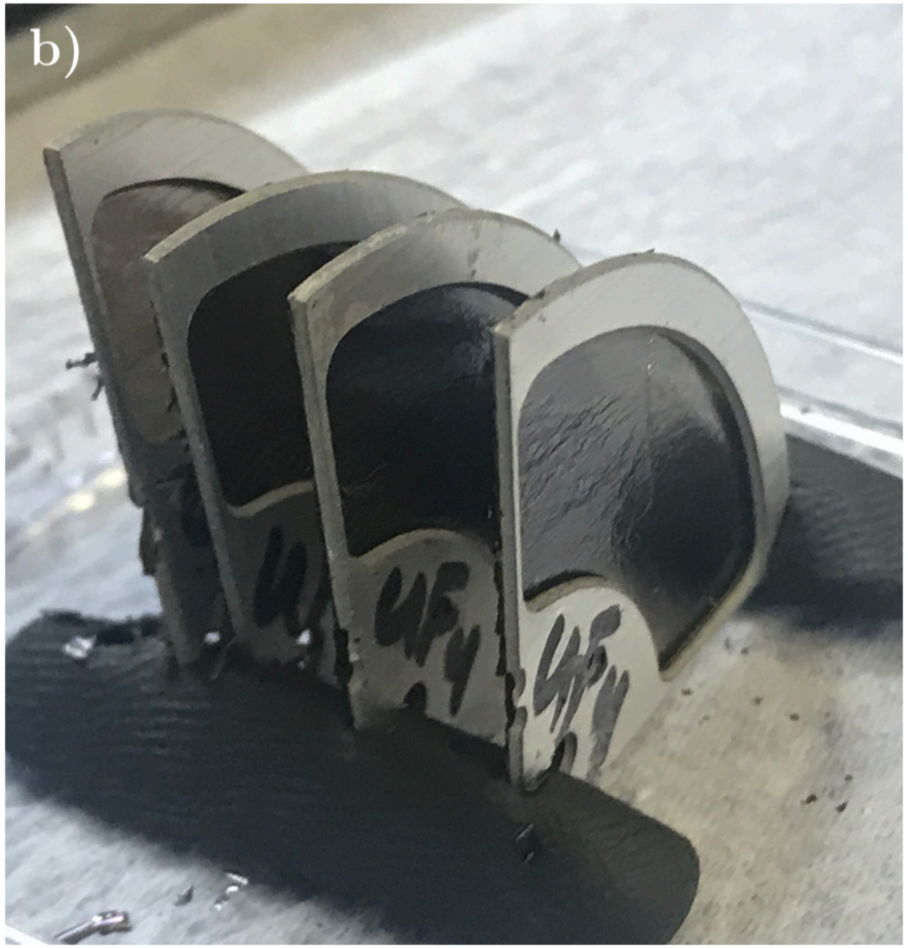
If the beam misses the target, there is significant amount that will hit the DSSD.

Monte-Carlo AGFA simulations



Charge states distributions

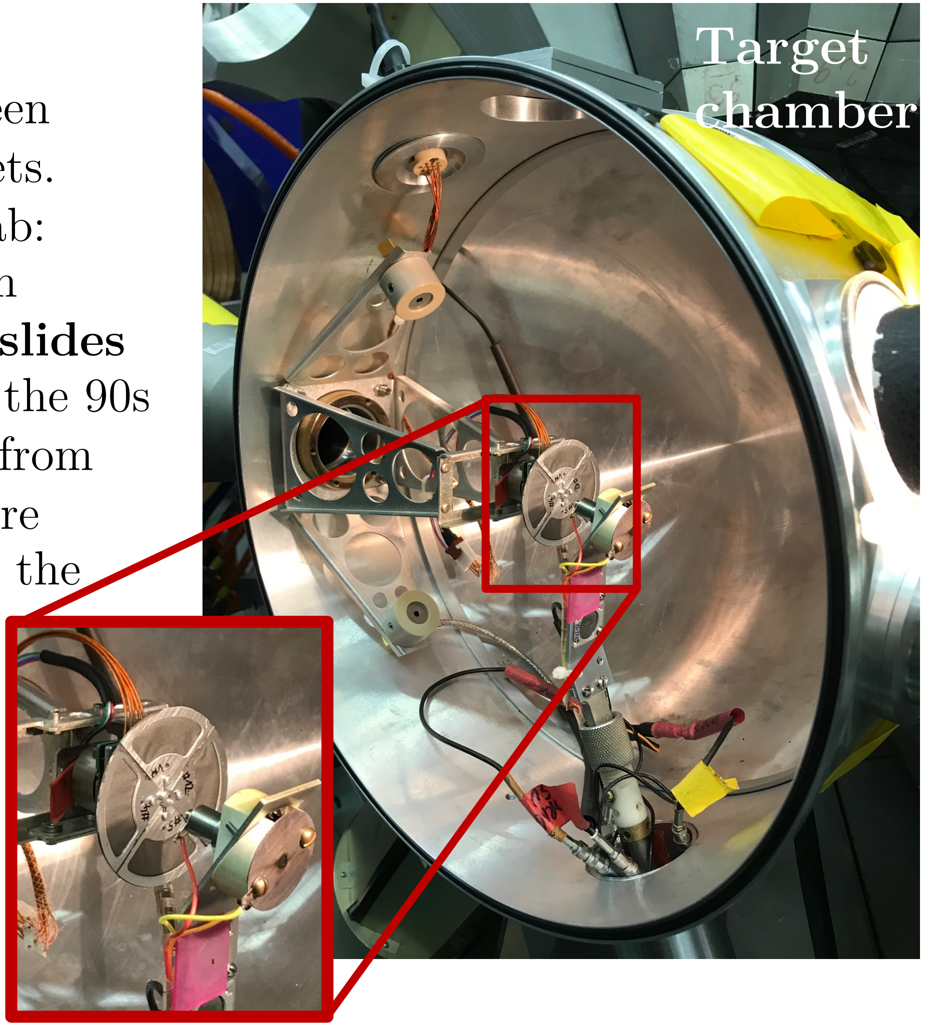
^{238}U Targets



^{238}U Targets

- **Up-to-now targets**
  - John P. Greene and his team have been striving on the preparation of the targets.
  - Old UF_4 thin targets are the target lab: **300 µg/cm² UF_4** prepared by vacuum evaporation onto **40 µg/cm² carbon slides**
    - from the APEX[1] experiment in the 90s
    - they also prepared many slides from this era as well. All these slides are now exhausted and are floated in the Hot Lab.

- **Wheel with slits**
  - Small target wheel quadrants



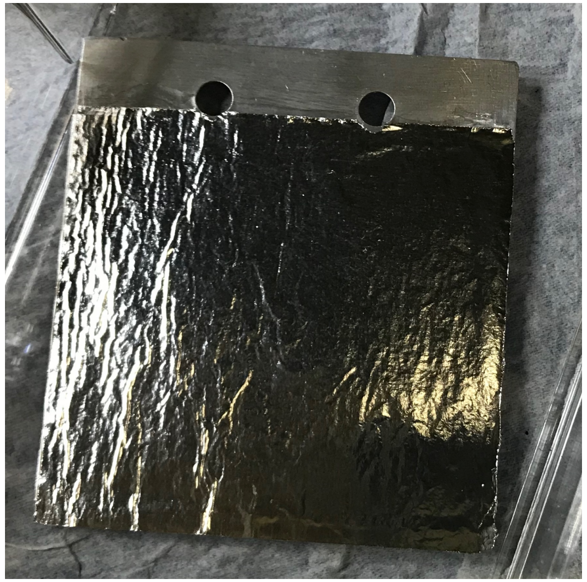
[1] J.P. Greene, et al. NIM in Physics Research A 362 (1995) 81-89

[1] G.E. Thomas, et al. NIM in Physics Research A 362 (1995) 201-204

Windows and degraders

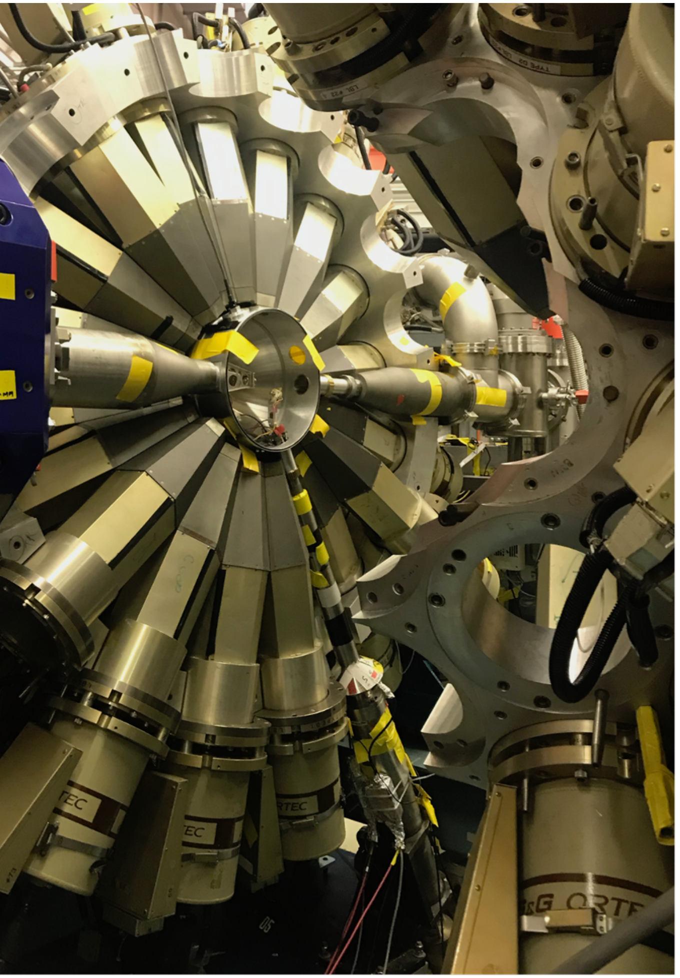
- **Windows**
  - John P. Greene made a Titanium Window
  Thickness is 0.451 mg/cm^2

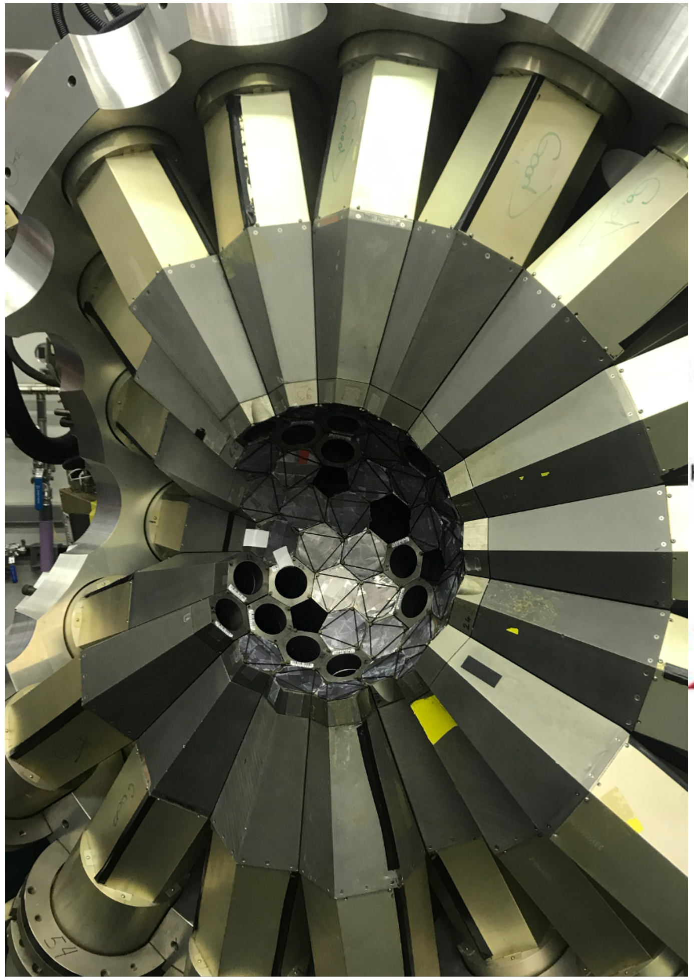
- **Degraders for the DSSD**
  - Different thicknesses of Aluminum foils



At 2 Torr		
	Ti window	
E_beam (MeV)	Al degrader thickness (mg/cm2)	E_remain (MeV)
605	4,26	115
	5,42	60
	6,44	30
	7,36	5
809	4,26	130
	5,42	100
	6,44	65
	7,36	37
	all energies +/- 15 MeV	

Gammasphere

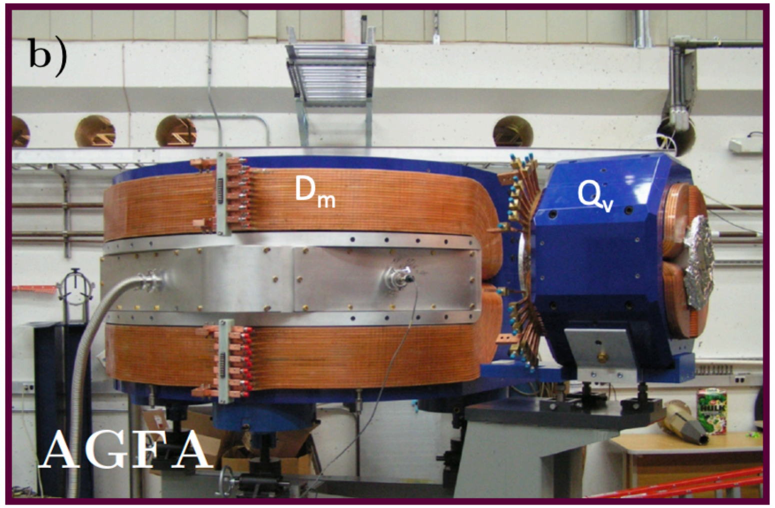


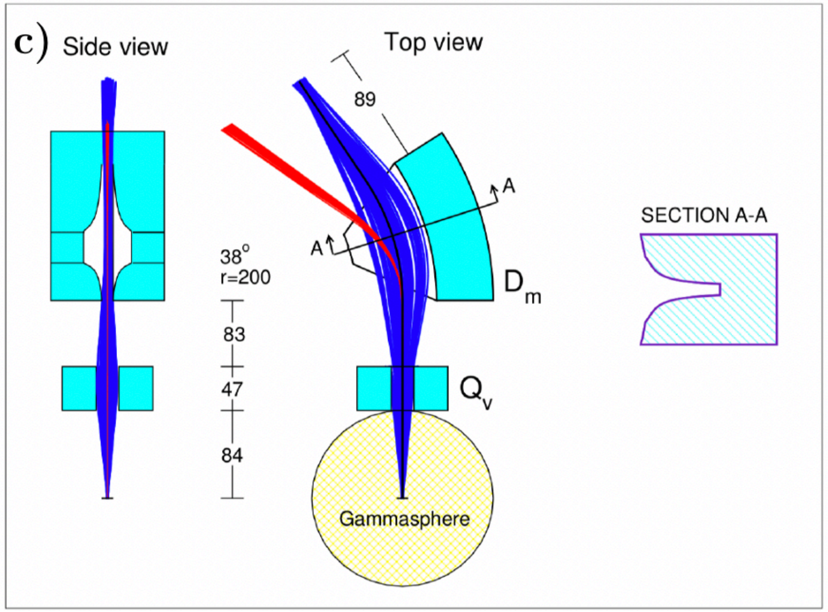


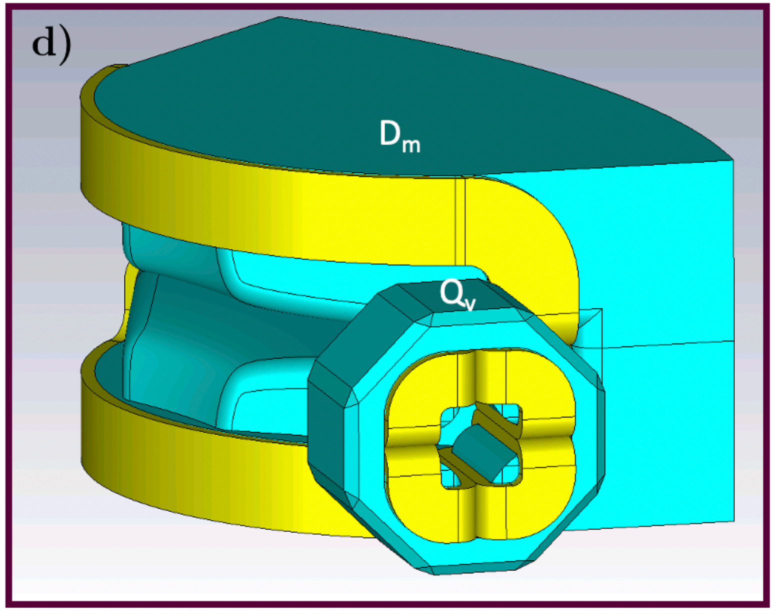
AGFA

a)

Parameter	Value	
Configuration	$Q_v D_m$	
Maximum bending power, $B\rho$	2.5 Tesla-m	
Maximum field at Q_v pole tip	1.24 Tesla	
Maximum field at D_m pole tip	1.7 Tesla	
Bend angle	38 degrees	
Target to Q_v distance	40 cm	84 cm
Solid angle, Ω	44 msr	22 msr
Target to focal plane distance	3.7 m	4.3 m

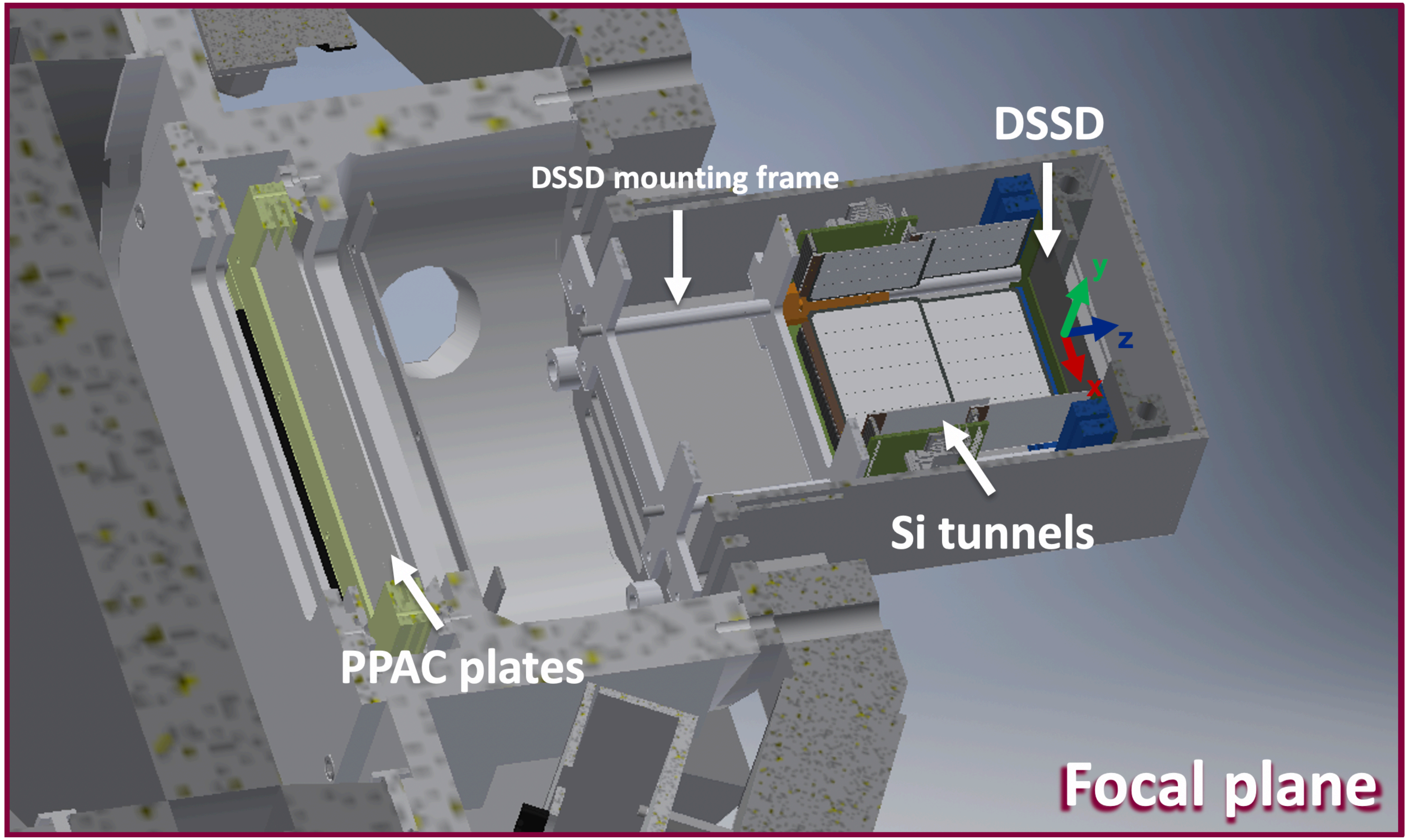


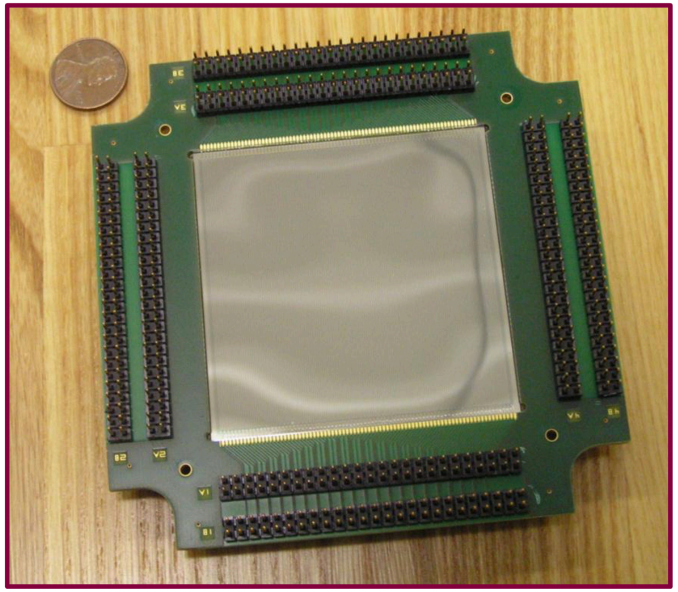




B.B. Black. EPJ Web of Conferences 163, 00003 (2017)

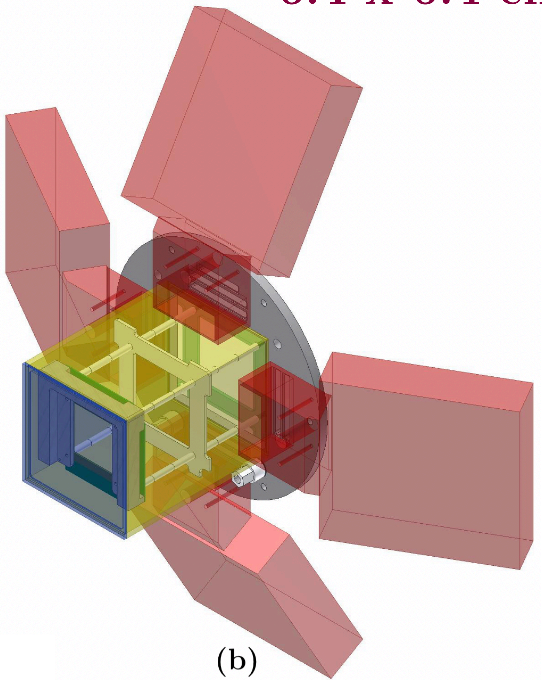
DSSD, PPAC and Si tunnels





(a)

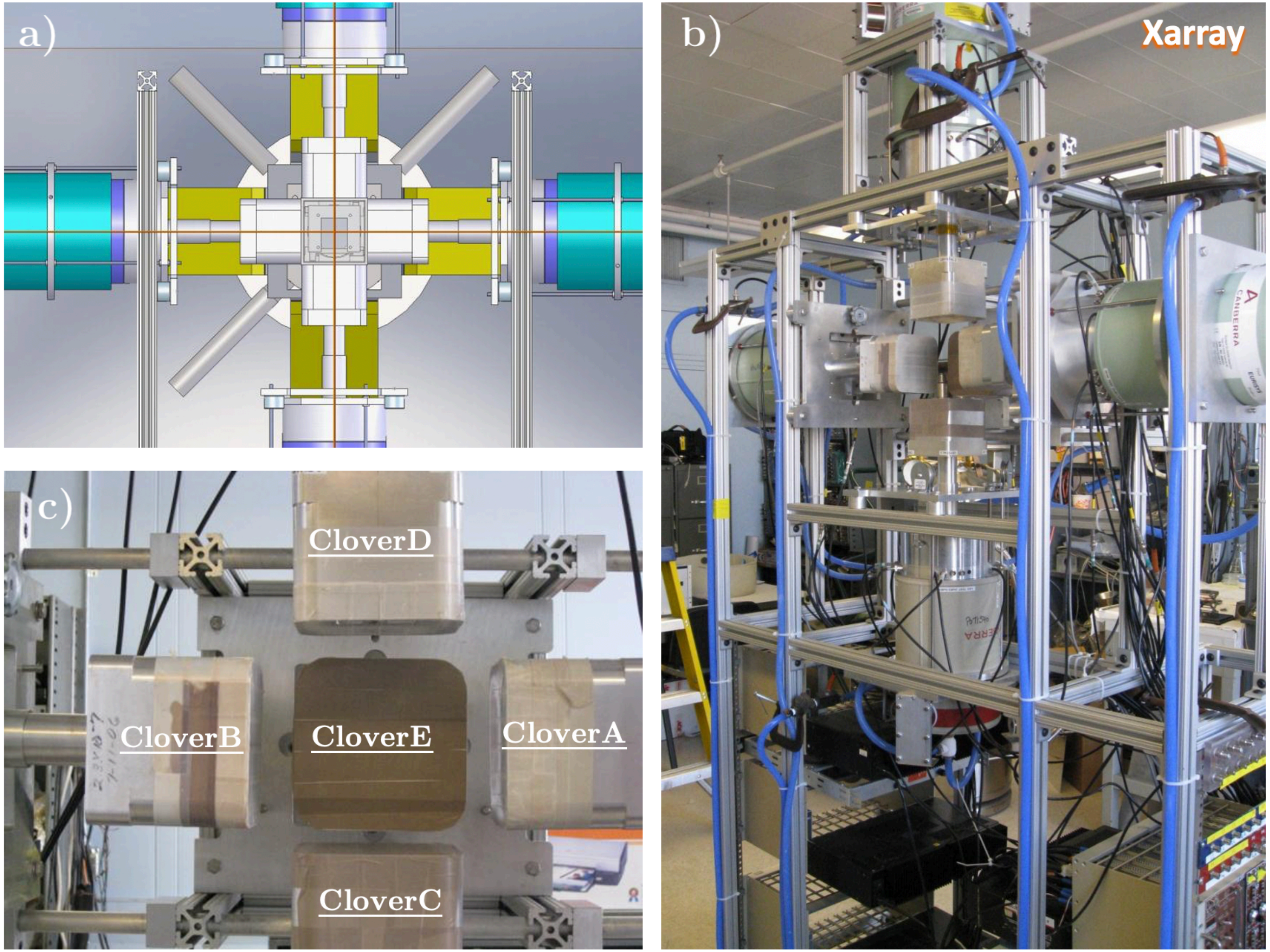
6.4 x 6.4 cm^2



(b)

XArray

EXOGAM Germanium clovers

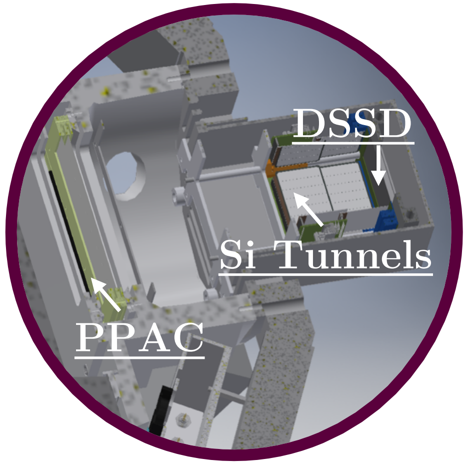


Clover B was missing

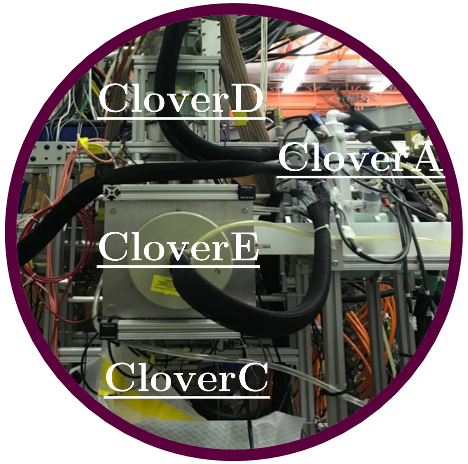
Digital electronics

DETECTORS

Gammasphere
(up to 110 GeHP)



Focal plane



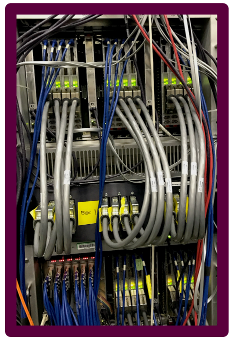
XArray
(4 Clovers GeHP)

Analogic signals

Analogic signals

DIGITAL ELECTRONICS

DGS digitizers



DFMA digitizers

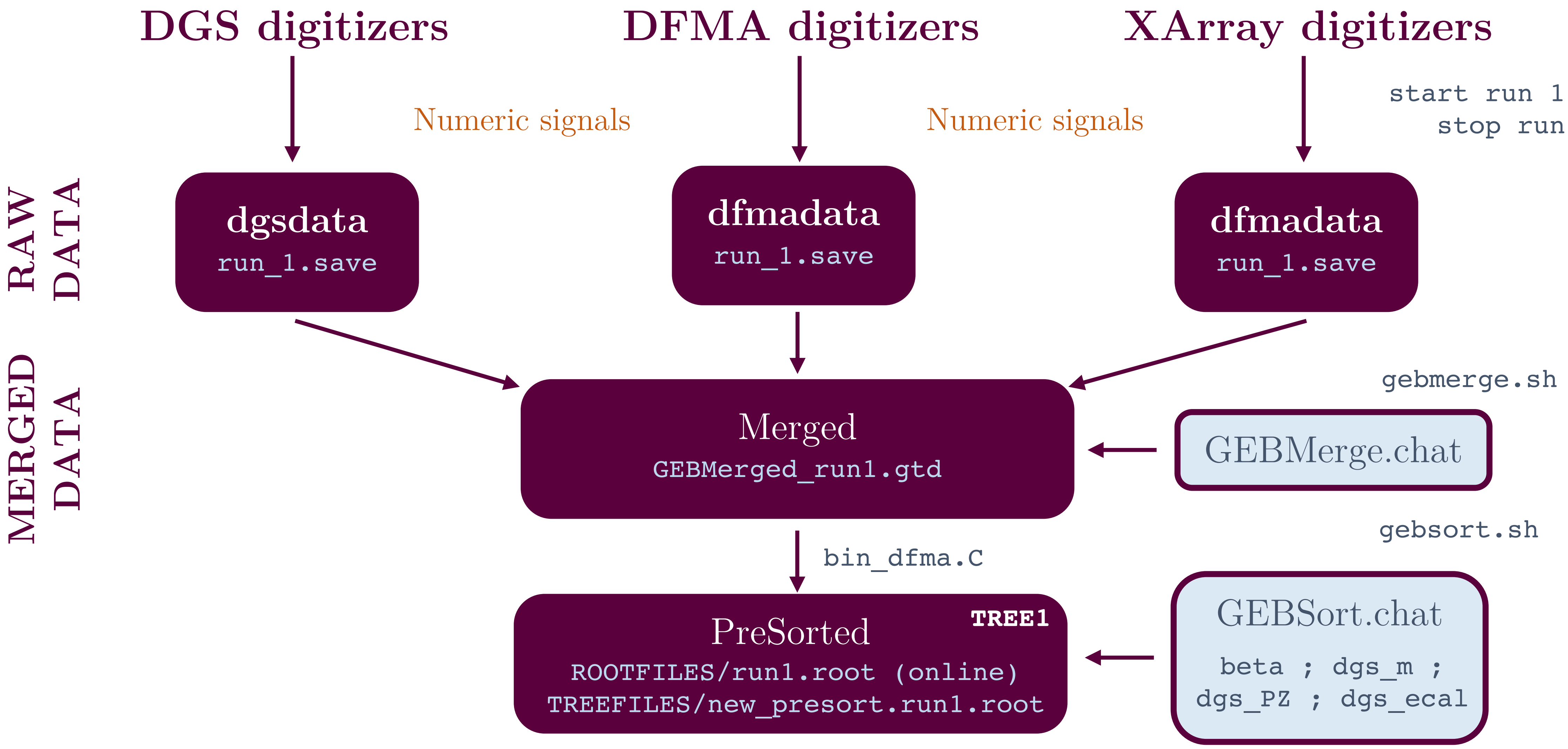
XArray digitizers

Numeric signals

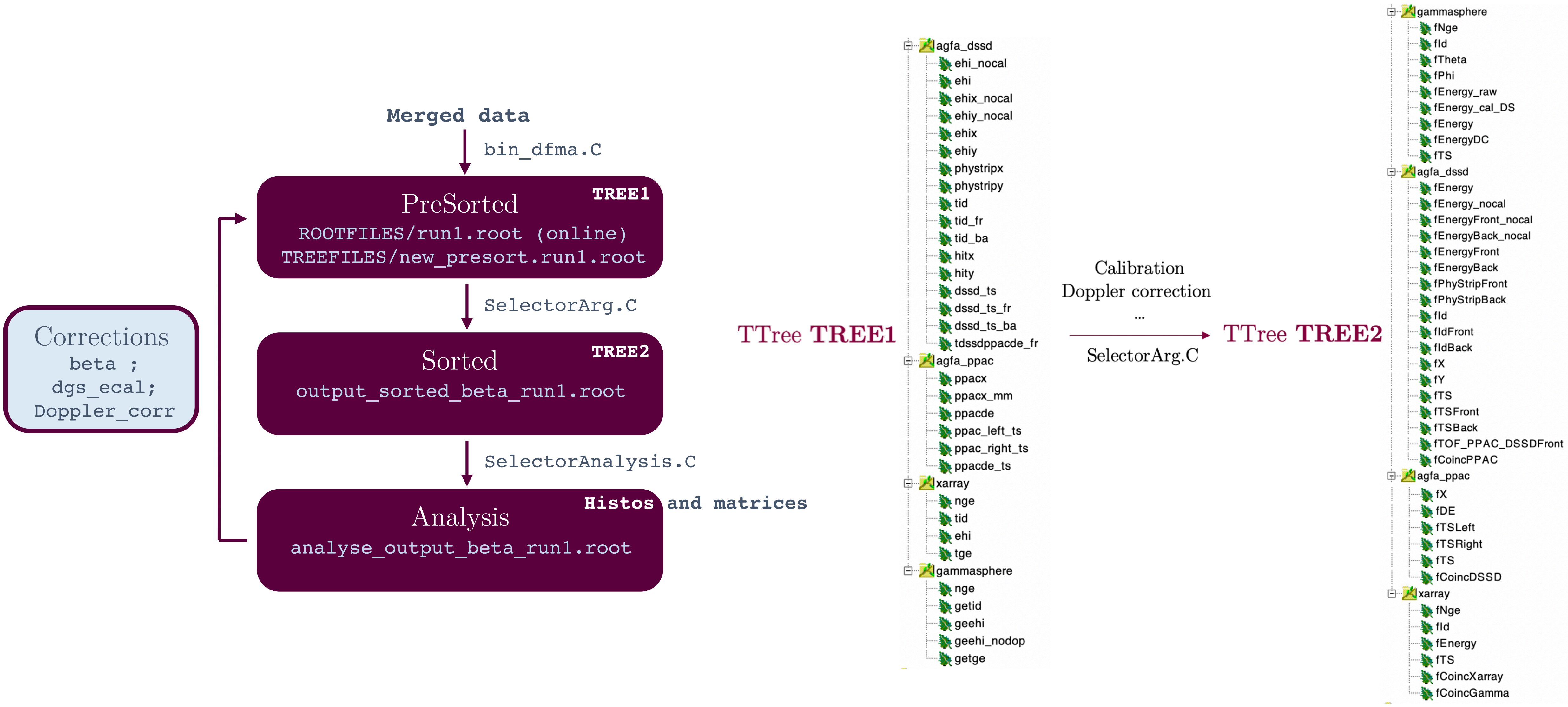
Numeric signals

```
start run 1
   stop run
```

Presorting scheme



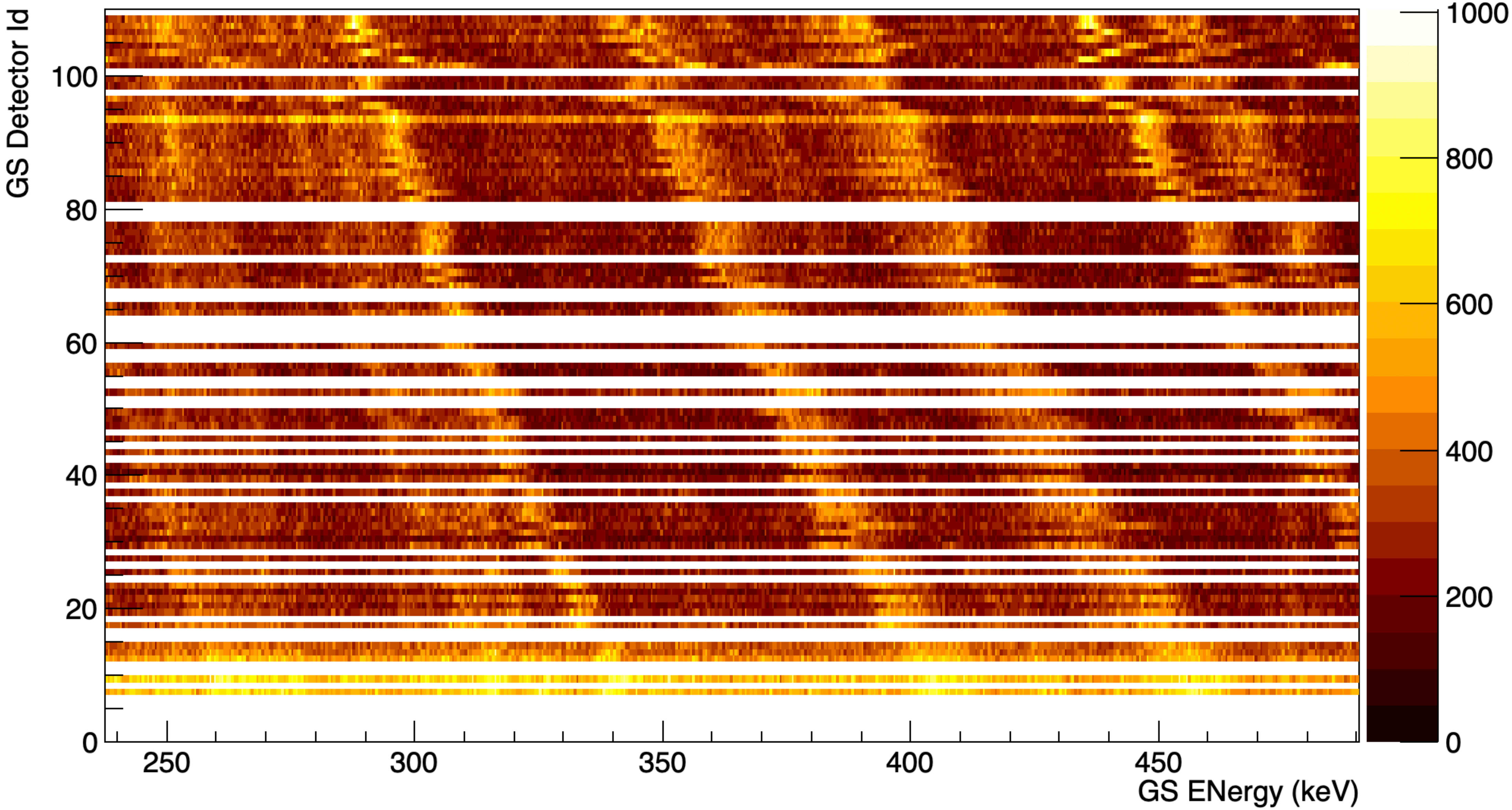
Sorting and analysis scheme



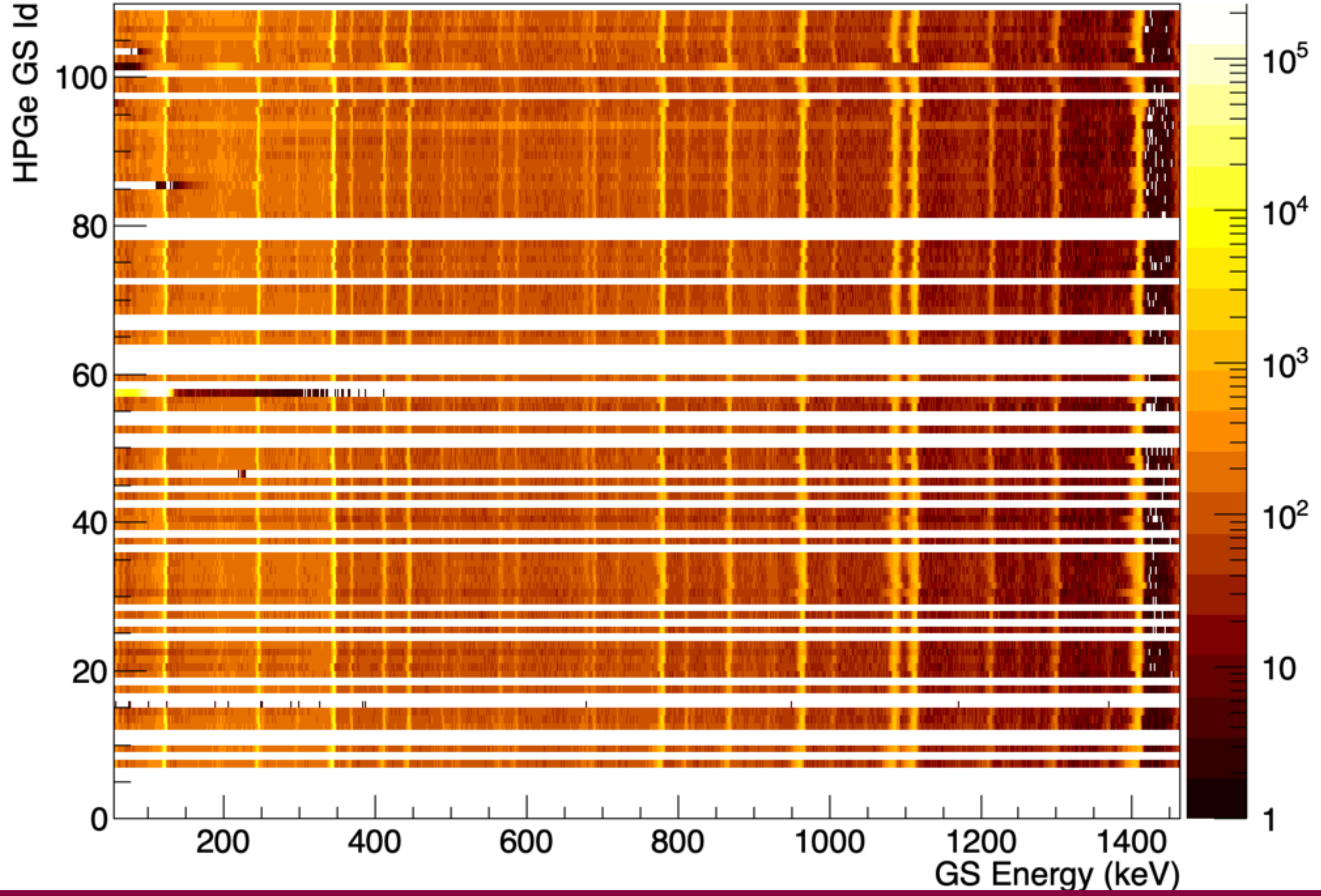
Calibrations

Detector	Source	Energy range [keV]	Activity [kBq]	Run number
Gammasphere	^{182}Ta	0-2000	85 (17/09/18)	127
	^{152}Eu	121-1410	?	126
	Mixed gamma	0-2000	115 (01/10/09)	125
Xarray	^{182}Ta	0-2000	85 (17/09/18)	123
	^{152}Eu	121-1410	?	124
	Mixed gamma	0-2000	115 (01/10/09)	129
	^{243}Am	5000-5400	148 (15/03/06)	128
DSSD	^{239}Pu, ^{244}Cm, (^{241}Am)	5000-6000	?	120

Without Doppler correction / Calibration



Doppler correction (7.55% at E_{beam}=705 MeV)

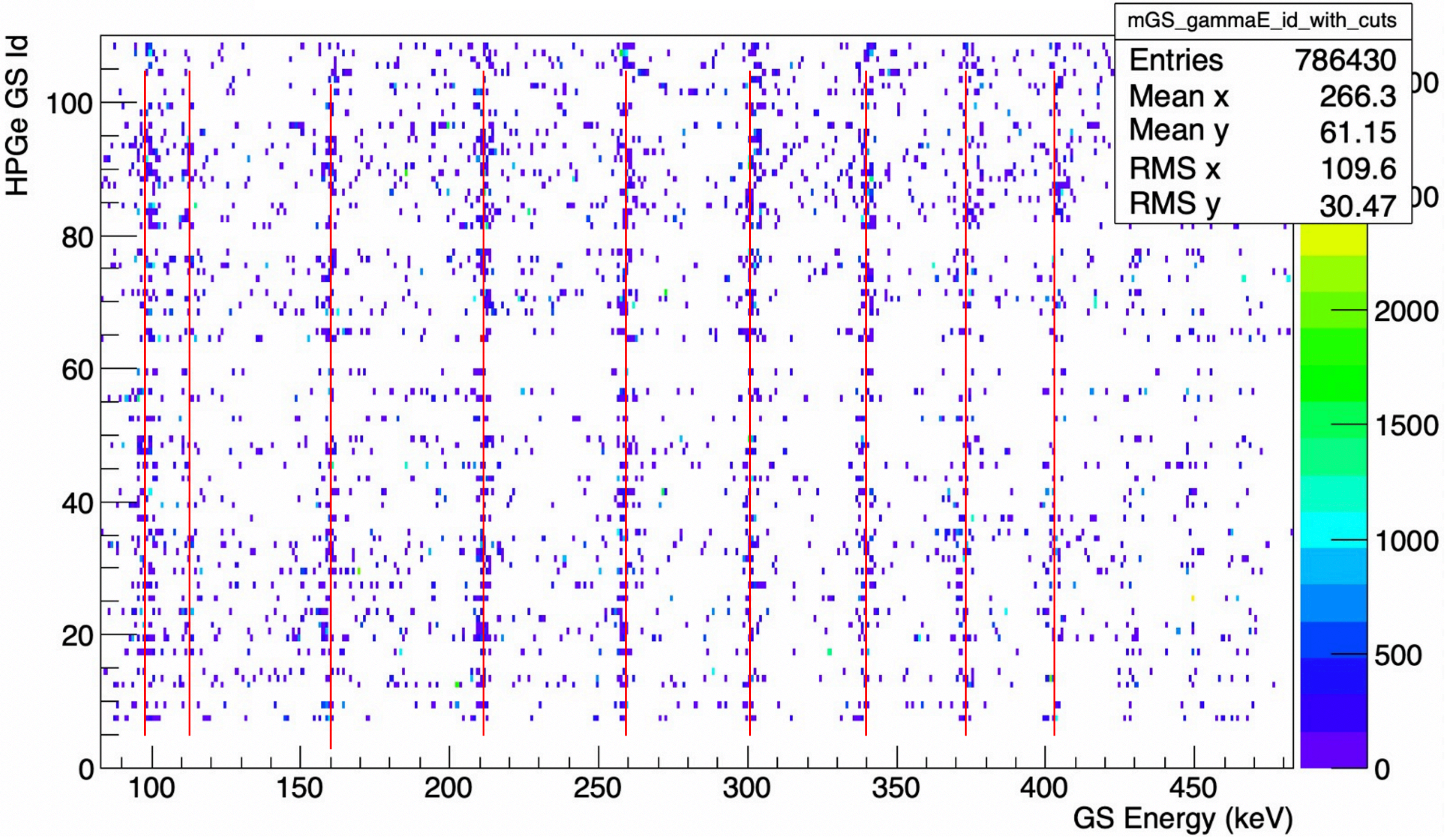


Doppler correction function:

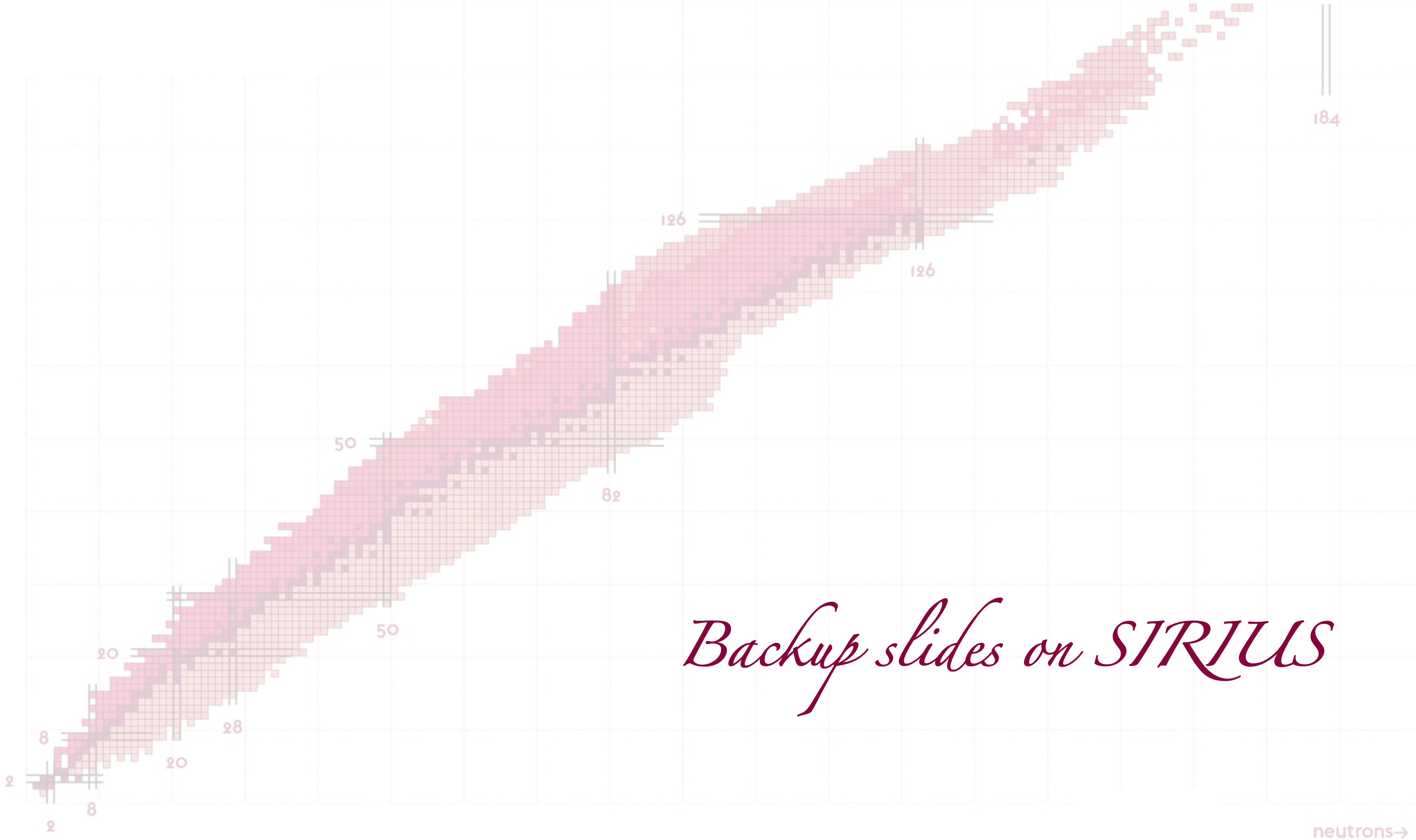
$$E_\gamma = E_0 \frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta}$$

Doppler correction (7.55% at E_{beam}=705 MeV)

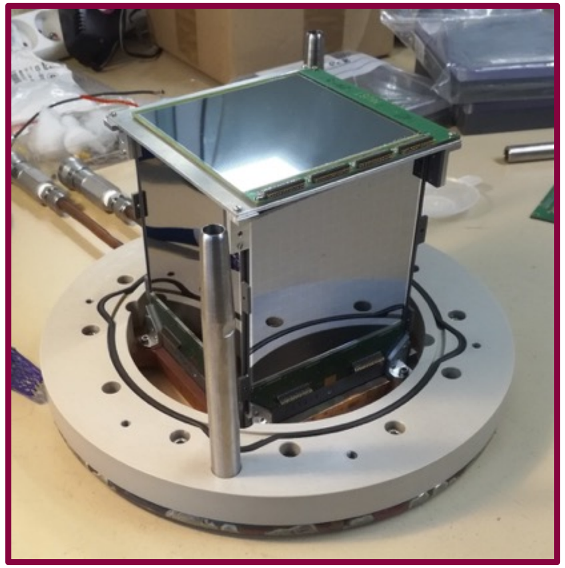
With cuts on the recoils



Backup slides on SIRIUS



DSSD test bench @CEA/Irfu

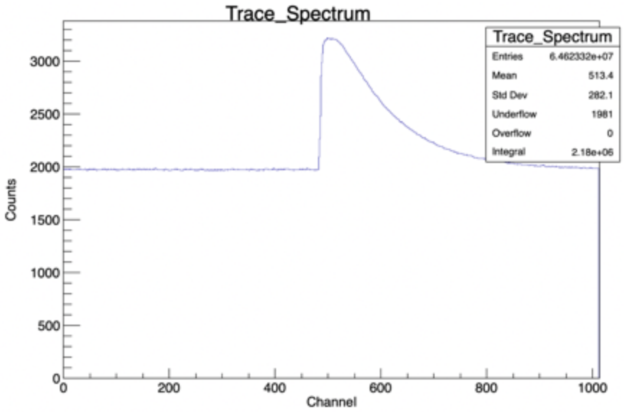


- Testing of DSSD, full electronics chain, with tri-alpha and electron sources
- Digital Signal Processing with Jordanov Filters (optimization of m and k)
- Characterization of the DSSD front-end electronics
- Write online and offline codes for data acquisition (NUMEXO2 cards)
- Different temperatures (-20, 0, +20°C)
- Test of low gain and high gain (0.5pF/1pF and 9pF)

DSSD
128 strips x
128 strips y

Conditions:
U=55V
I=1.4µA
Temp. 20°C

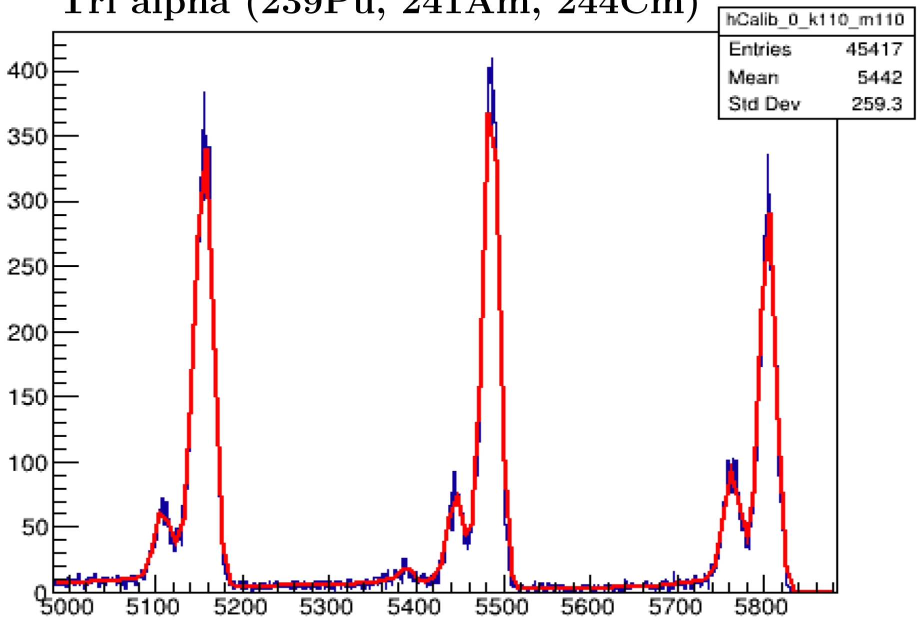
992 samples
Sampling period 5ns



Trace

Jordanov Filter

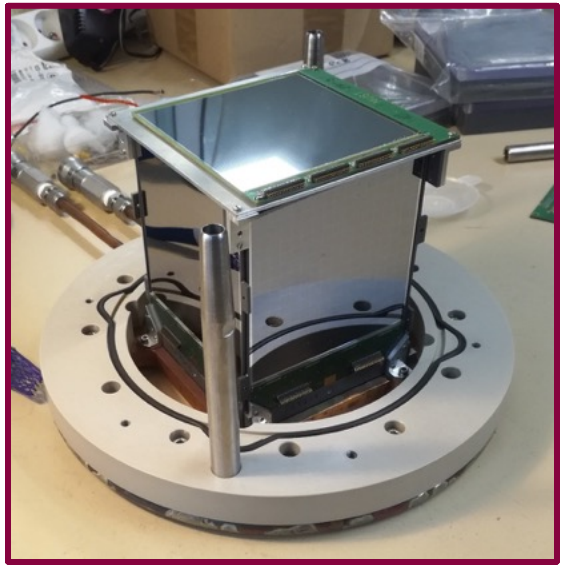
Tri alpha (239Pu, 241Am, 244Cm)

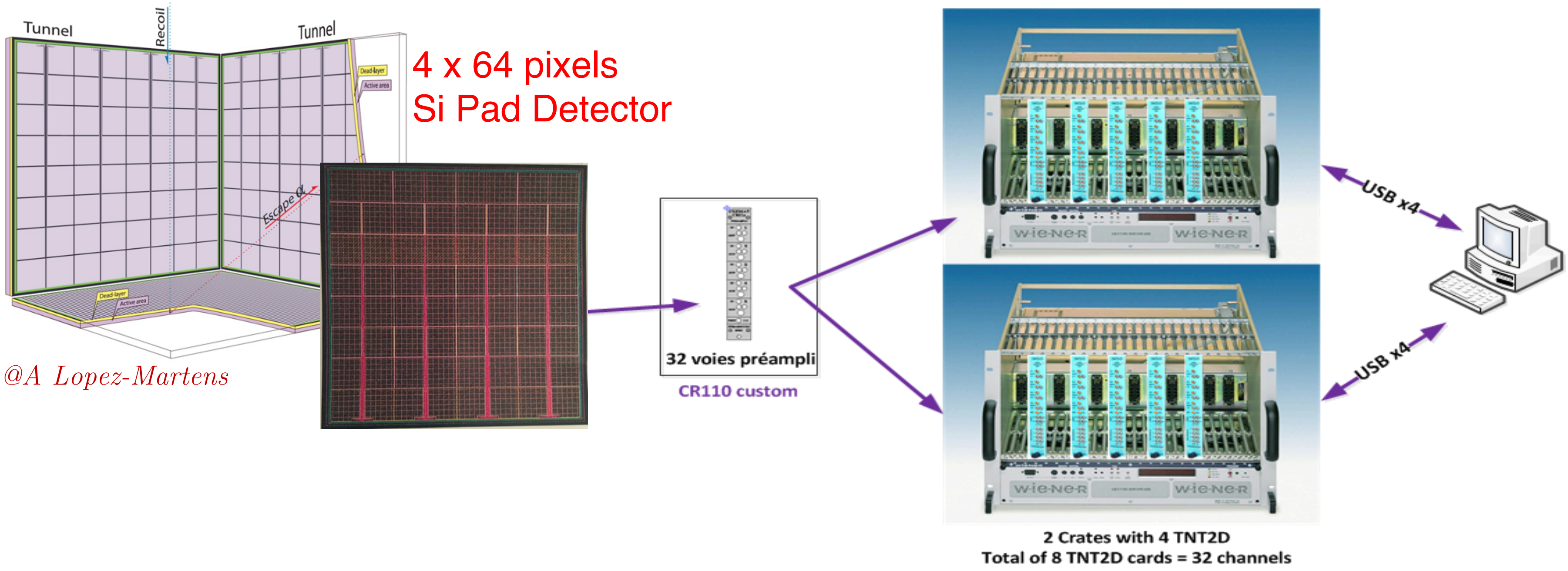


18 keV resolution

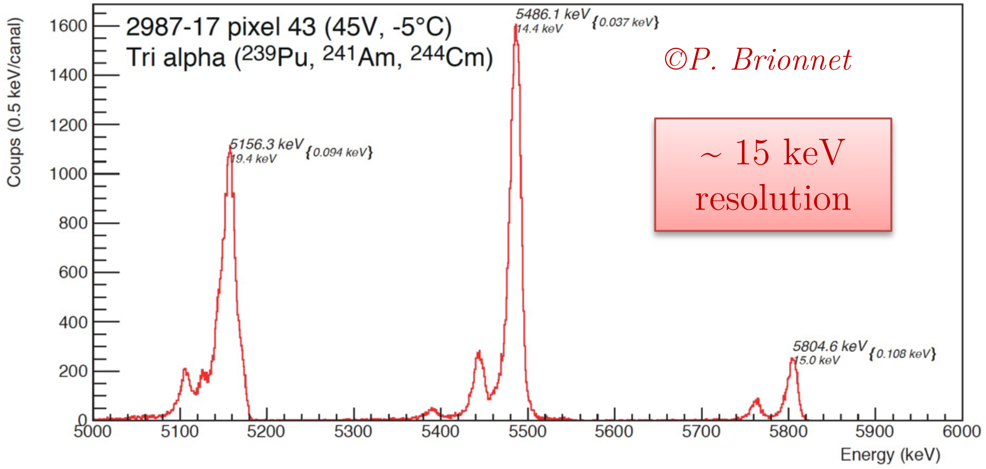
Tunnels test bench @IPHC/IJClab

Courtesy of O. Dorvaux





Still waiting for tests
with the Numexo2 electronics,
it will be finished at IJClab/GANIL



With CREMAT electronics

SIRIUS online commissioning @LISE2000?

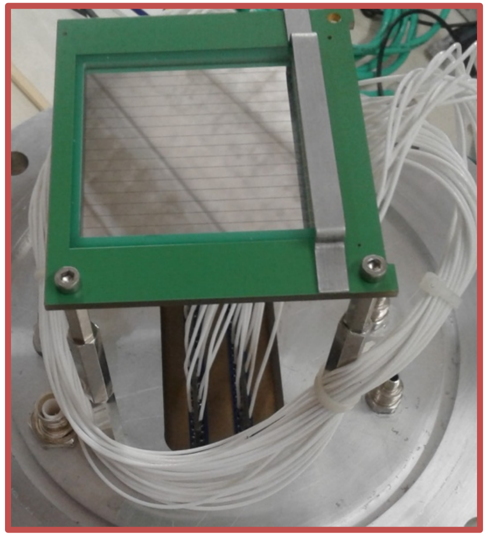
First test in June 2019
→ New test in April 2021

Objectives:
Testing the rejection of the line LISE2000 @GANIL with a small DSSD to study the feasibility of the SIRIUS commissioning at LISE2000.

Chosen reaction:

^{40}**Ar**+^{174}**Yb** → ^{209,210}**Ra.** 4,62MeV/u
Cross section: 1.4 mb

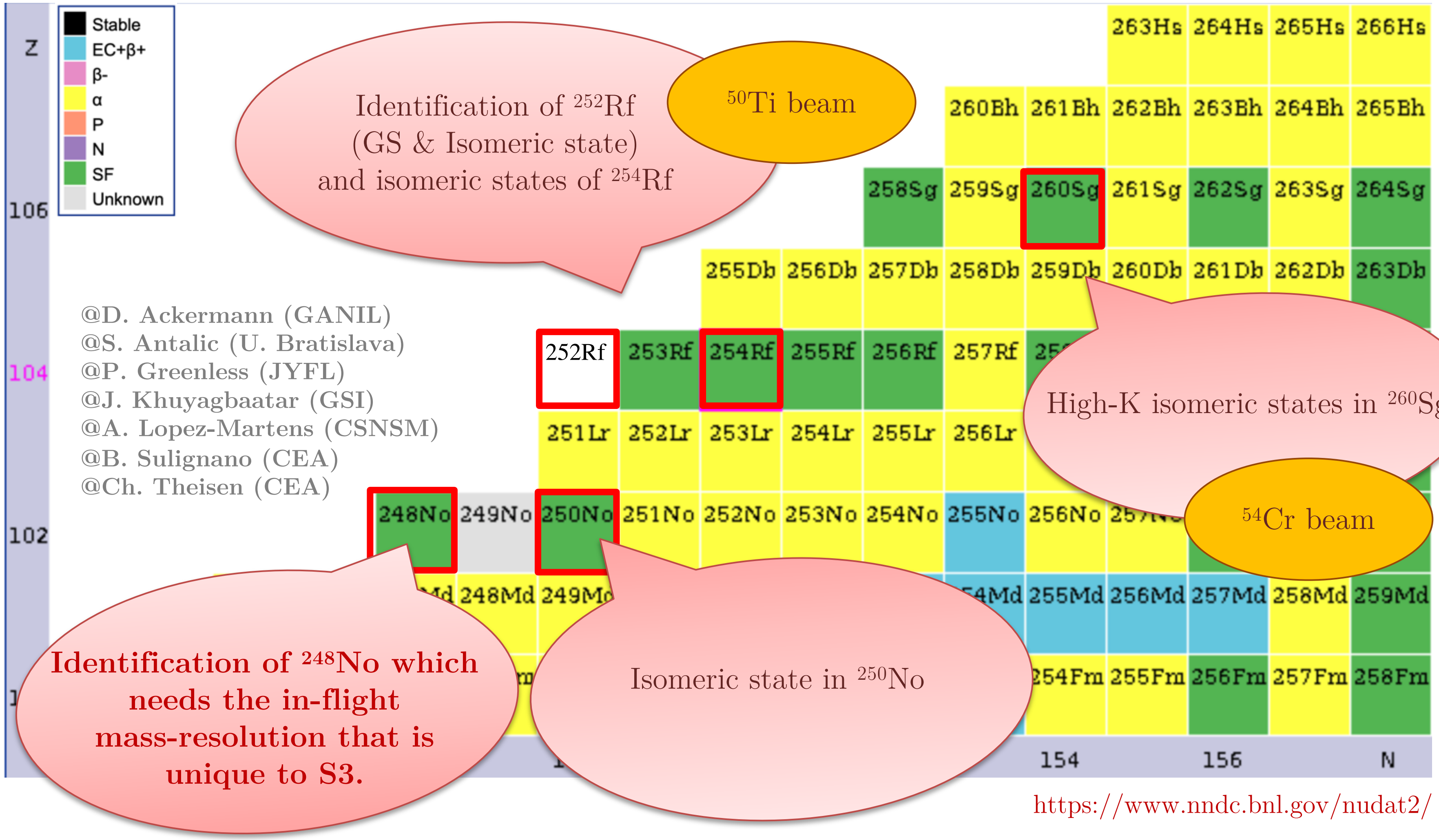
Set-up:
- 1 DSSD 16x16 strips 300 µm
(50x50 mm^2 active area with PAC 15mV/MeV)
- 2 amplifiers CAEN N568B
(OUT1: GANIL ADC,
FOUT1: 16 strips CFD CAEN N843)
- 1 MWPC (50x50 mm^2) for TOF measurements



Work has been done to improve the transmission of LISE2000!

SIRIUS Day1 experimental plan (A/Q=3)

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.



https://www.nndc.bnl.gov/nudat2/

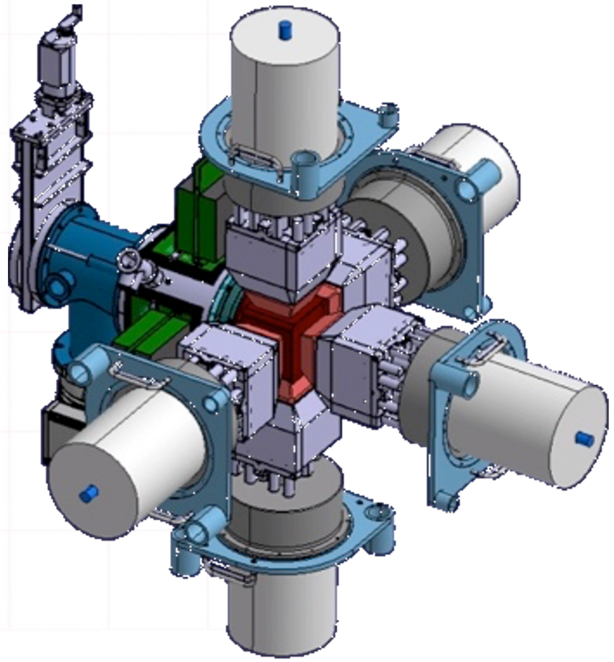
Conclusions and perspectives

- **Developing a cutting-edge technology**
  - **SIRIUS in the SPIRAL2/S³ 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
  - Since July 2020, SIRIUS @CEA/Irfu (DSSD+Tunnels)
  - **Offline commissioning and tests of the complete acquisition chain!**

- **March 23-24, 2021:**
  - **Move SIRIUS from CEA-Saclay to GANIL!**

- **March-April 2021:**
  - **Continuation of the tests of SIRIUS @GANIL (Trackers, HPGe, electronics…)**

- **April 23, 2021:**
  - **T21-01 new test with LISE2000**
    $^{40}Ar^{6+}$ 4,6 MeV/u
  - ^{40}**Ar**+^{174}**Yb** → ^{209,210}**Ra**
  - Online commissioning of SIRIUS with LISE2000?



SIRIUS Collaboration

CEA/IRFU : ZF, Th. Chaminade, B. Sulignano, M. Authier,, E. Delagnes, D. Desforge, A. Drouart, A.Grabas, W. Korten, H. Le Provost, Ch. Theisen, M. Vandebrouck, M. Zielinska

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

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

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