

Cross-section measurements of actinide production via multi-nucleon transfer (MNT) reactions in the $^{136}\text{Xe} + ^{238}\text{U}$ system

Jonathan Bequet,

Barbara Sulignano (CEA), Iulian Stefan (IJCLab)

European Nuclear Physics Conference 2025

Outline

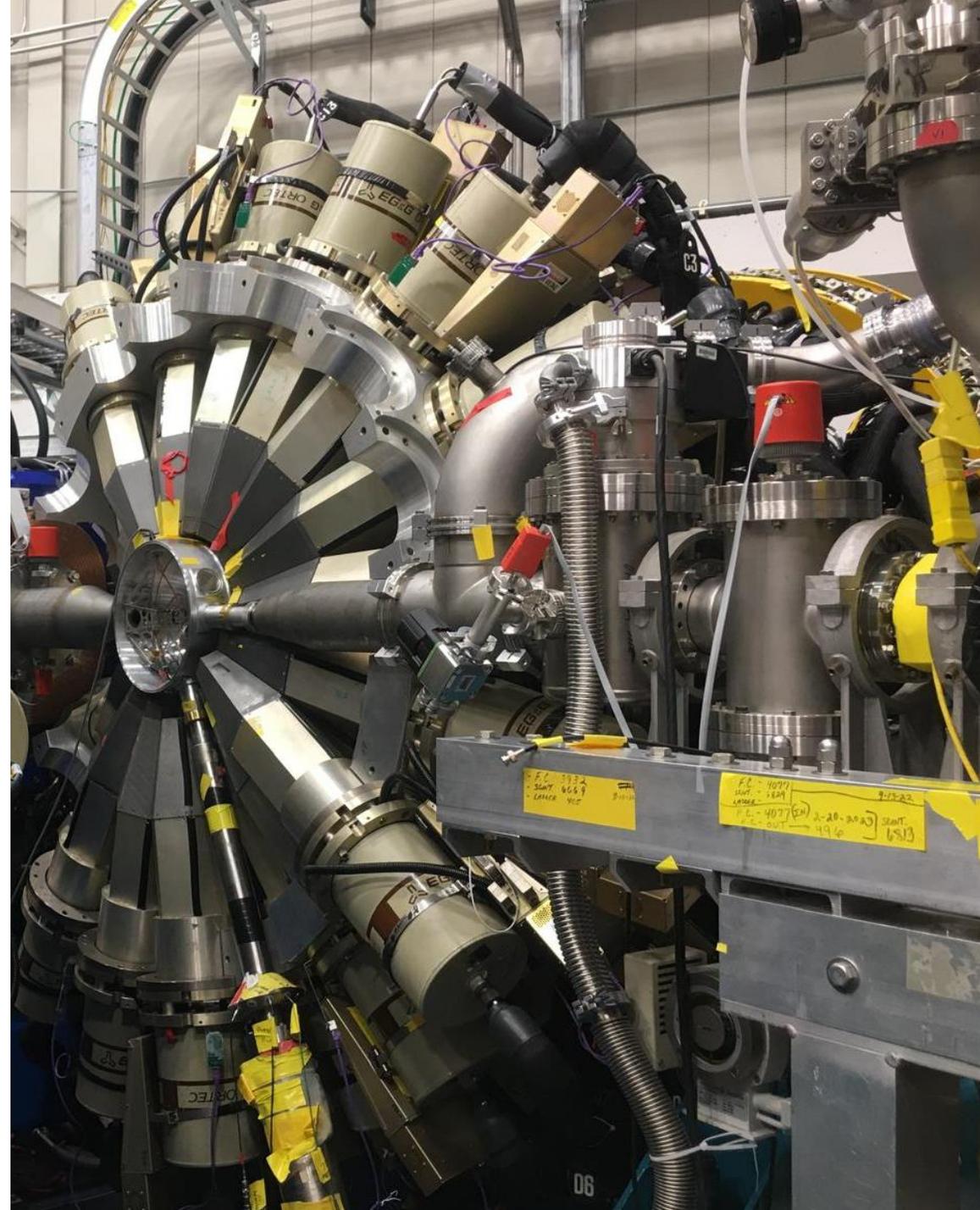
1. Motivation & context

2. MNT experiment : $^{136}\text{Xe}+^{238}\text{U}$ at ANL

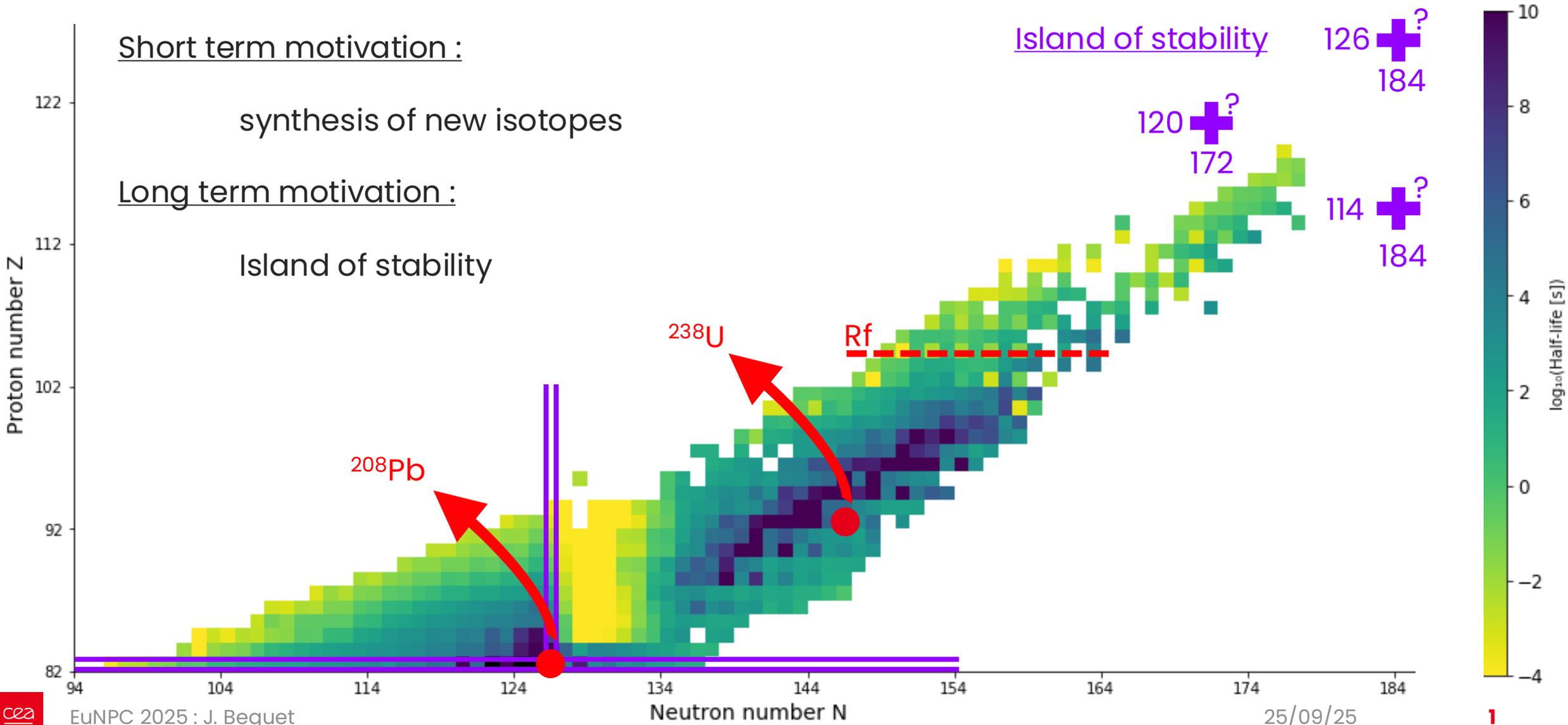
3. Results

4. Interpretation

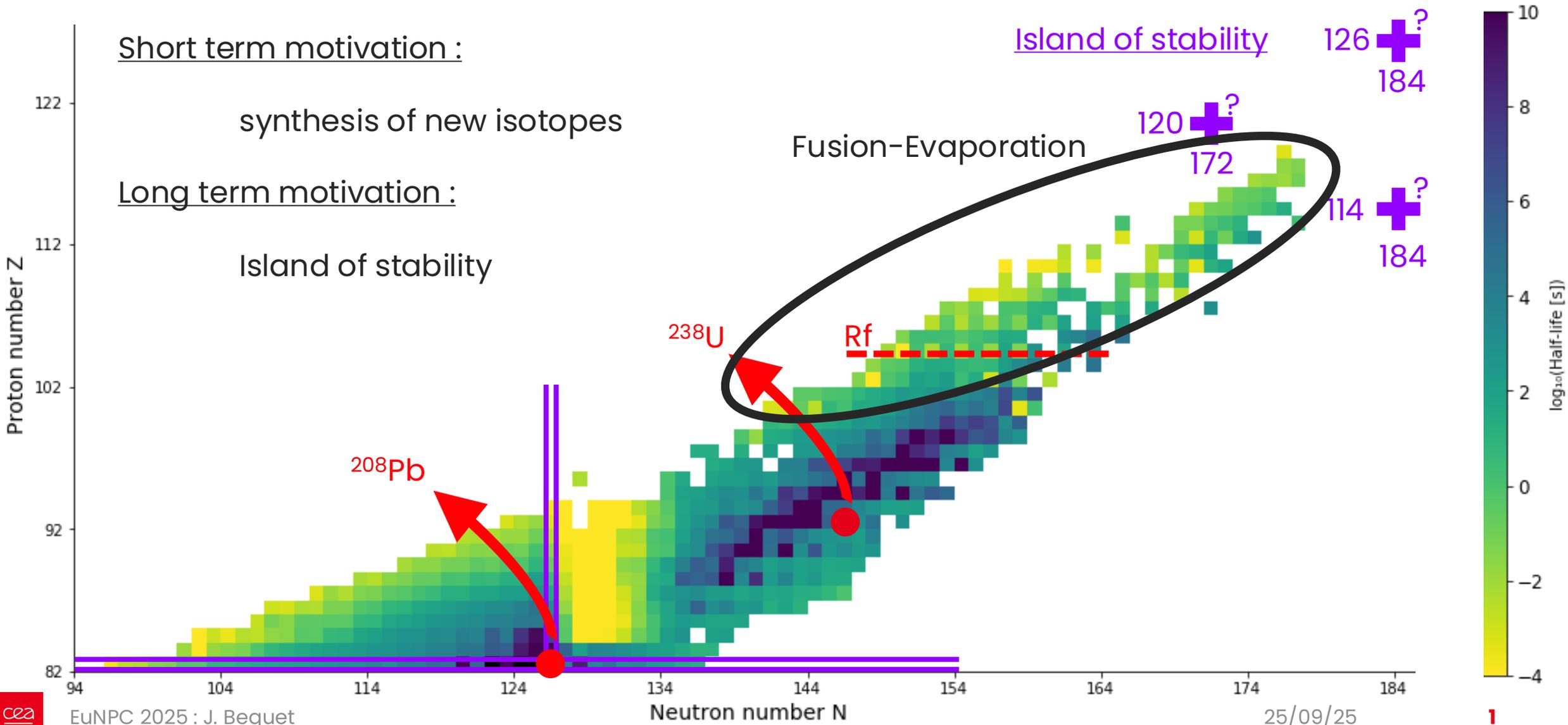
5. Conclusion and outlook



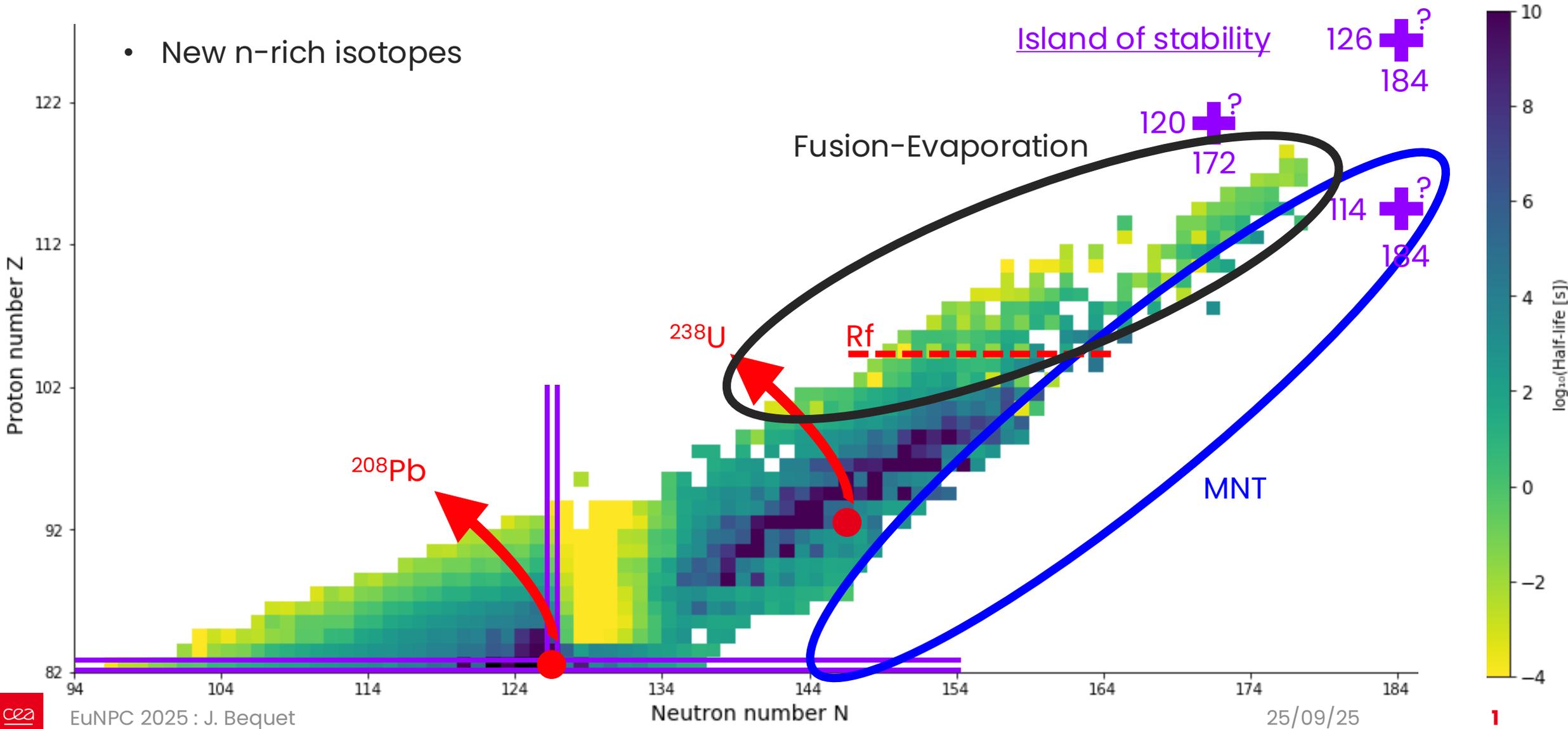
Motivation : the island of stability



Motivation : the island of stability

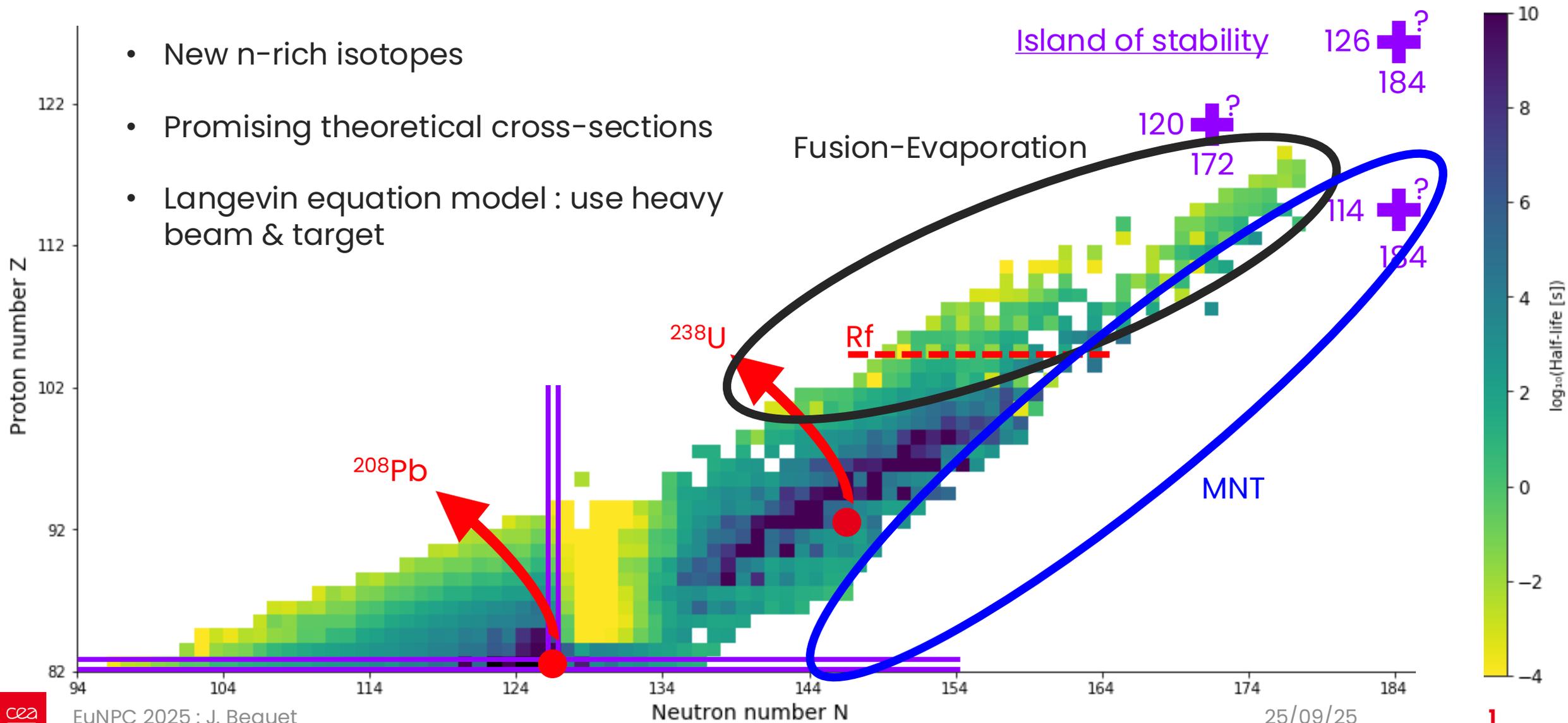


MNT: a complementary mechanism

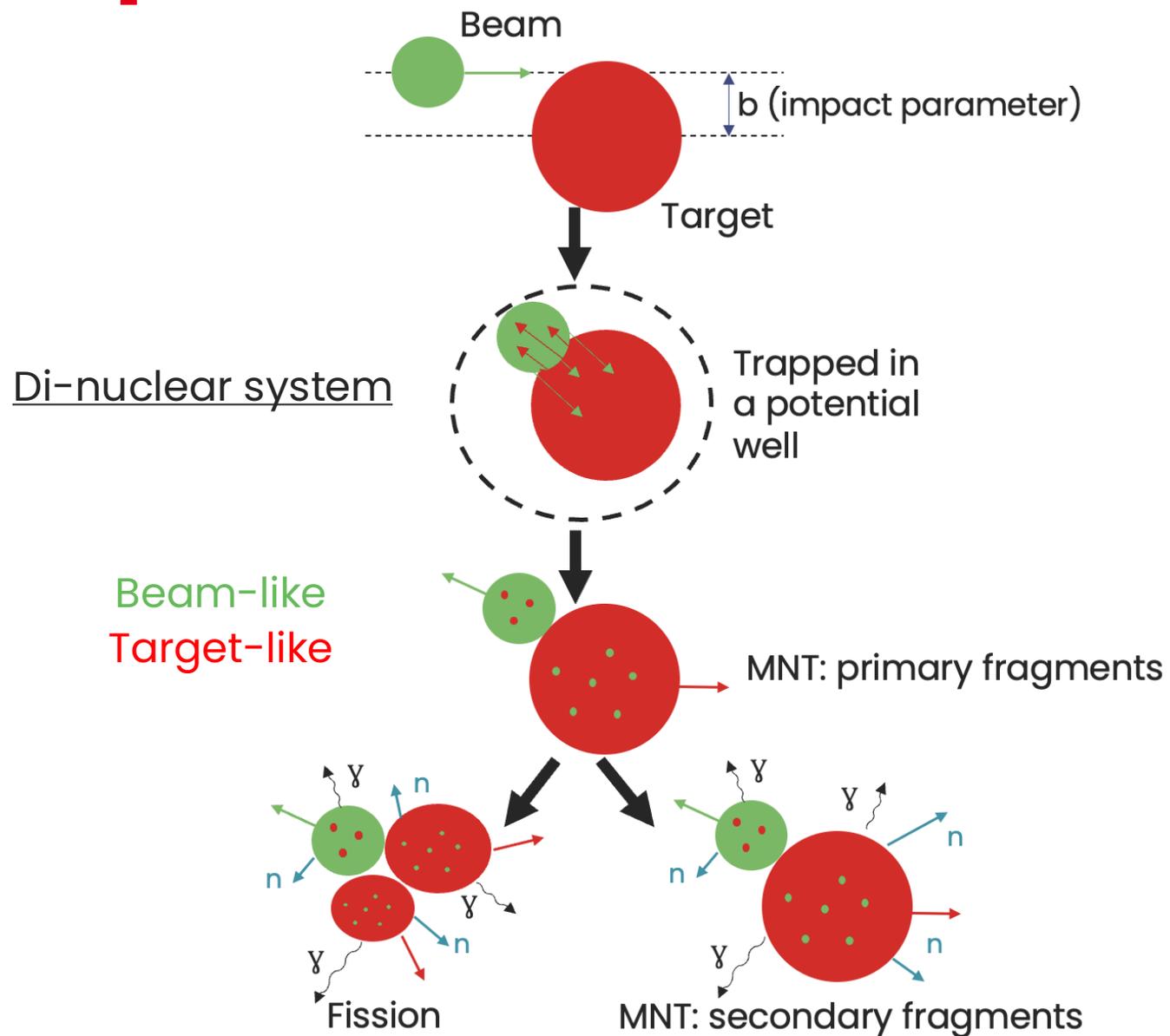


MNT: a complementary mechanism

- New n-rich isotopes
- Promising theoretical cross-sections
- Langevin equation model : use heavy beam & target



MNT: principles



Outline

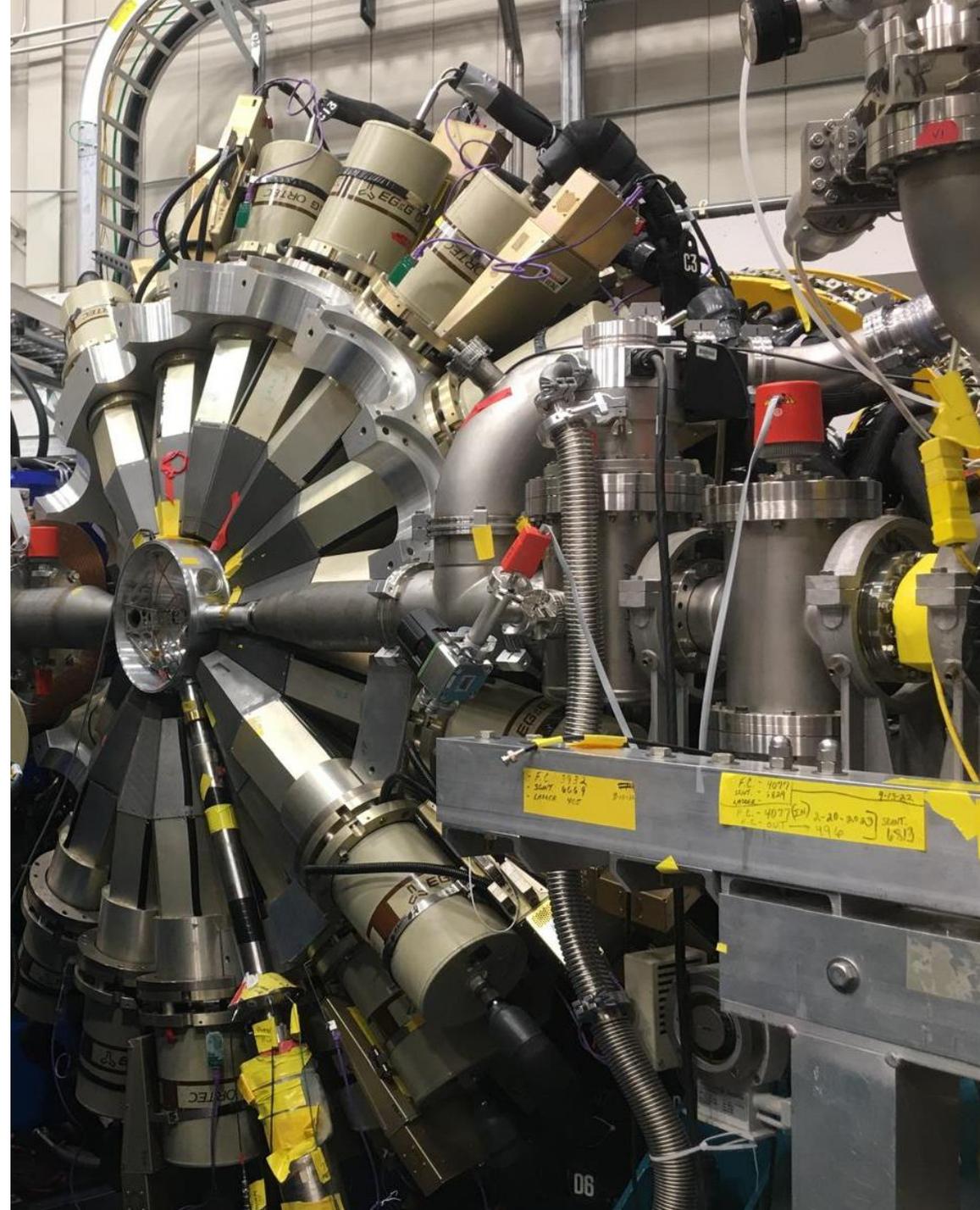
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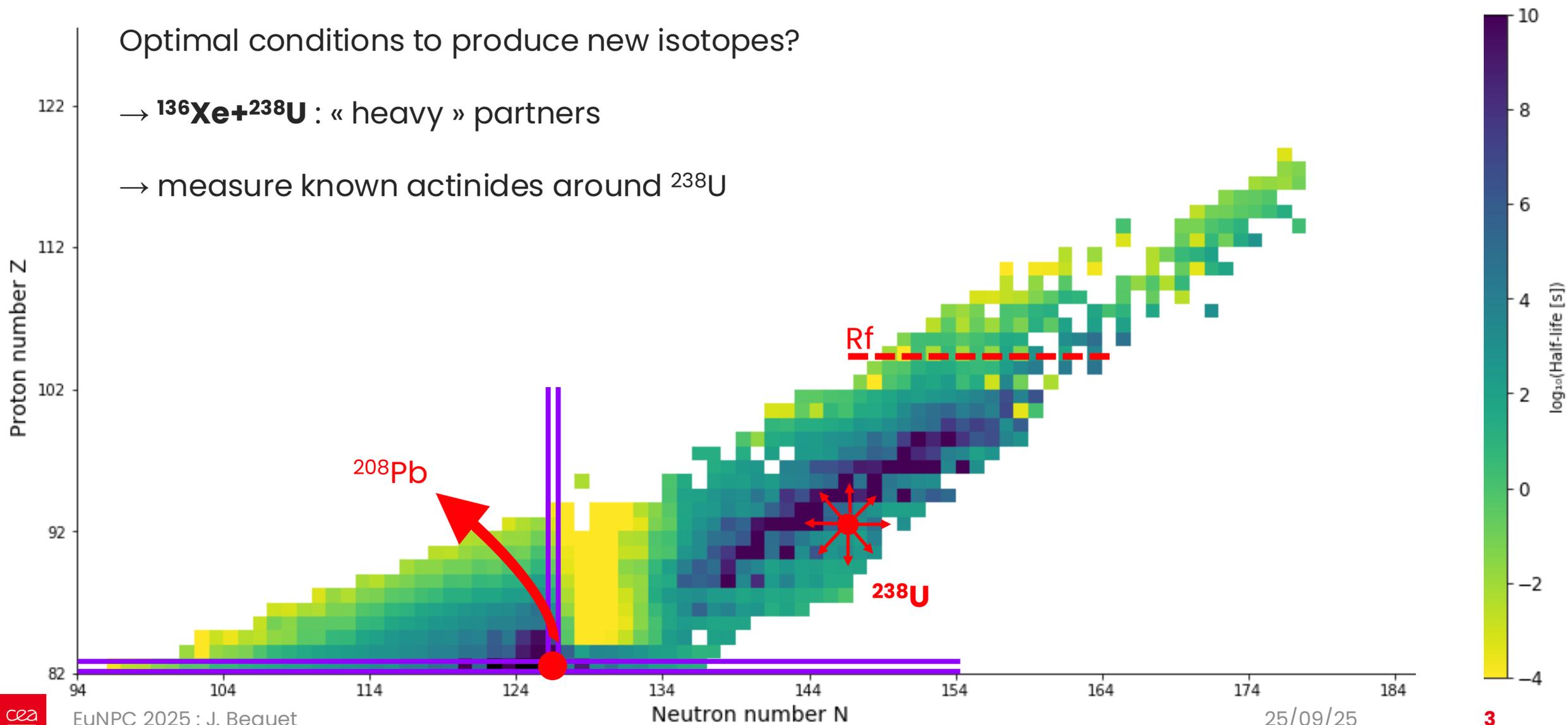


Physics case

Optimal conditions to produce new isotopes?

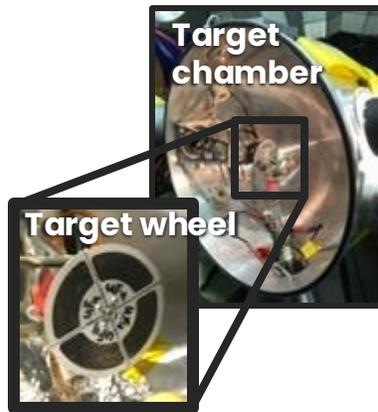
→ $^{136}\text{Xe} + ^{238}\text{U}$: « heavy » partners

→ measure known actinides around ^{238}U



The experimental setup: $^{136}\text{Xe} + ^{238}\text{U}$

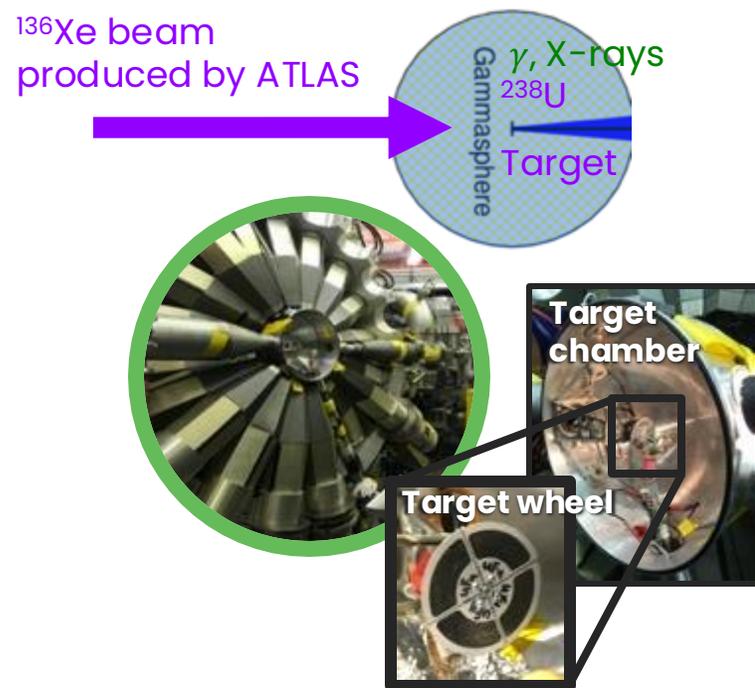
Beam: ^{136}Xe at 5.15 and 5.88 MeV/u
Target: ^{238}U (U 350 $\mu\text{g}/\text{cm}^2$ + C 45 $\mu\text{g}/\text{cm}^2$)



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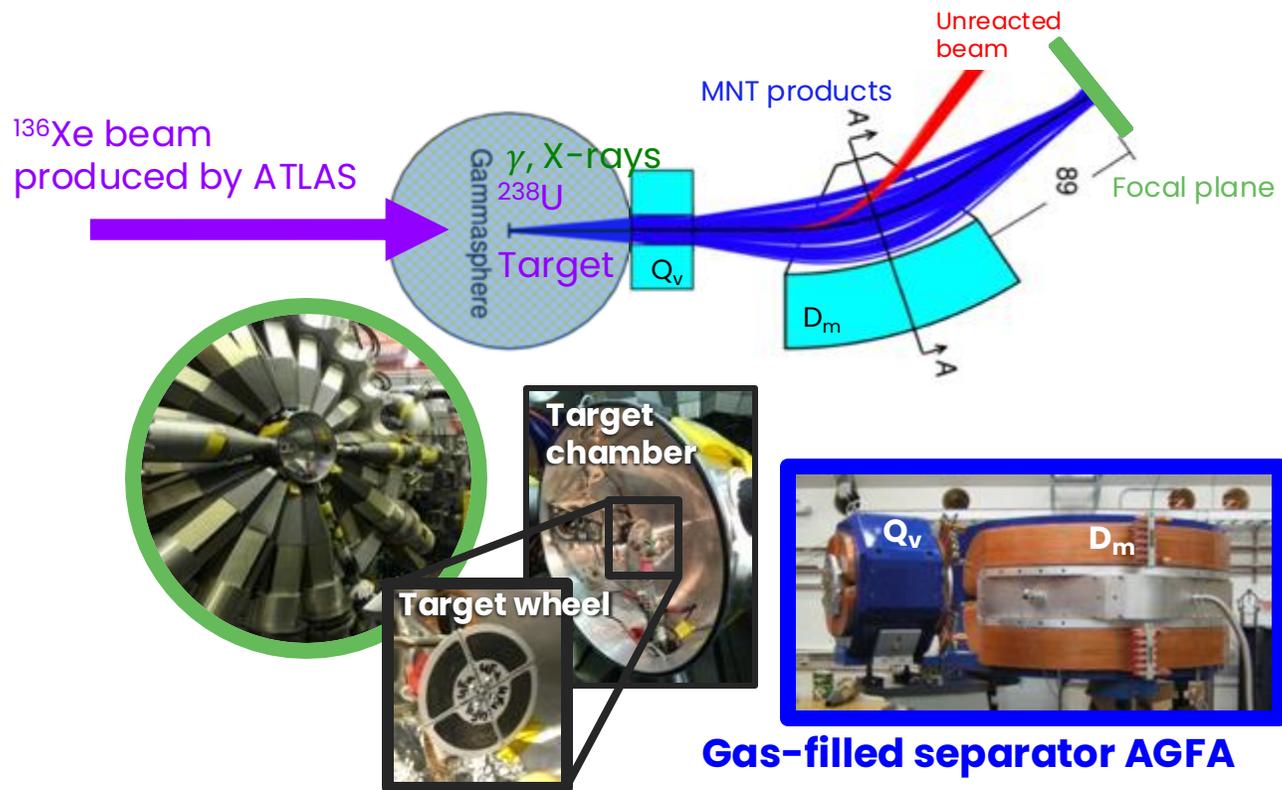


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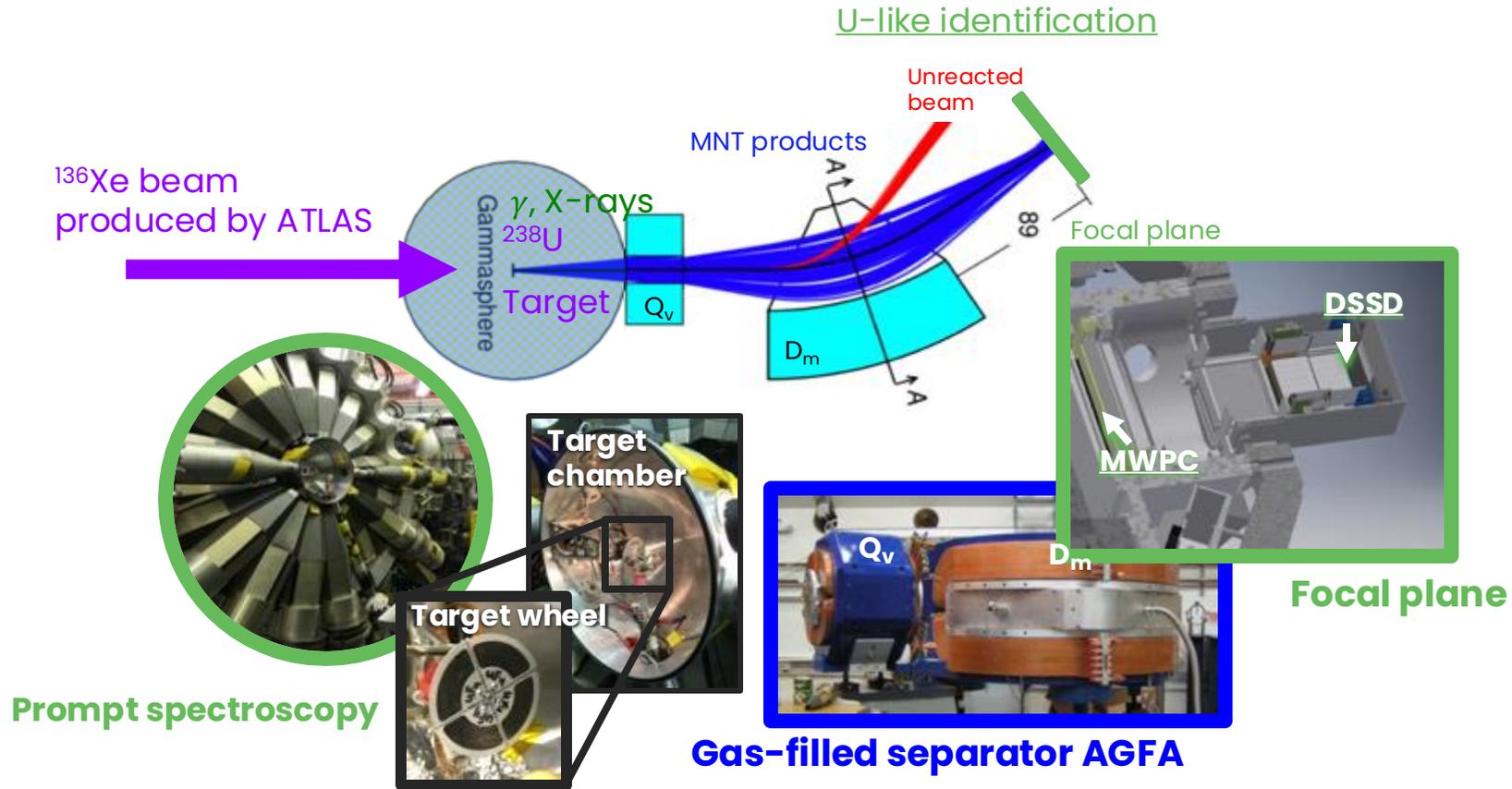
U-like identification



The experimental setup: $^{136}\text{Xe} + ^{238}\text{U}$

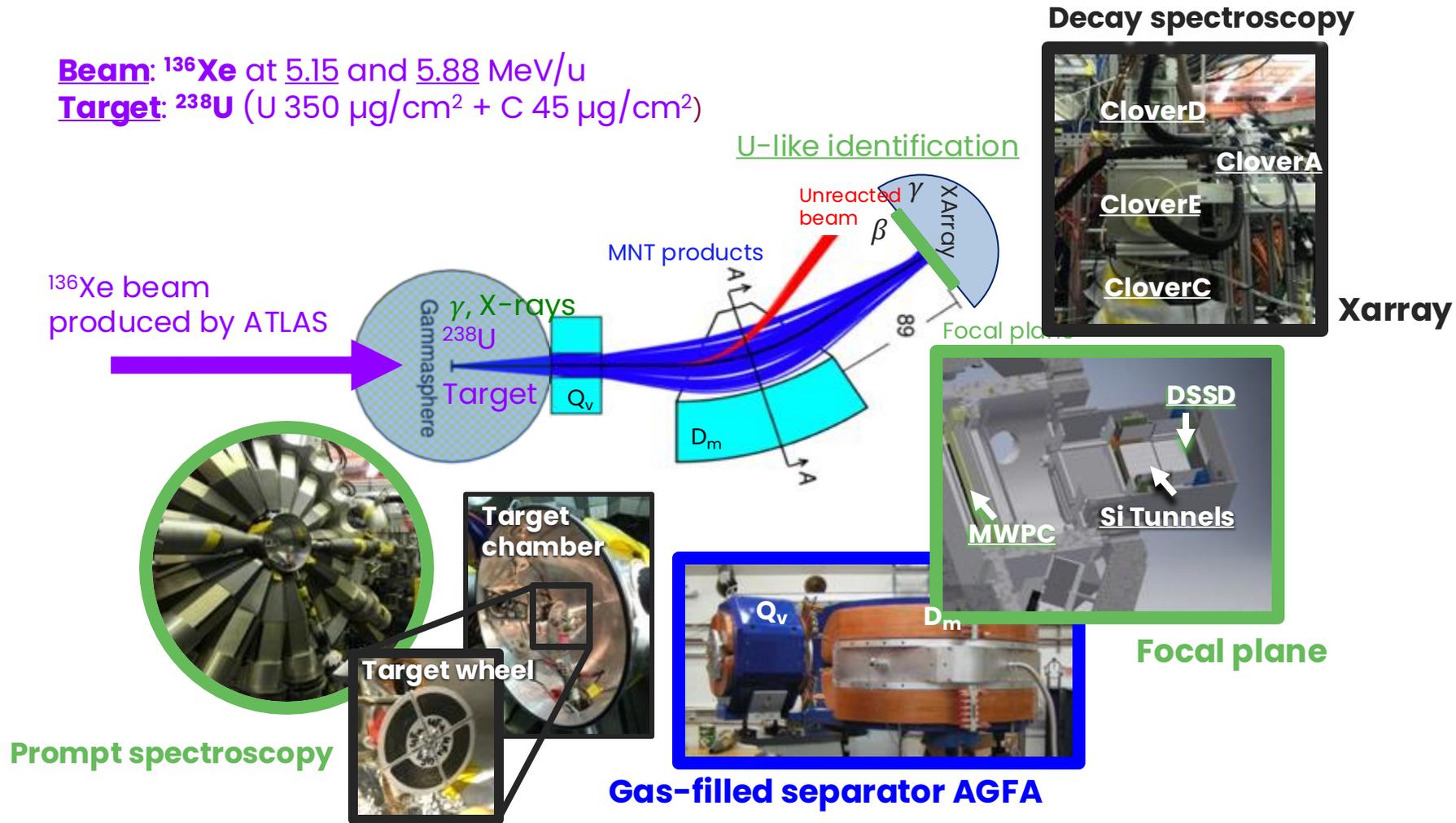
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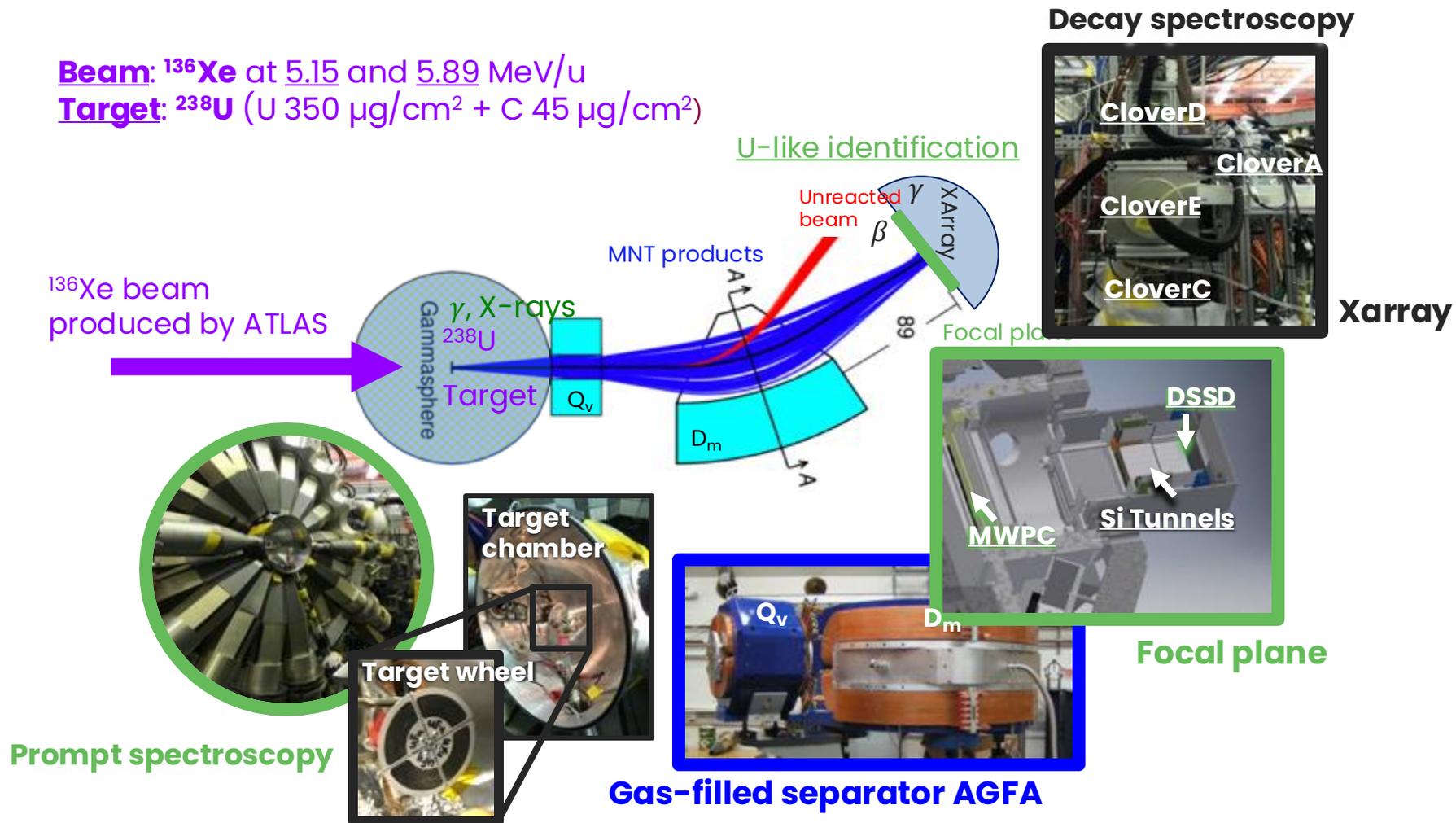
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The experimental setup: $^{136}\text{Xe} + ^{238}\text{U}$

Beam: ^{136}Xe at 5.15 and 5.89 MeV/u
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Analyzed data:

- Prompt spectroscopy
- 5.15 MeV/u
- 11 h
- 11 pA
- $B\rho = 1.65 \text{ T}\cdot\text{m}$
- $P_{\text{AGFA}} = 4 \text{ Torr}$
- 72 HPGe in Gammashpere

Outline

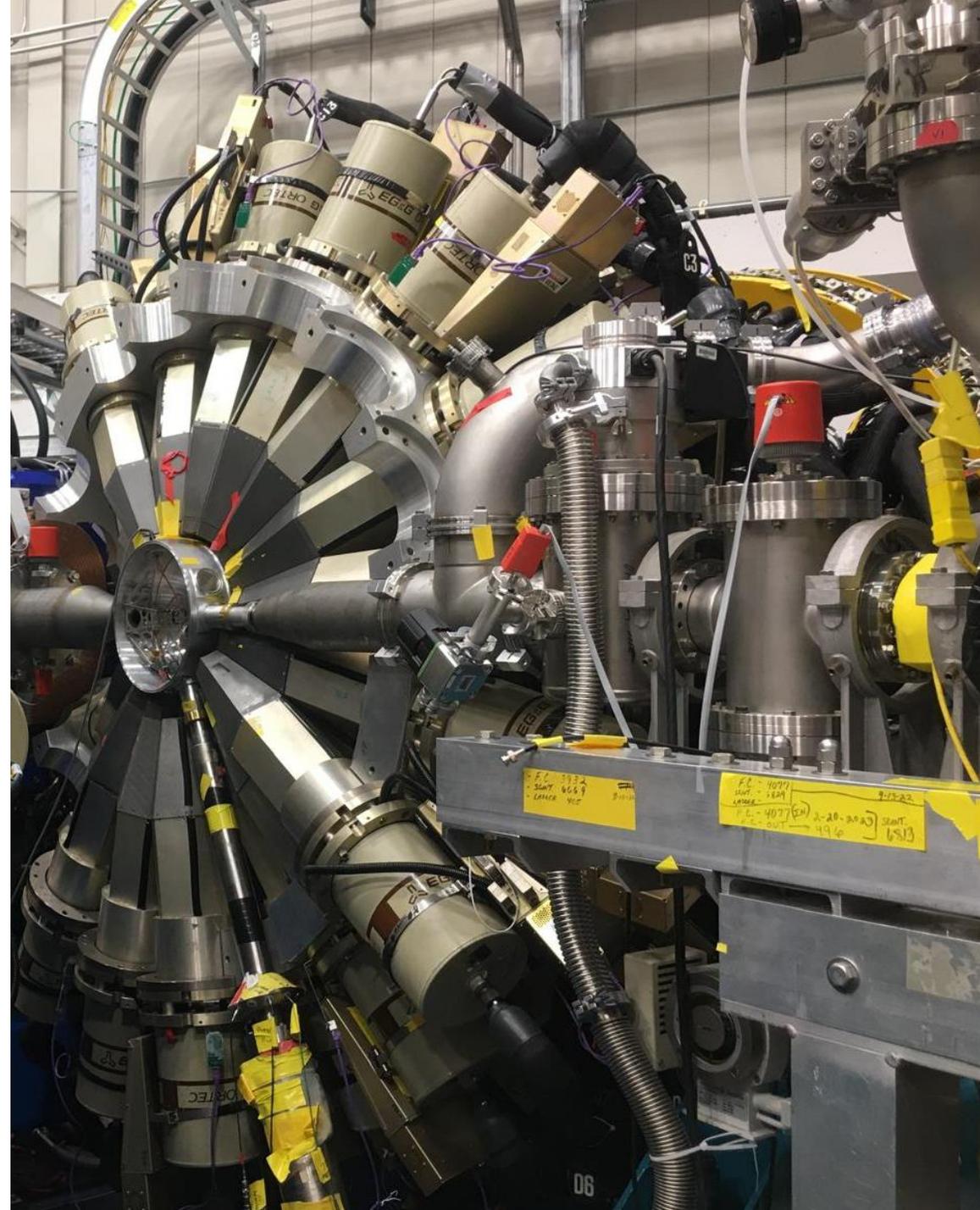
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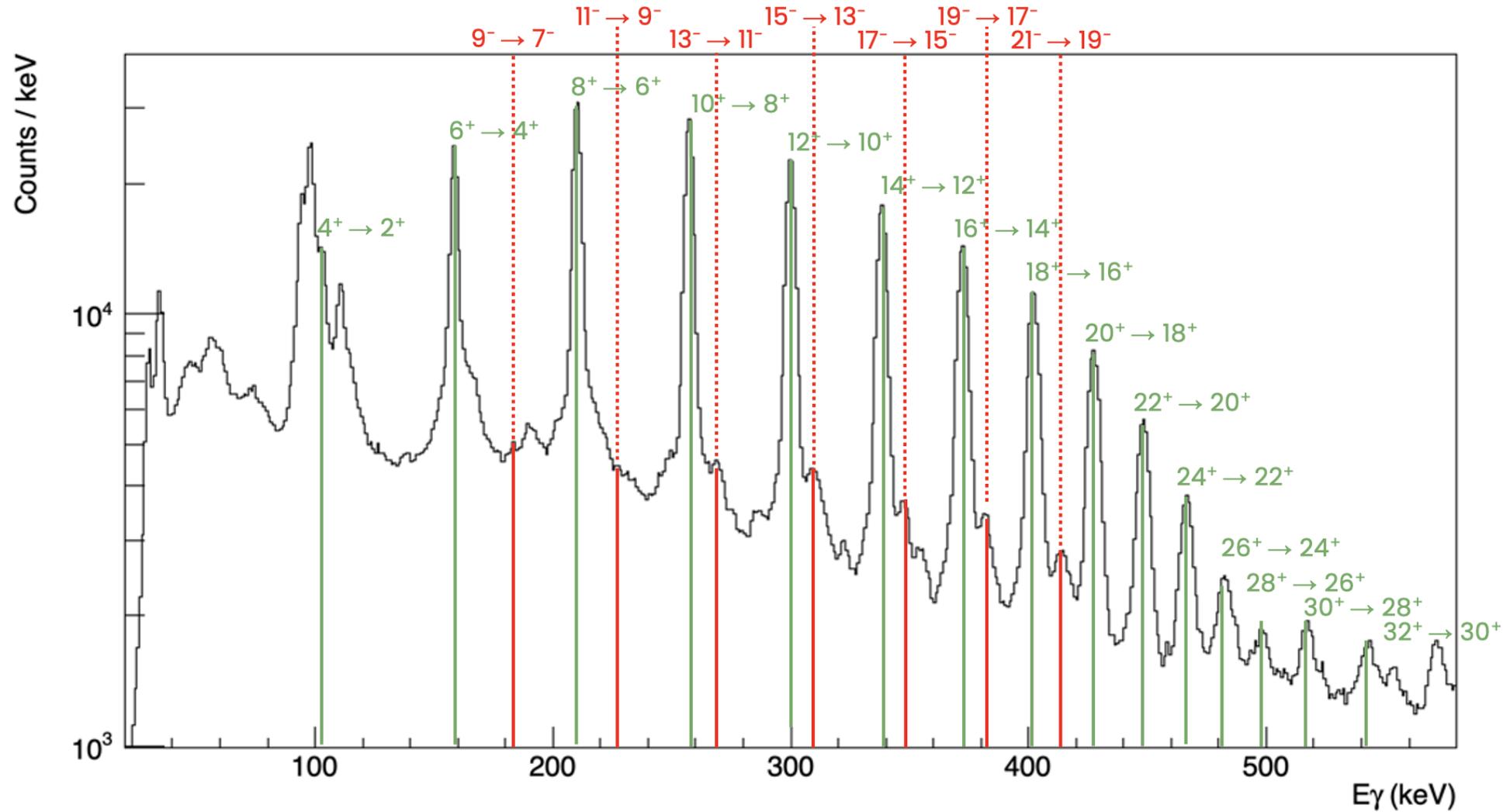
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Correlated single γ -ray spectrum

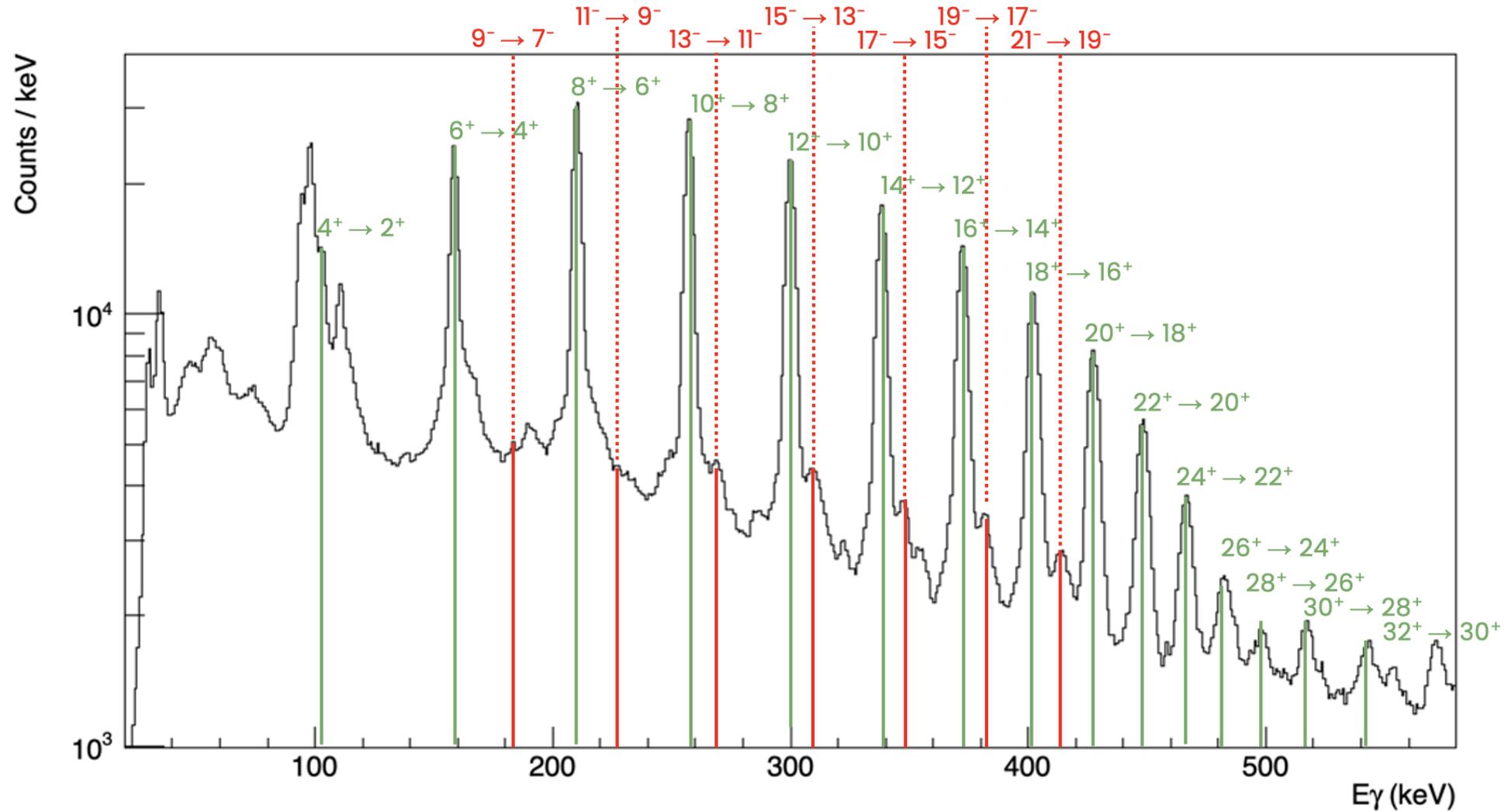


^{238}U : g.s. rotational band

^{238}U : octupole vibrational band

→ Background to be suppressed

Correlated single γ -ray spectrum



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γ - γ - γ correlations for final identification

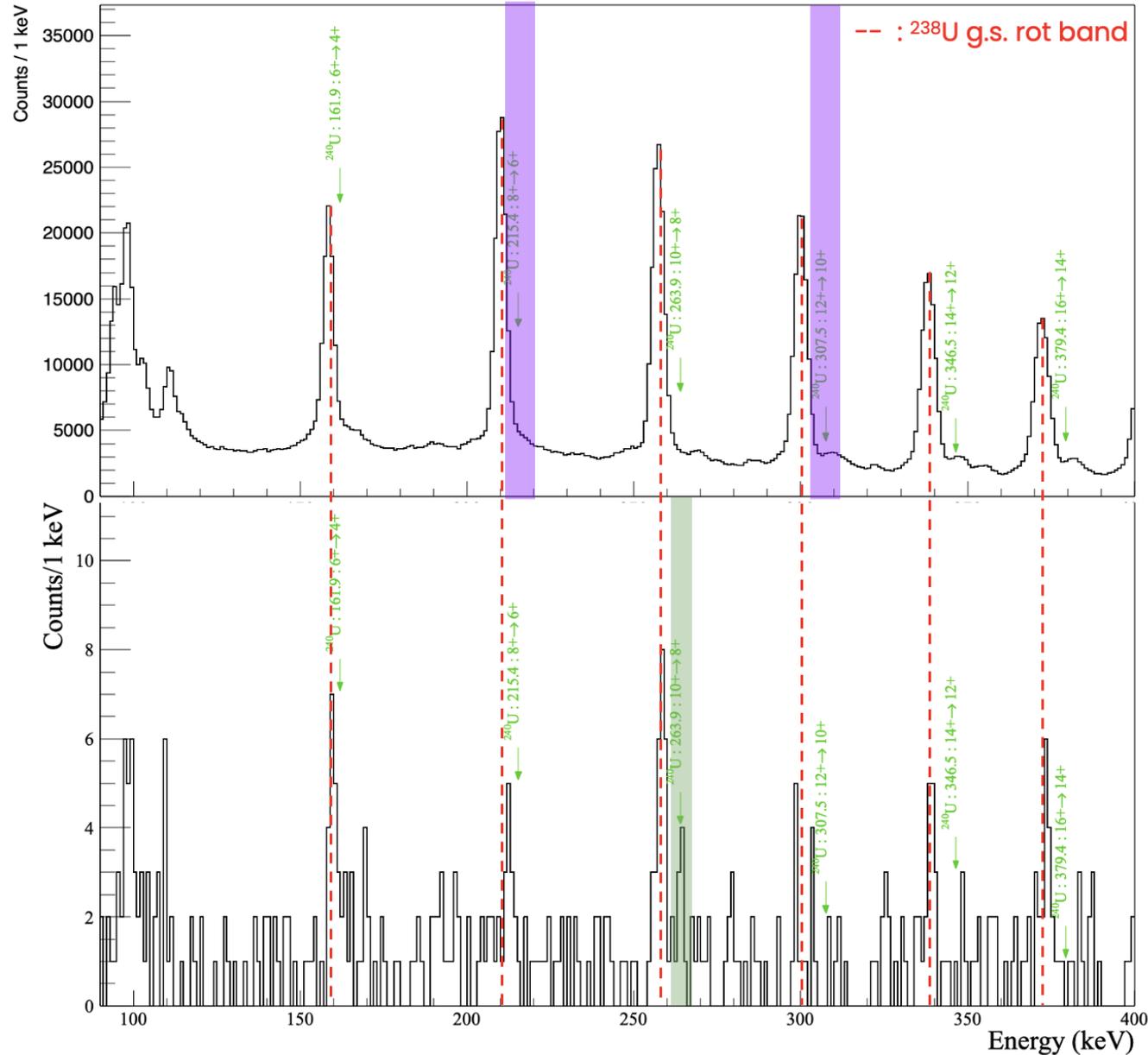
^{240}U : From identification to measurement



Poisson statistics:

True number of ^{240}U counts in a 95 % confidence interval:

[1.42 , 10.833]



Cross-sections calculation

$$\sigma_{\gamma\gamma} = \frac{(1 + \alpha_1) \cdot (1 + \alpha_2) \cdot (1 + \alpha_3) \cdot N_{\gamma 2}}{\varepsilon_{gs1} \cdot \varepsilon_{gs2} \cdot \varepsilon_{gs3} \cdot \varepsilon_{AGFA} \cdot \Gamma_1 \cdot \Gamma_3} \cdot \frac{Q_e}{I \cdot \Delta t} \cdot \frac{M_{\text{target}}}{\rho \cdot e}$$

N_{produced} $1 / N_{\text{beam}}$ $1 / N_{\text{target}}$

Cross-sections calculation

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N_{produced} :

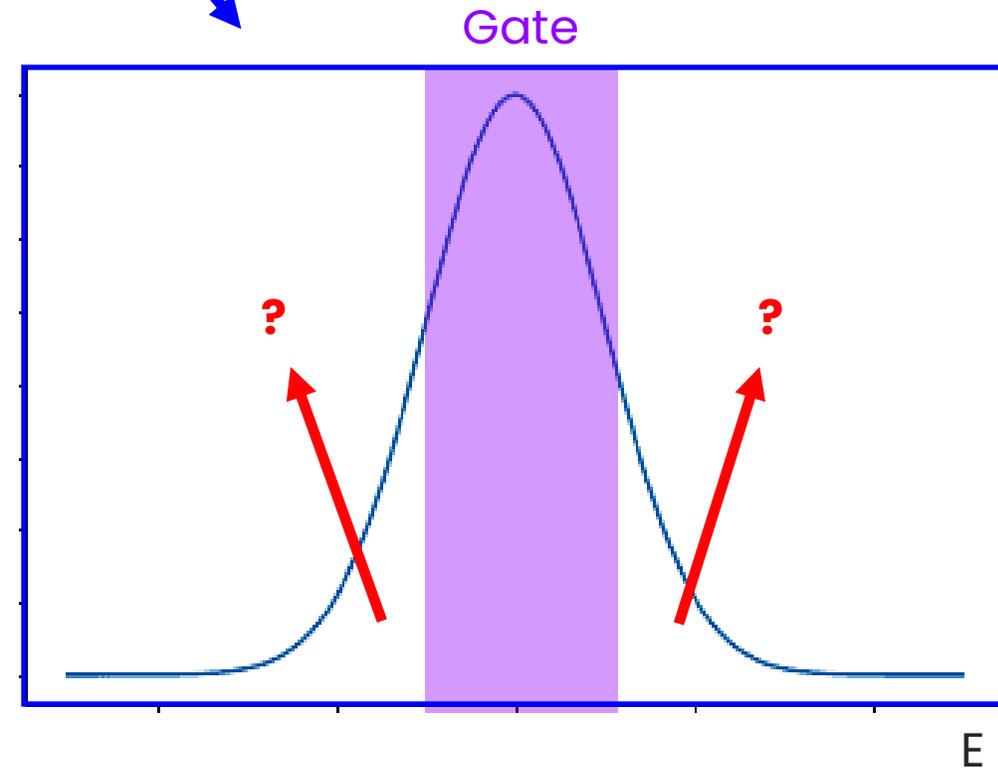
- Integral of the measured transition
- Conversion coefficients of the three transitions
- Absolute efficiency at the energy of the three transitions
- Transmission through the separator

Cross-sections calculation

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N_{produced} :

- Integral of the measured transition
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Cross-sections calculation

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N_{produced} :

- Integral of the measured transition
- Conversion coefficients of the three transitions
- Absolute efficiency at the energy of the three transitions
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N_{beam} :

- Beam intensity (pA)
- Electron Charge
- Integrated beam time

N_{target} :

- Target thickness
- Target mass (^{238}U)

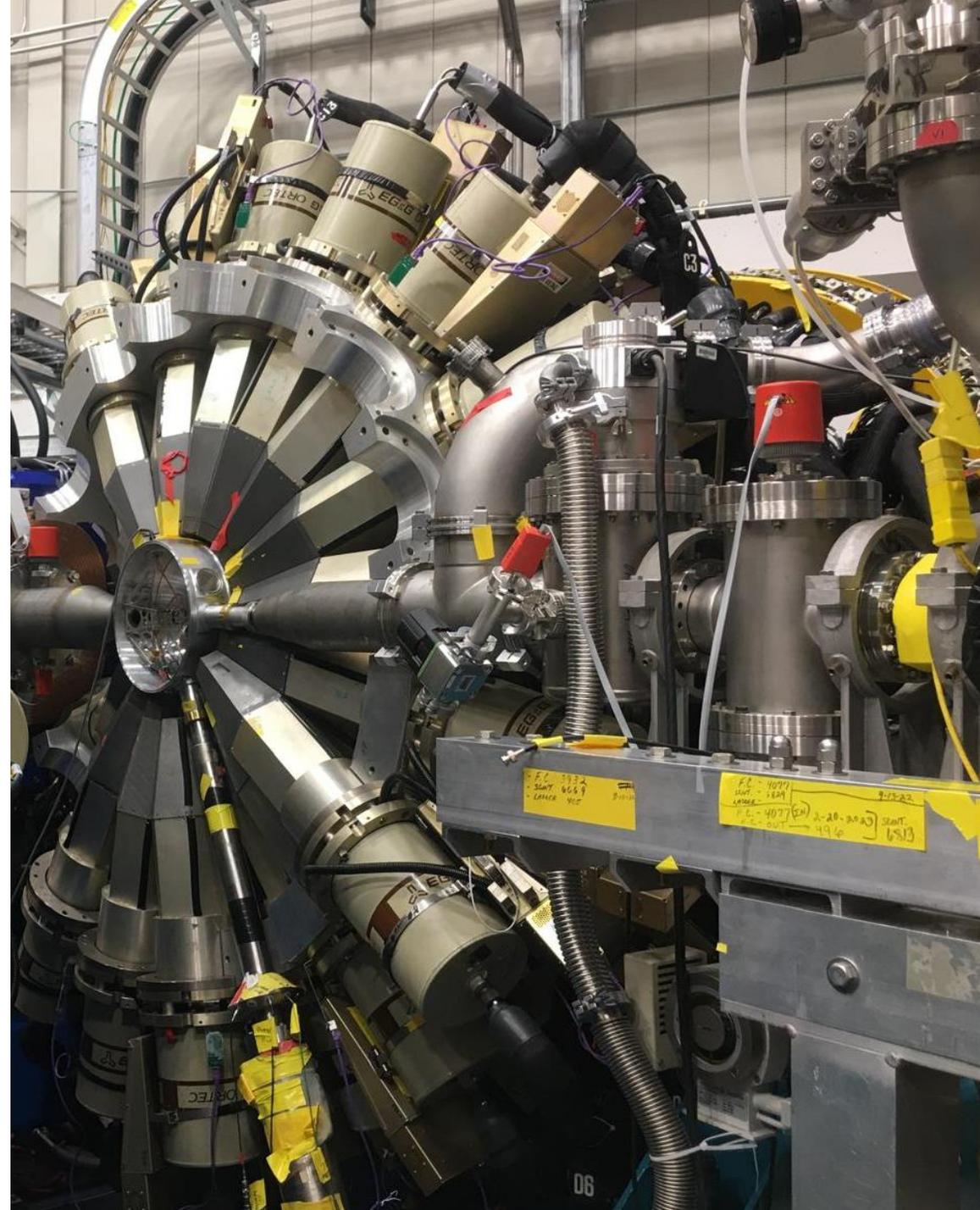
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Isotope	α_1	α_2	α_3	$N_{\gamma 2}$	ε_1 (%)	ε_2 (%)	ε_3 (%)	Γ_1	Γ_3	N_{prod}	σ (mb)
^{240}U	0.569(8)	0.282(4)	0.174(3)	6	9.58	8.89	8.29	0.981	0.963	81767	$0.063 \pm_{0.049}^{0.052}$
$^{236}\text{U}(\text{rot})$	0.598(9)	0.297(5)	0.183(3)	5.2	9.61	8.95	8.35	0.655	0.408	255363	$0.198 \pm_{0.193}^{0.423}$
$^{236}\text{U}(\text{oct})$	0.764(11)	0.363(5)	0.144(2)	4	9.77	9.17	8.03	0.964	0.960	77050	$0.060 \pm_{0.040}^{0.075}$
^{234}U	2.14(3)	0.734(11)	0.367(6)	7	9.74	9.18	8.63	0.990	0.988	237651	$0.184 \pm_{0.142}^{0.148}$
^{232}U	0.546(8)	0.279(4)	0.177(3)	1.8	9.54	8.88	8.31	0.627	0.802	45474	$0.035 \pm_{0.031}^{0.106}$

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Cross-sections: Uranium isotopes at 5.15 MeV/u

R.J. Charity, IAEA, Vienna, 2008, Report INDC(DNC)-530.
L. Tassan-Got and C. Stéphan, NPA 524 (1991) 121

DIT & GEMINI++ :

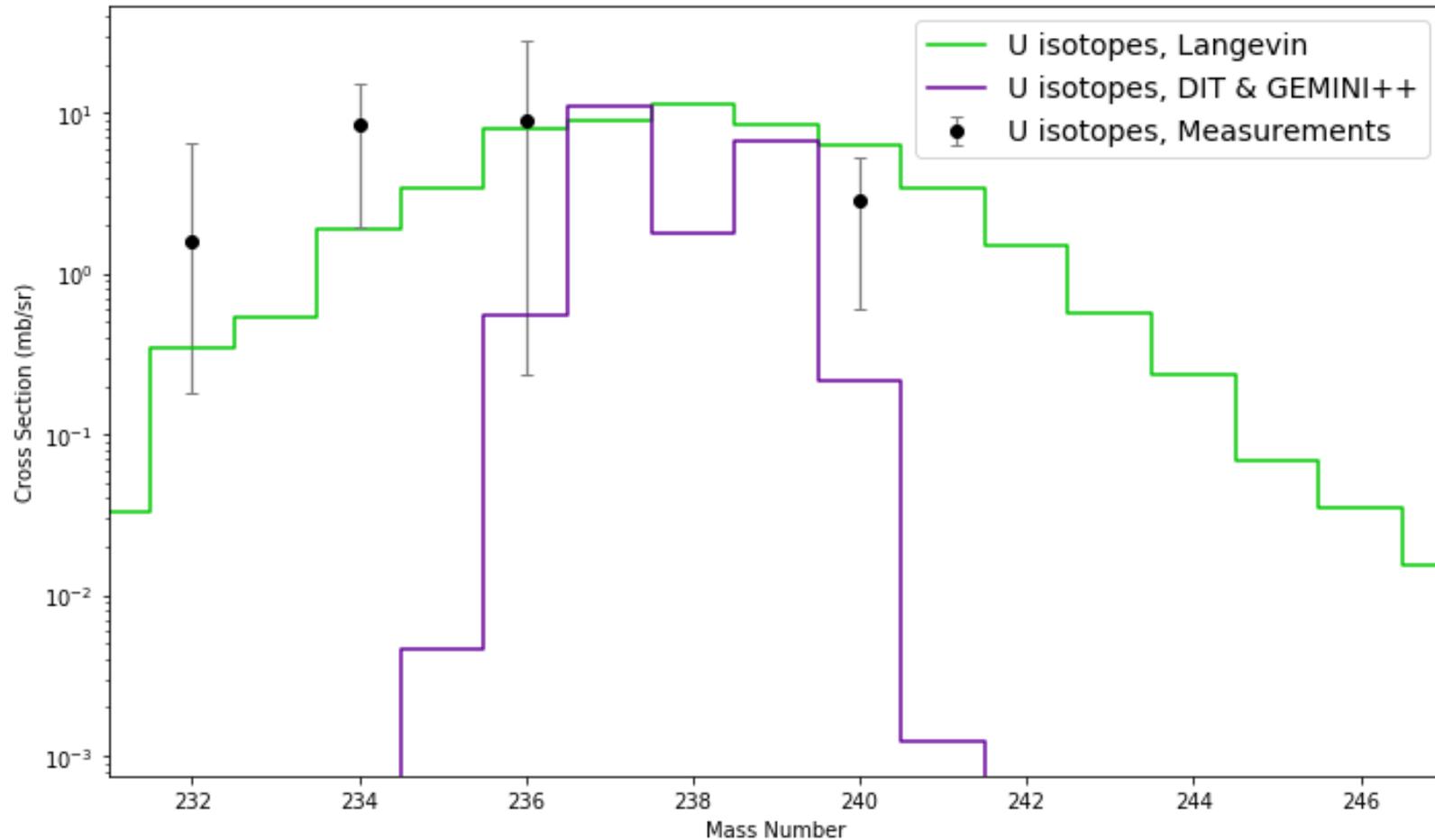
Langevin equations model:

A. V. Karpov; V. Saiko, private communication

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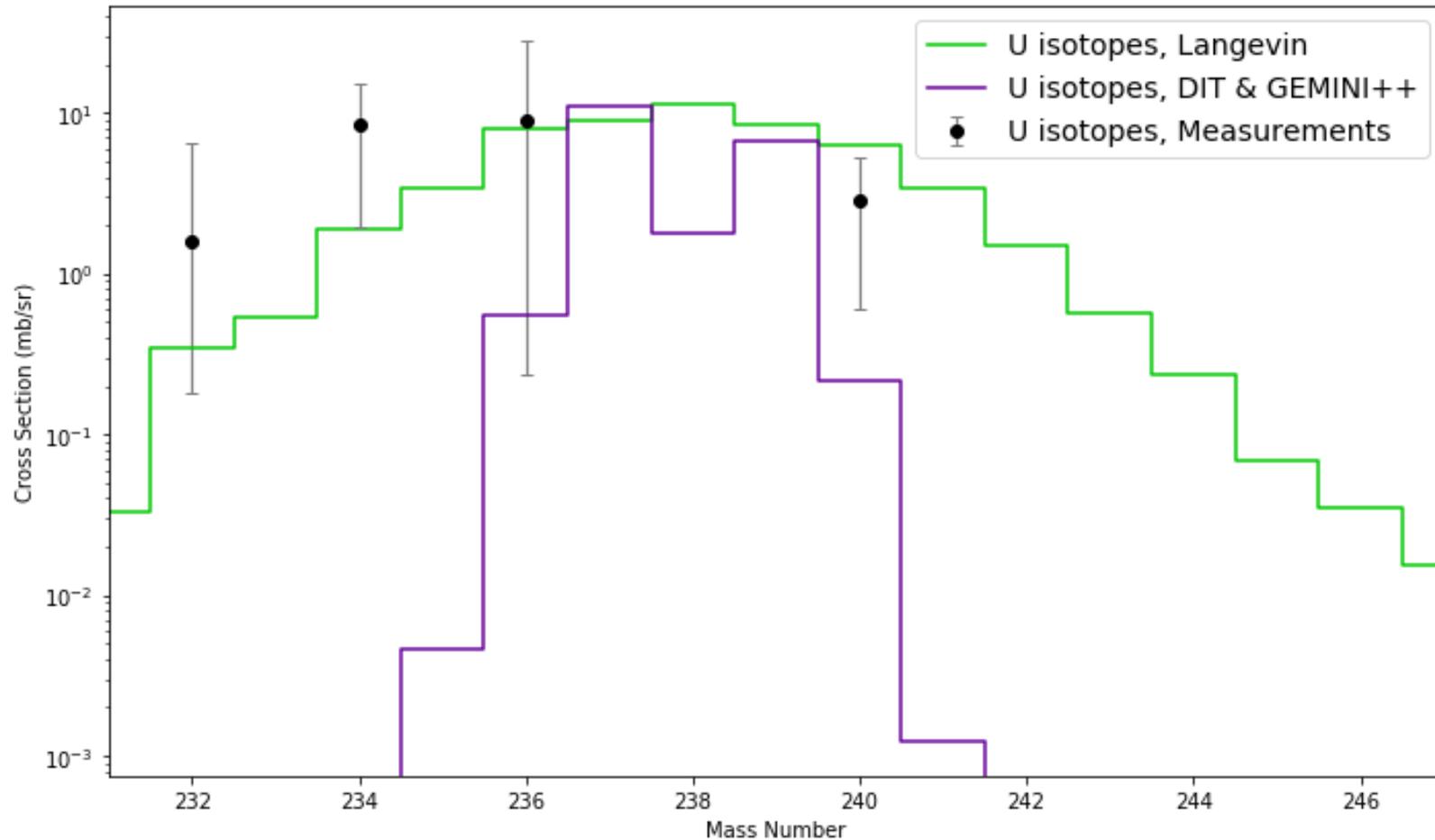
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DIT & GEMINI++ :

completely fails for this physics case

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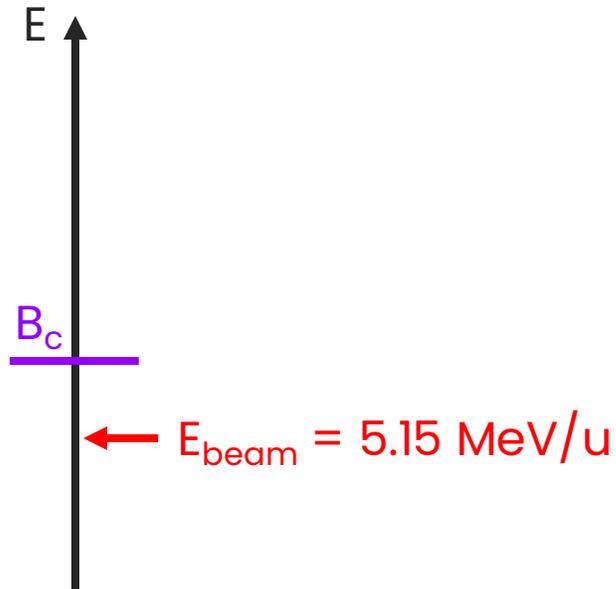
overall agreement with measurements

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Models for comparison:

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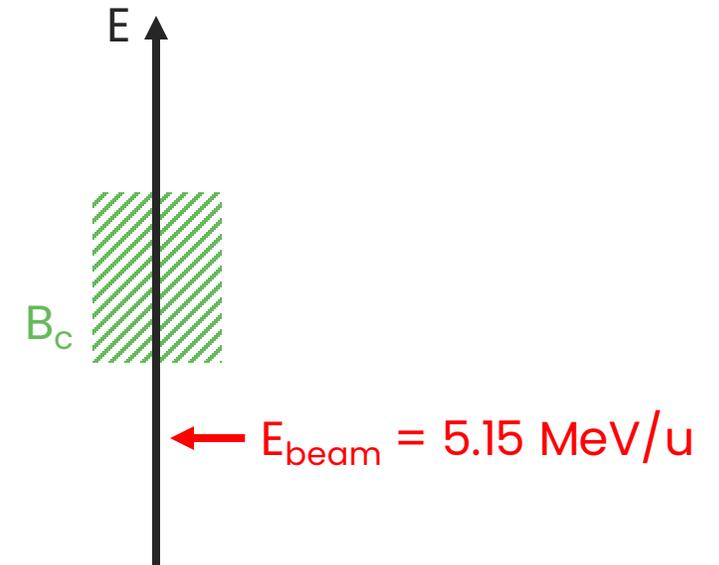
- Purely spherical nuclei
→ $B_c = 5.29 \text{ MeV/u}$



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Langevin equations model :

- Deformations & relative orientations accounted for
→ $B_c \in [5.28, 5.68] \text{ MeV/u}$

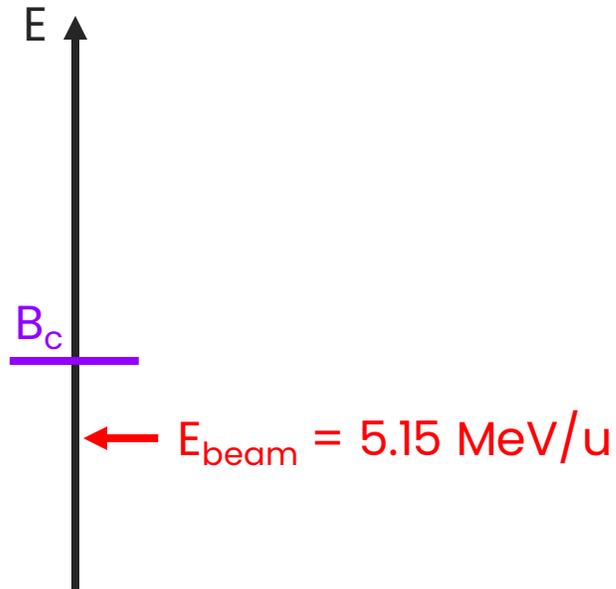


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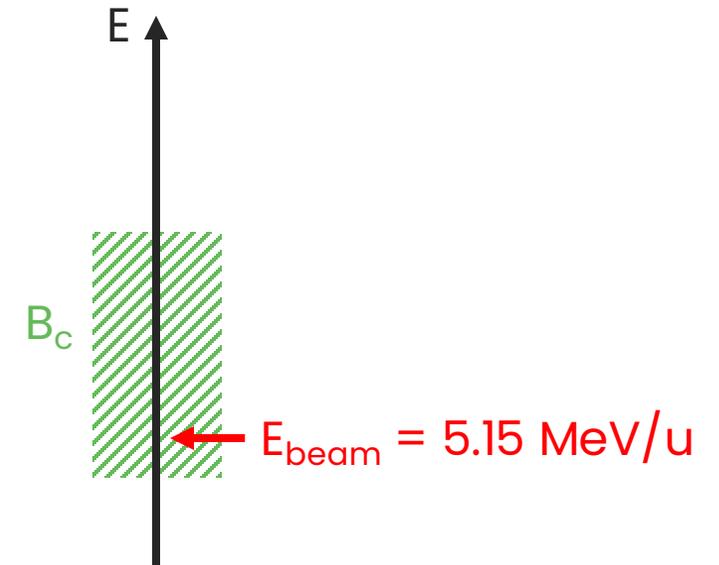
- Purely spherical nuclei
→ $B_c = 5.29 \text{ MeV/u}$
- Static nuclear properties during the interaction



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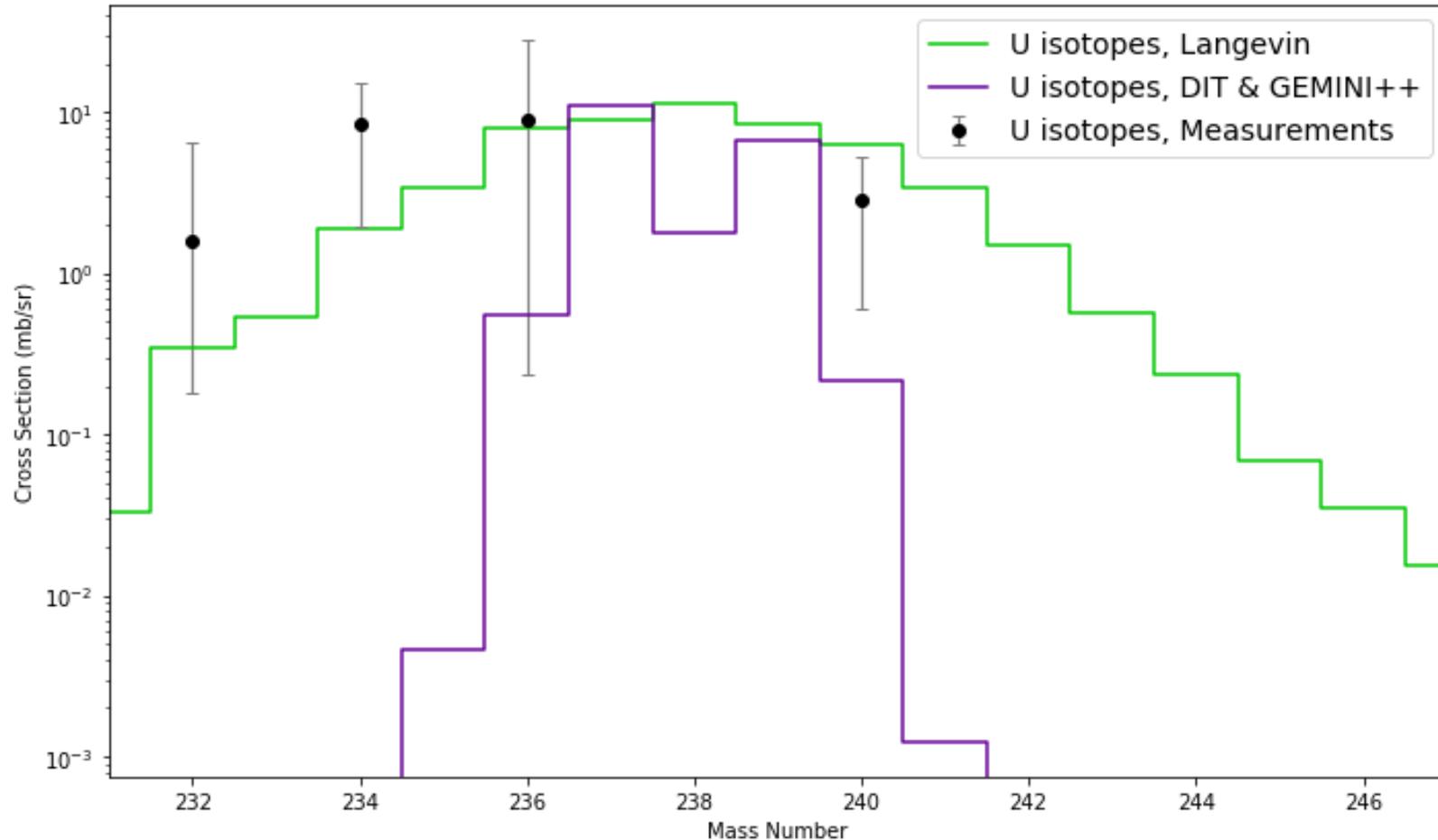
Langevin equations model :

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→ $B_c \in [5.28, 5.68] \text{ MeV/u}$
- Dynamical deformation of nuclei while approaching



A. V. Karpov; V. Saiko, private communication

Cross-sections: Uranium isotopes at 5.15 MeV/u



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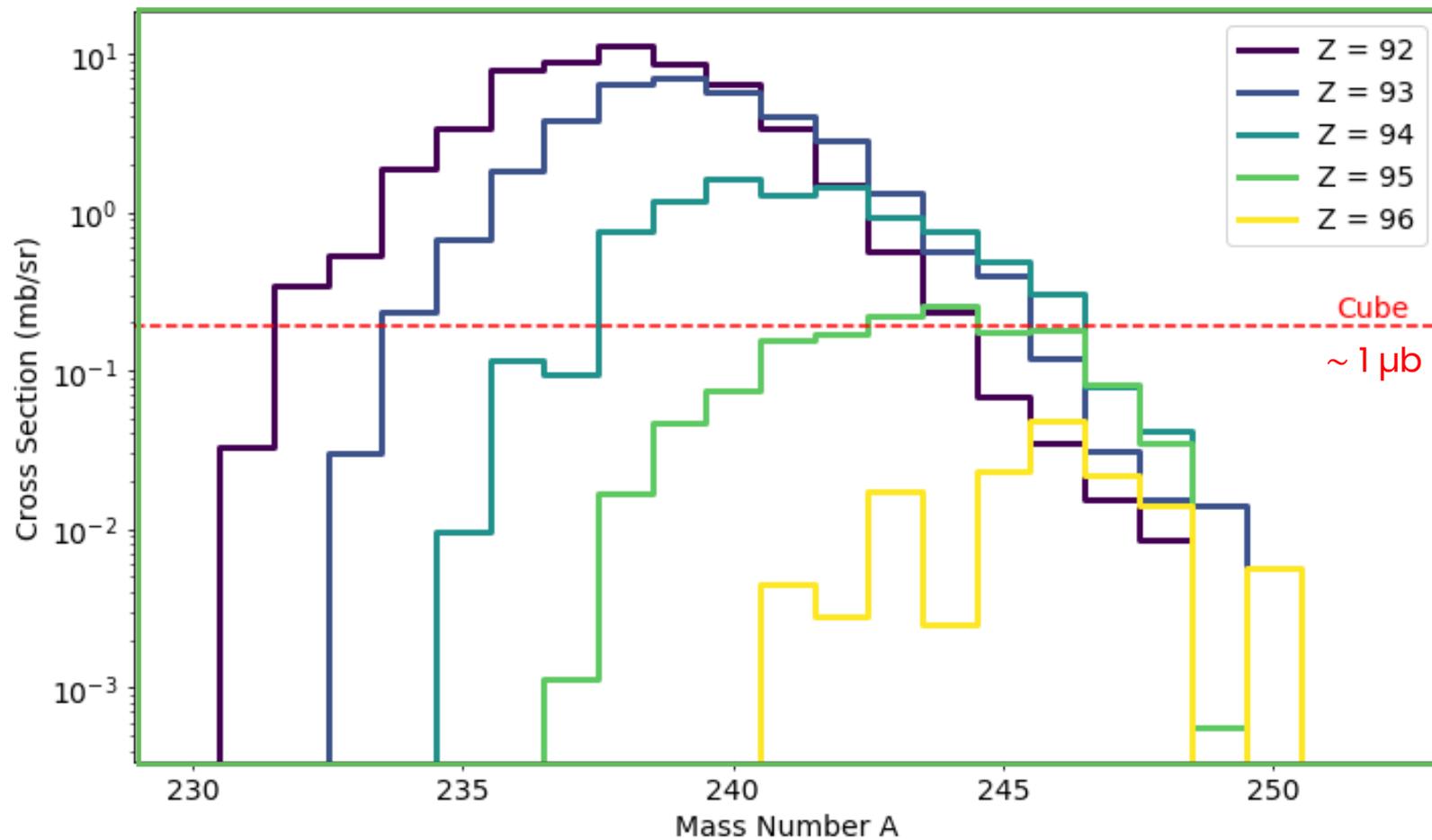
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Langevin equations model:

overall agreement with measurements

Large difference with DIT interpreted as a signature of dynamical deformations lowering the barrier

Sensitivity limit of the experiment



Langevin equations model predictions

Optimal sensitivity limit with cube

Exploratory experiment with heavy partners, near-barrier & forward angle :

massive transfers out of reach for now

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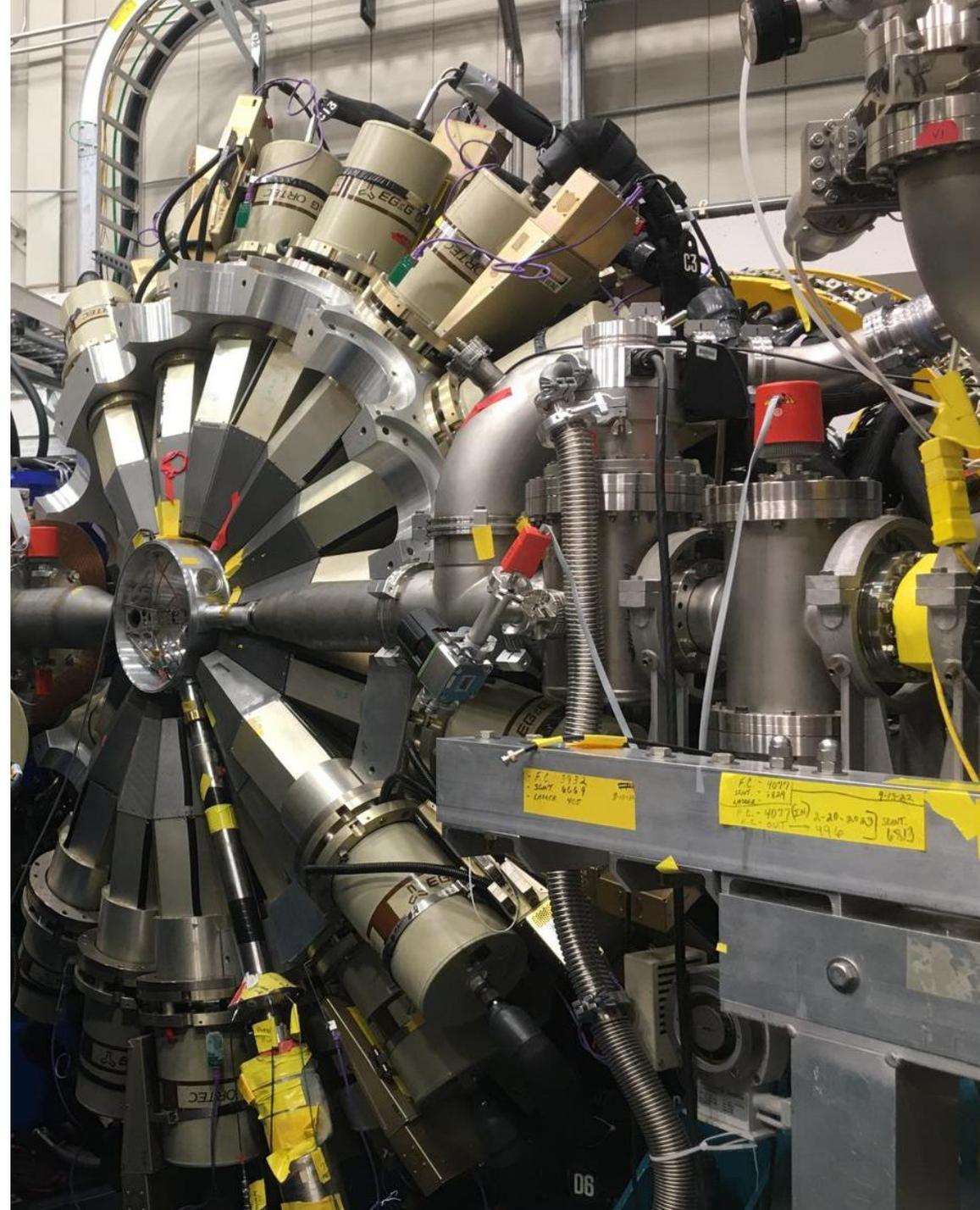
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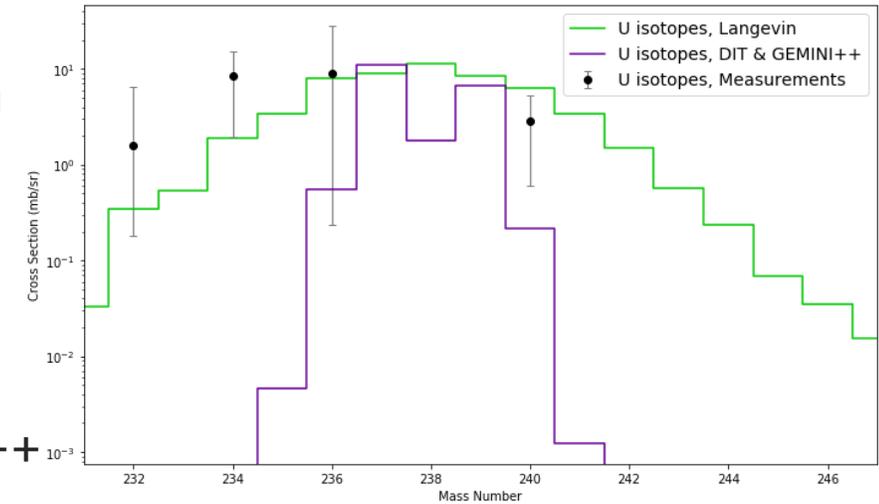
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Conclusion

Successes :

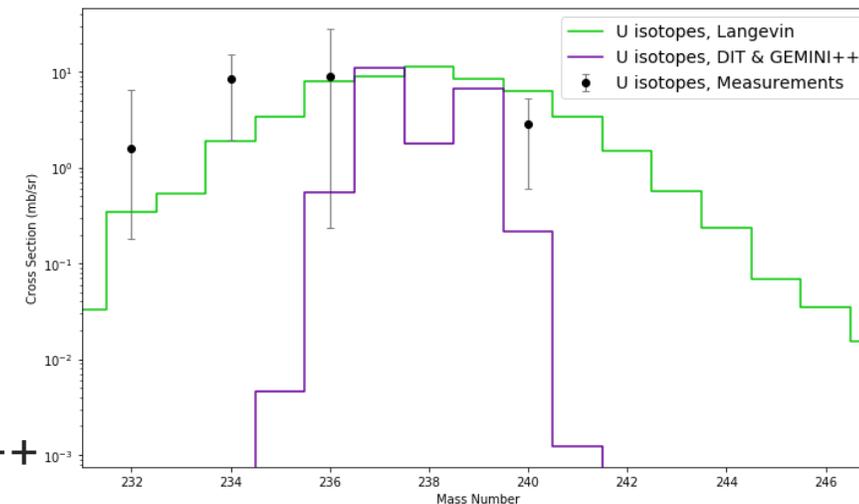
- MNT neutron-transfer channels observed using $^{136}\text{Xe} + ^{238}\text{U}$
- The extracted cross-sections :
 - Agree with Langevin equations model
 - Highlight potential improvements of DIT & GEMINI++



Conclusion

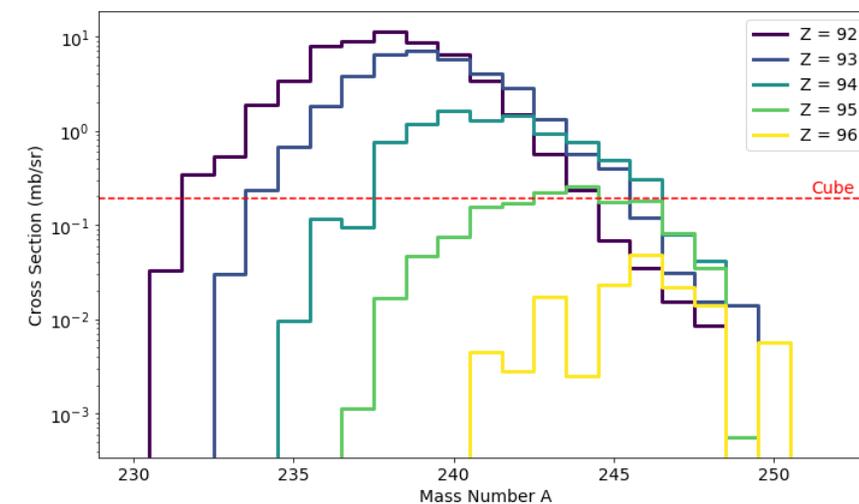
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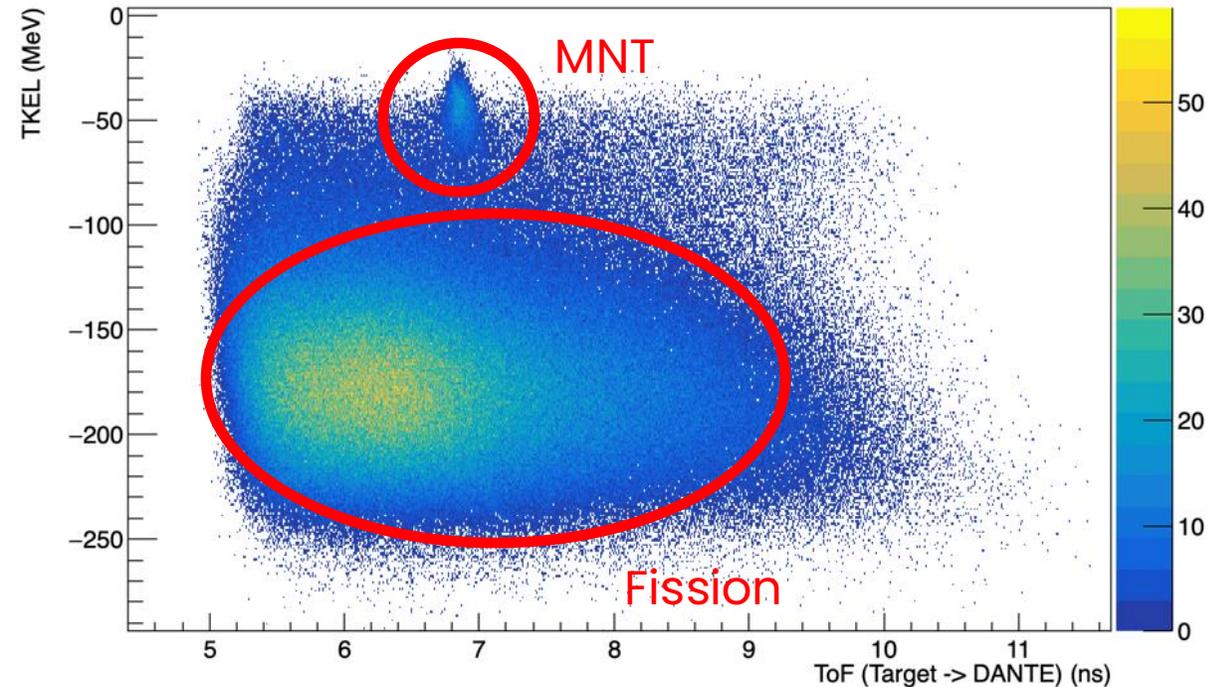
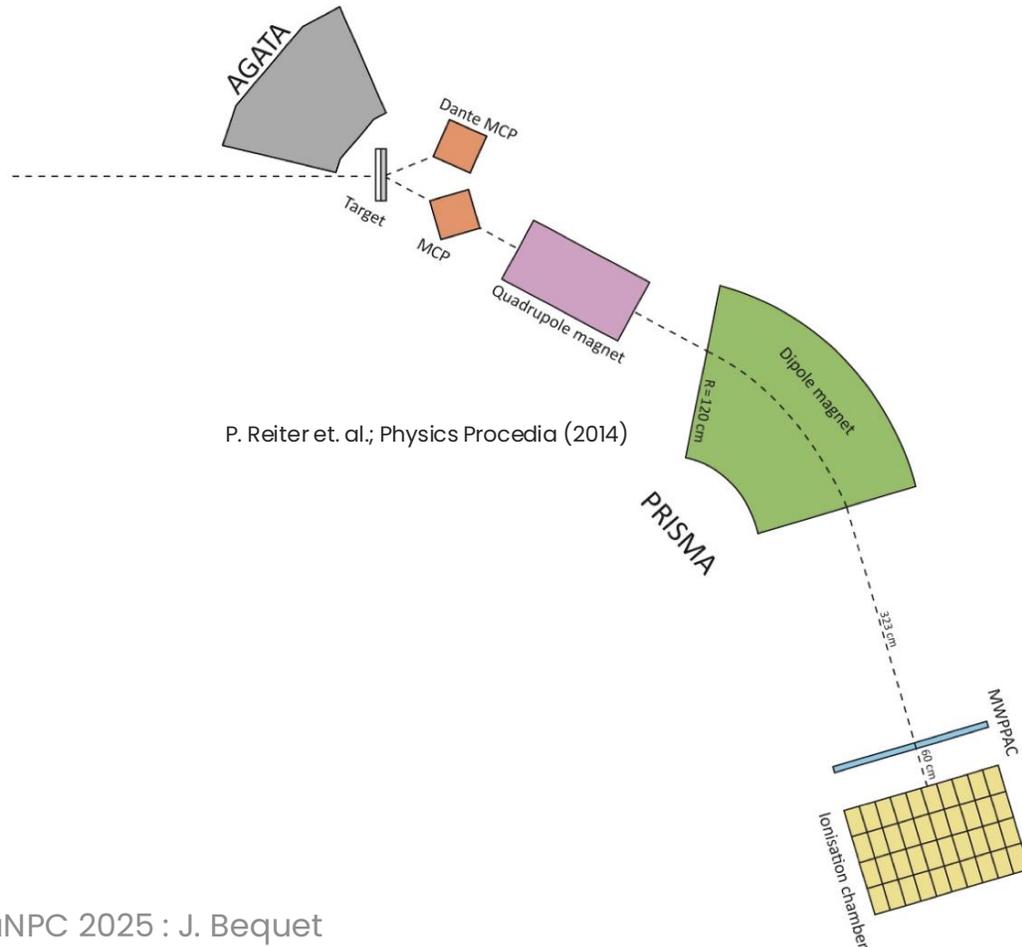
Limitations :

- No mass selection → High CoulEx background
- Symmetry limit for studies with gas-filled separators



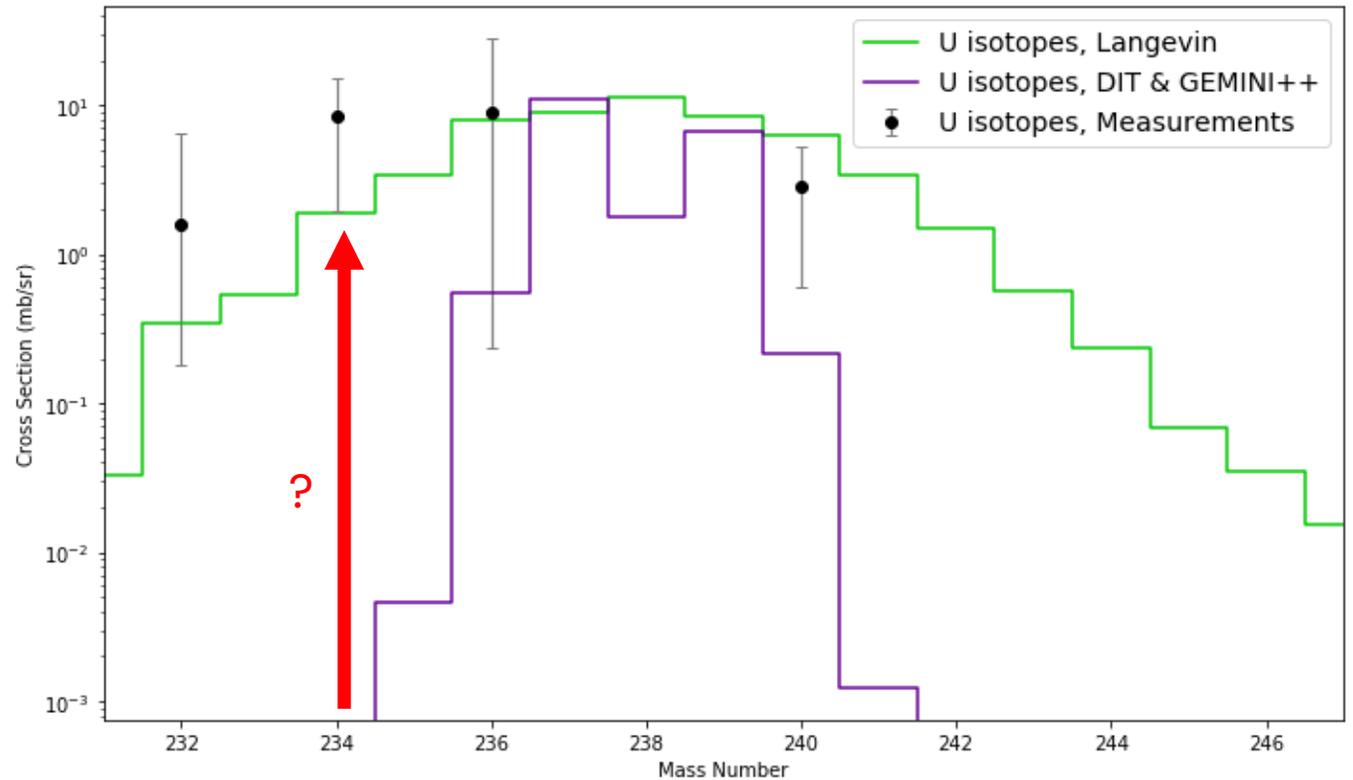
Outlooks : future experiments & dit improvement

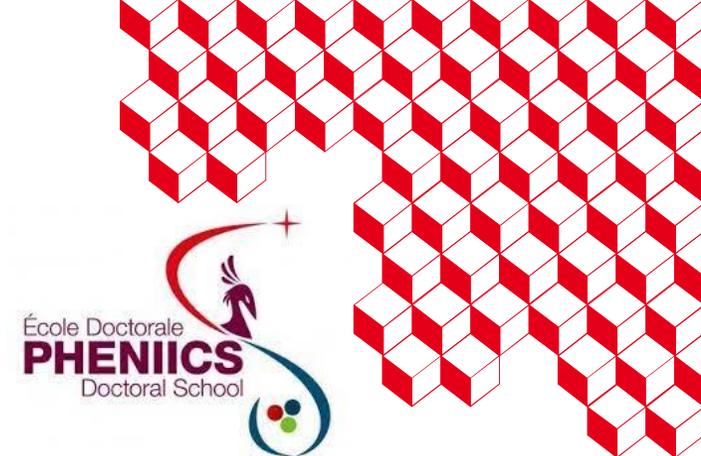
- $^{232}\text{Th} + ^{96}\text{Zr}$, 6 MeV/u at GANIL → accepted experiment
- $^{238}\text{U} + ^{64}\text{Ni}$, 7.2 MeV/u at LNL → Proposal submitted to the PAC



Outlooks : future experiments & dit improvement

- $^{232}\text{Th} + ^{96}\text{Zr}$, 6 MeV/u at GANIL → accepted experiment
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- Add deformation to the DIT code





**Thank you
for your
attention**

CEA SACLAY

91191 Gif-sur-Yvette Cedex

France

jonathan.bequet@cea.fr



6 ■ Backup

Barriers



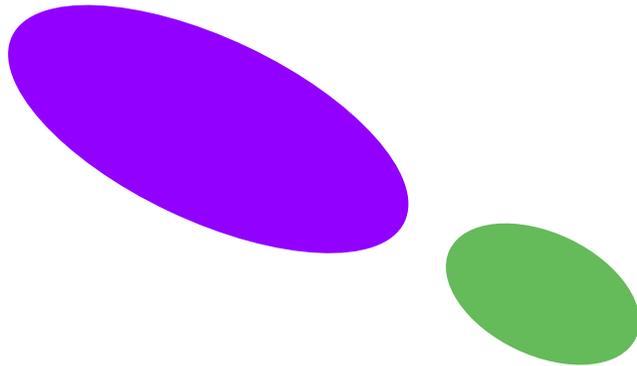
Coulomb barrier

$$B_C = \frac{e^2 Z_b Z_t}{R_0(A_b^{1/3} + A_t^{1/3}) + 2.7}$$

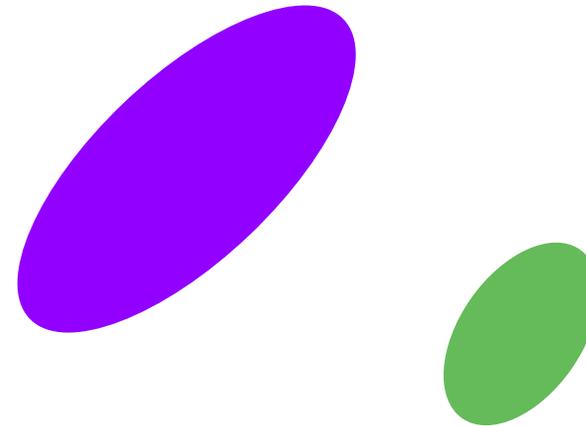
Bass interaction barrier

$$B_{int} = \frac{e^2 Z_b Z_t}{R_0(A_b^{1/3} + A_t^{1/3}) + 2.7 \text{ fm}} - 2.9 \text{ MeV} \frac{A_b^{1/3} A_t^{1/3}}{A_b^{1/3} + A_t^{1/3}}$$

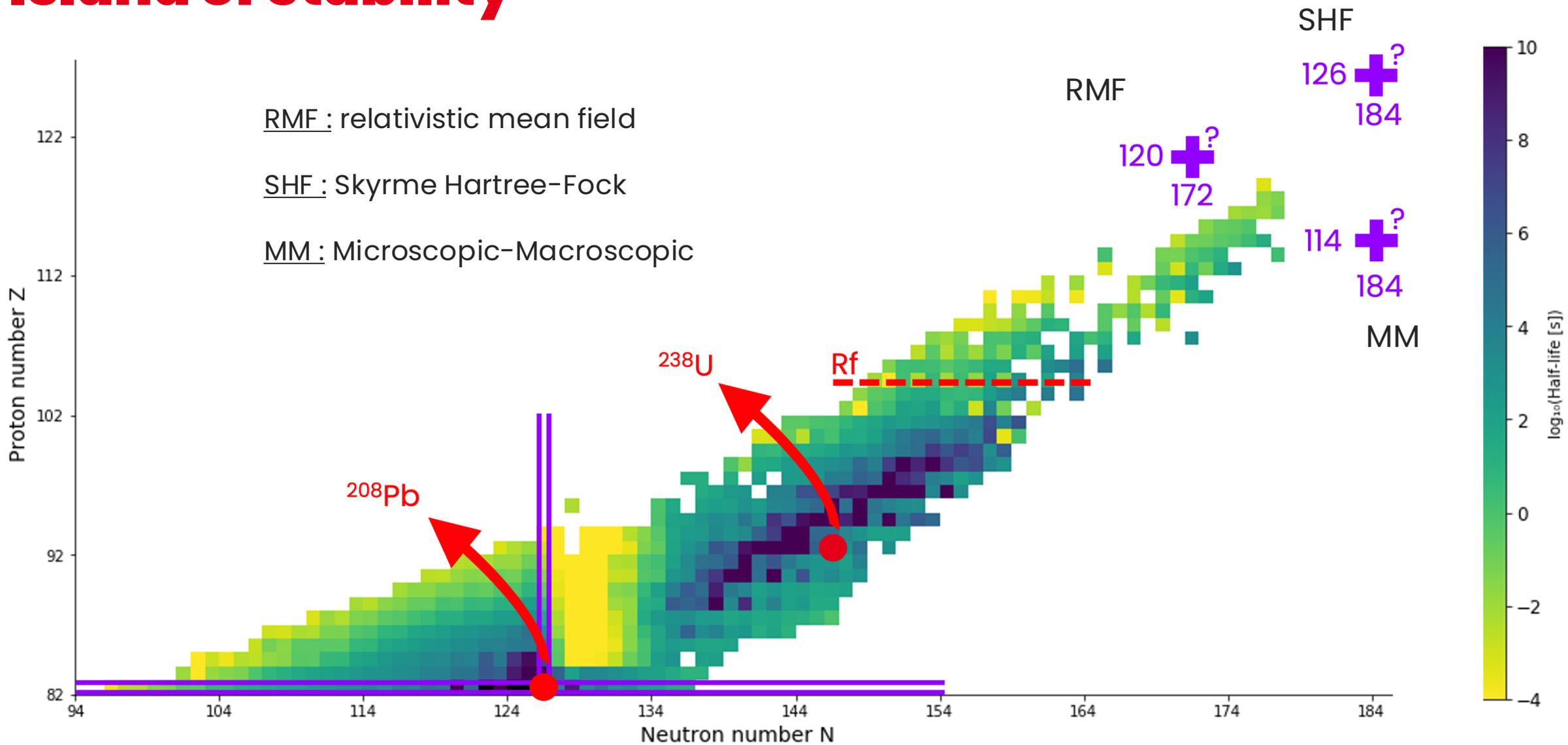
Minimum barrier



Maximum barrier



Island of stability



Island of stability

SLy4

SkI3

M. B., Heenen, J. Phys. Conf. Ser. 420 (2013) 012002

SkI4

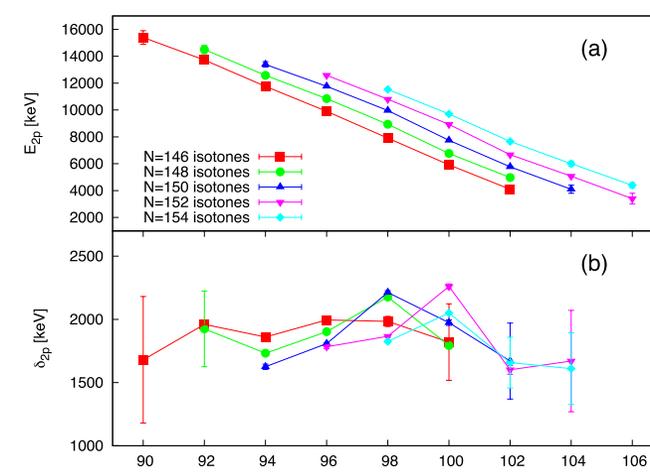
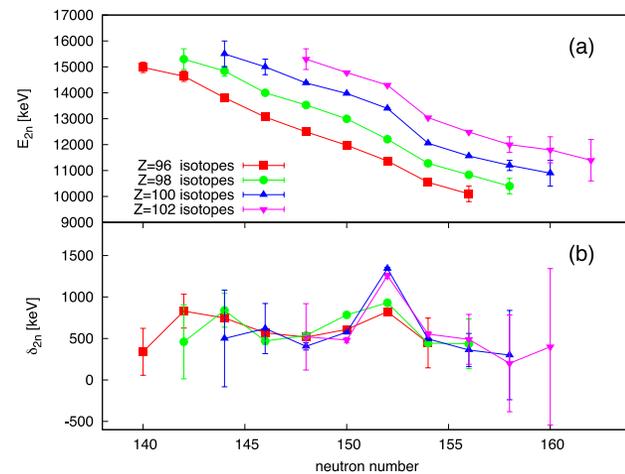
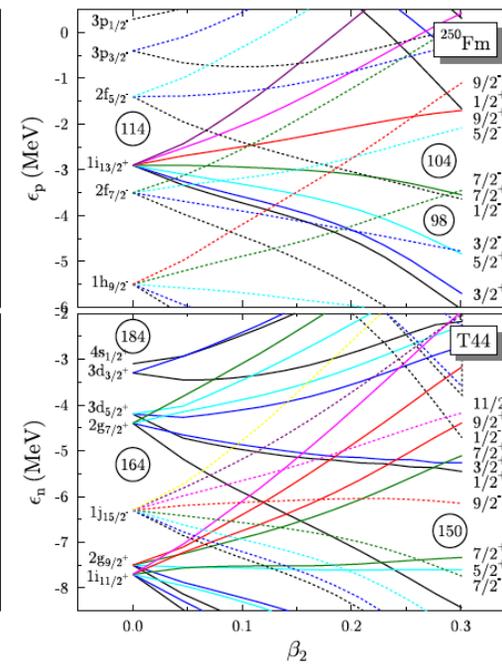
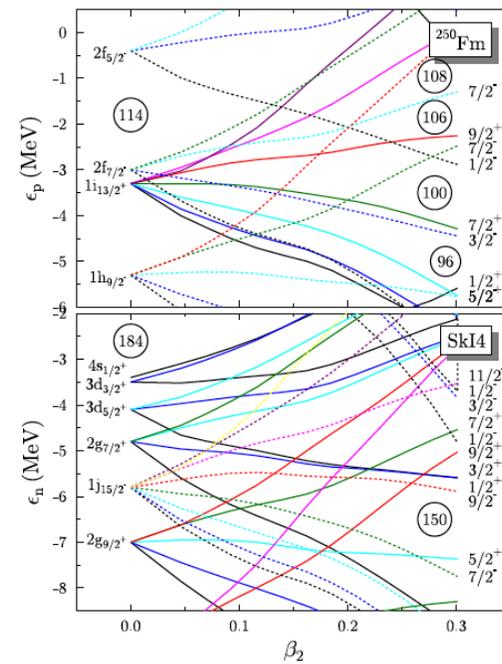
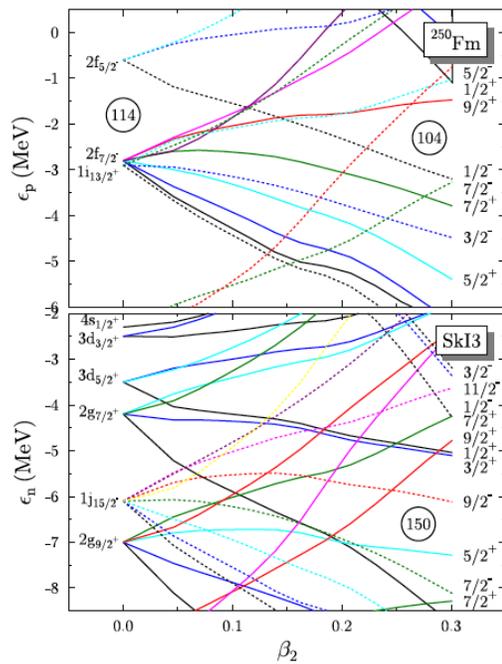
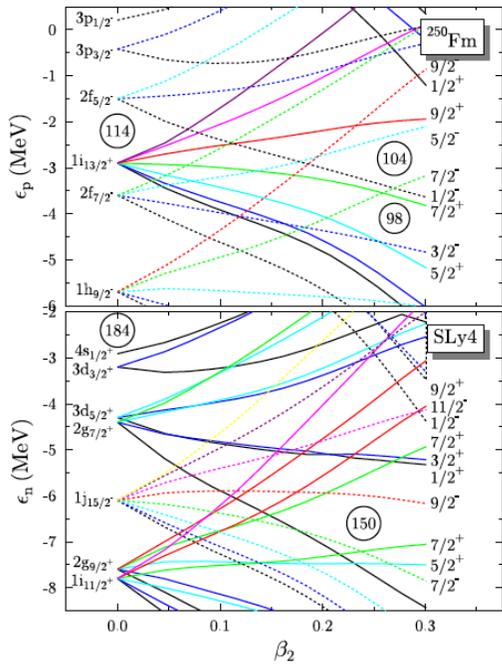
T44

standard spin-orbit

modified spin-orbit

modified spin-orbit

tensor force added

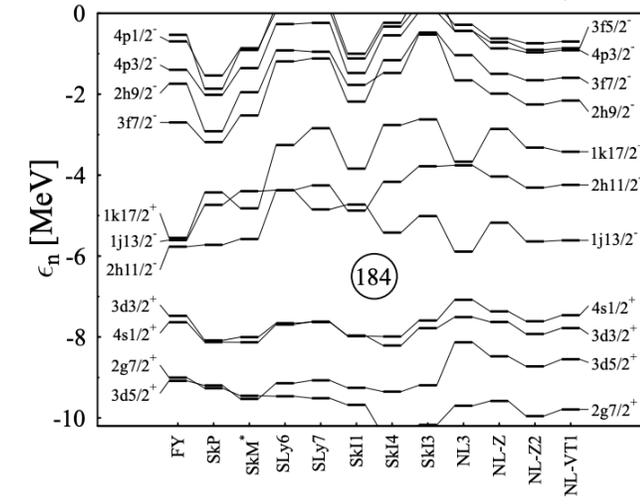
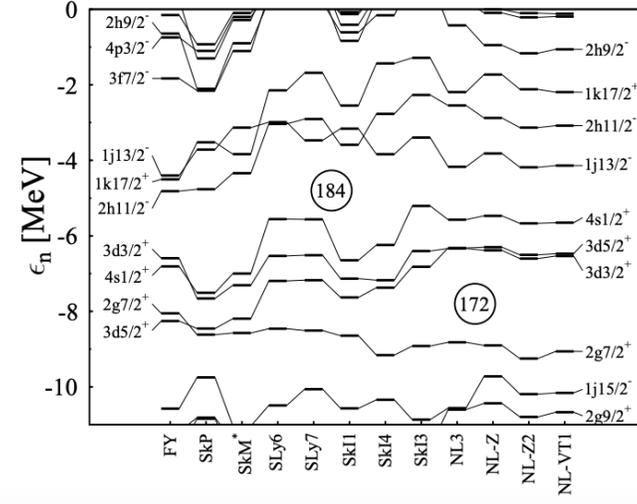
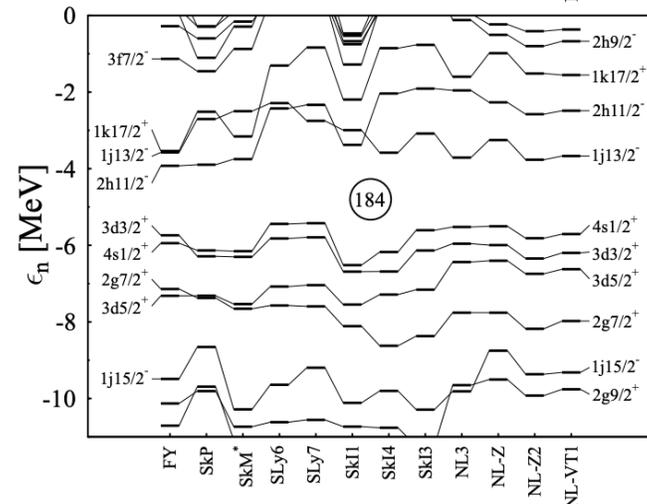
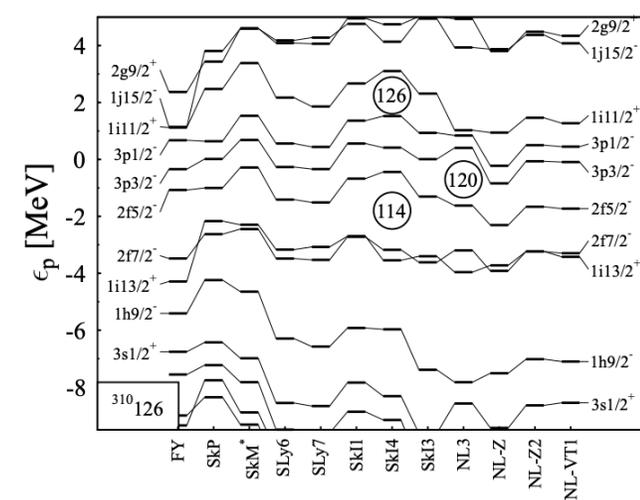
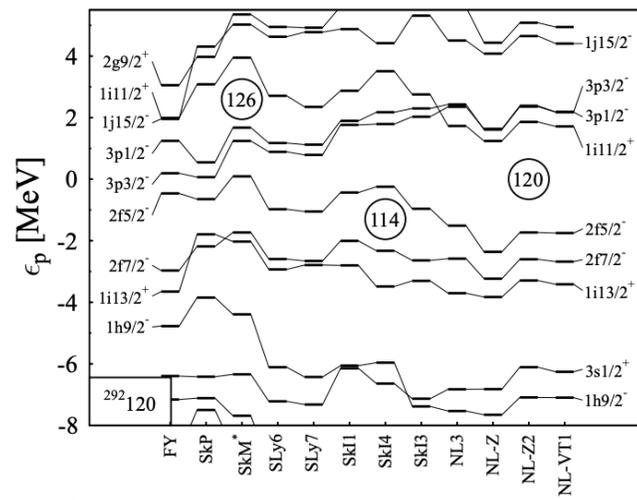
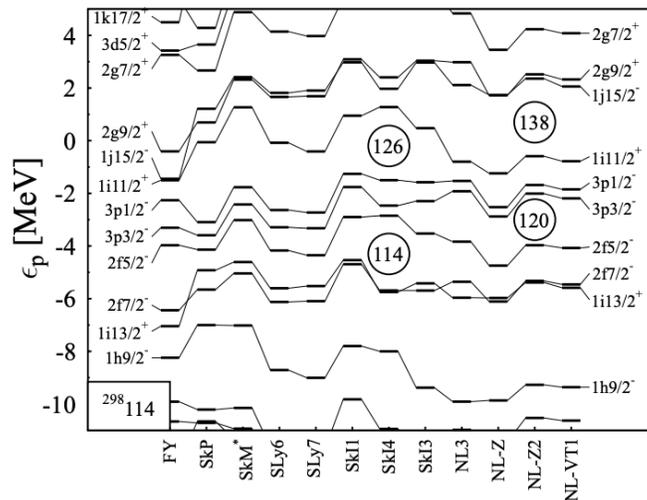


S. Ketelhut, PhD thesis (2010)



Island of stability

M. Bender et. al.; PRC 60 (1999)



$^{298}_{184}114$

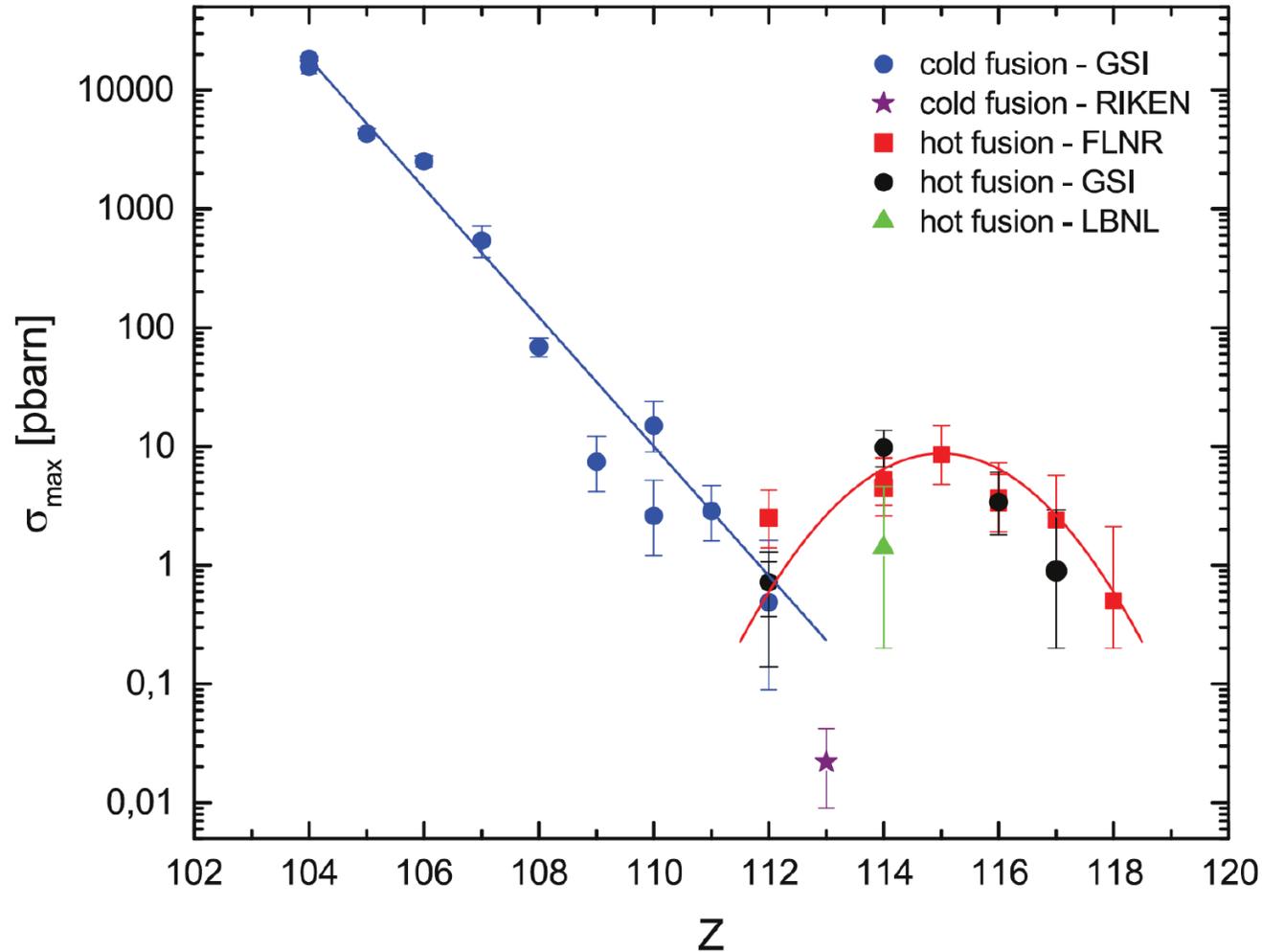
$^{292}_{172}120$

$^{310}_{184}126$

Hot vs Cold fusion



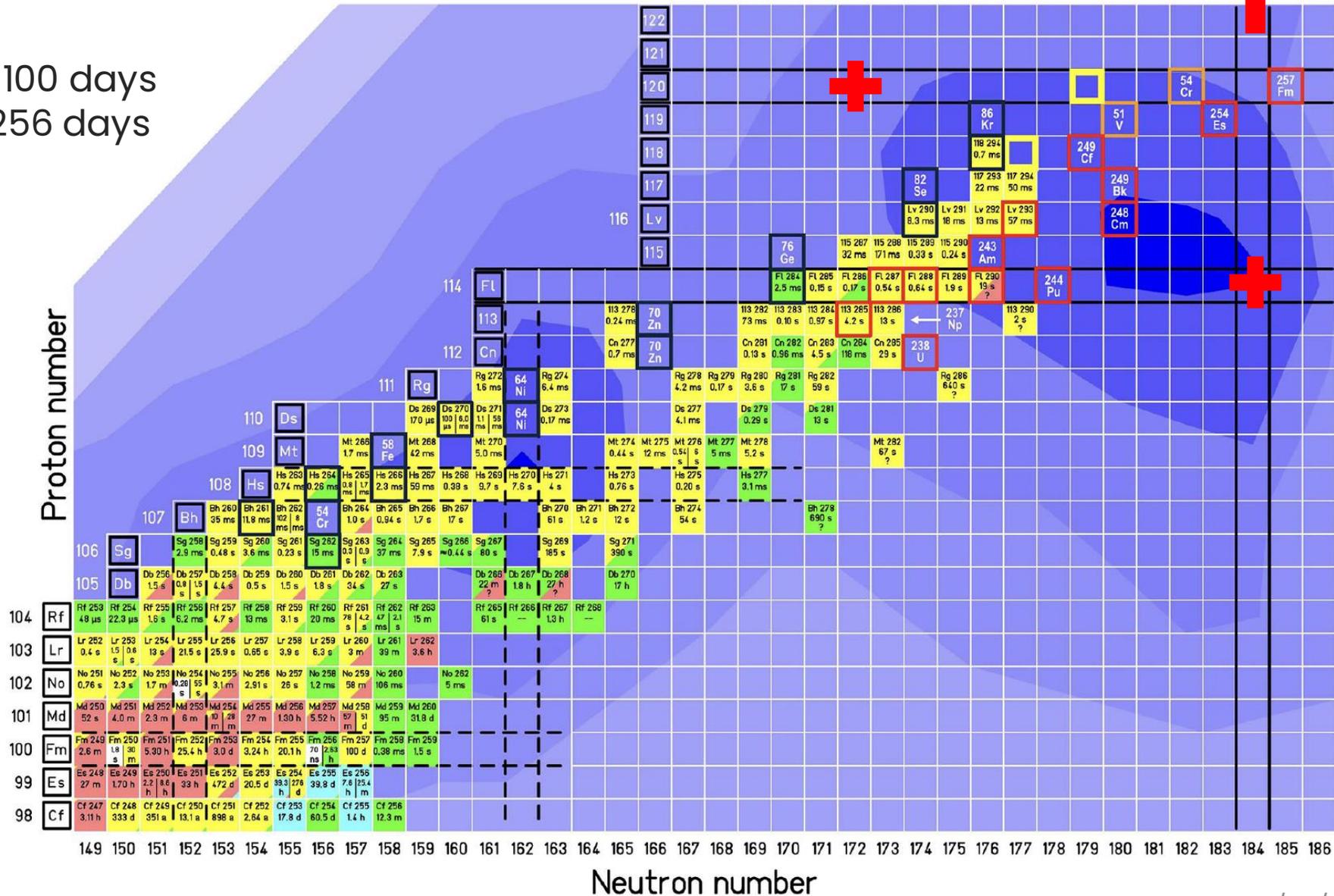
Cold Fusion
Complementary + ^{208}Pb
↑
Doubly magic
→ $E^* \sim 10 \text{ MeV}$



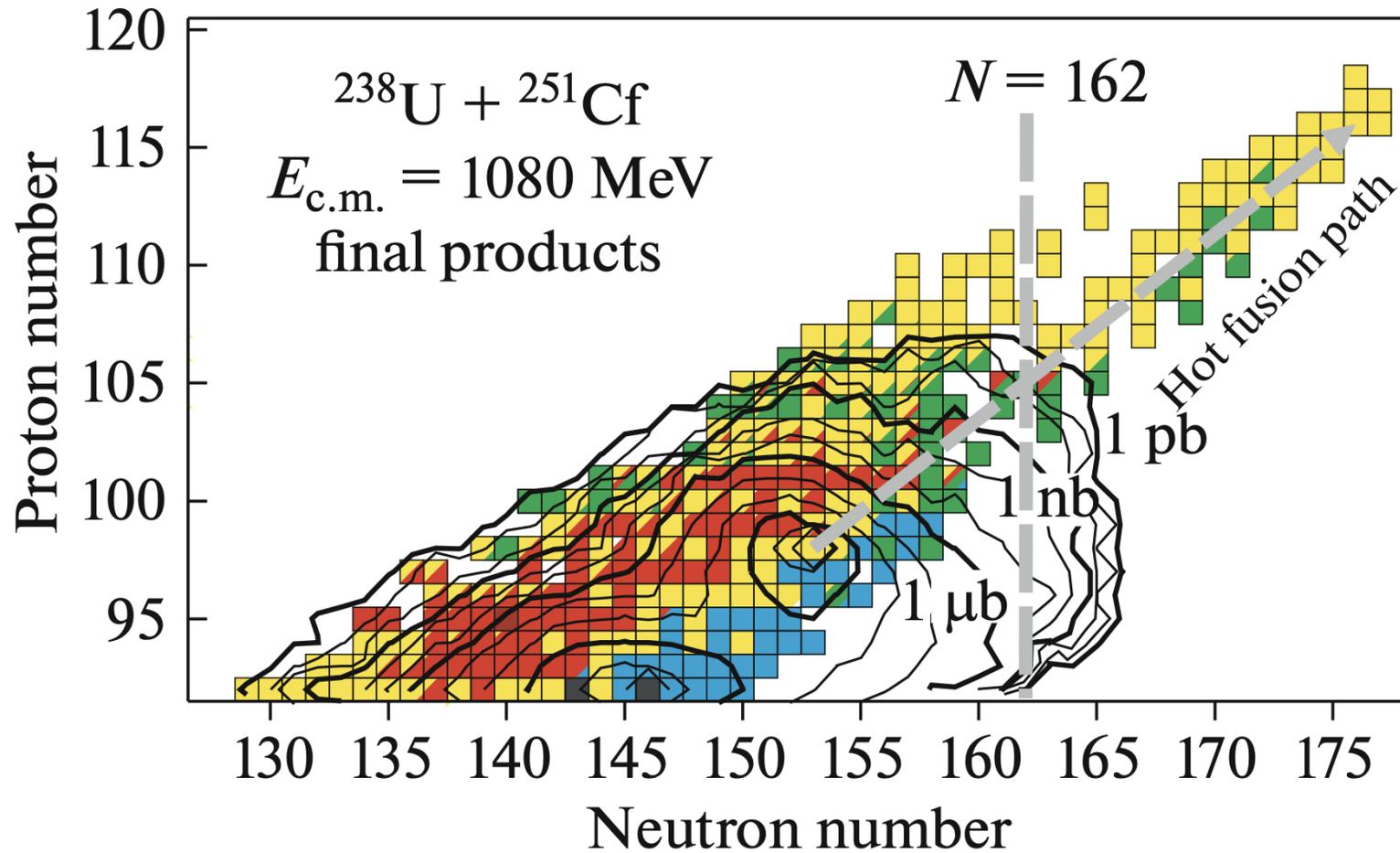
Hot Fusion
 ^{48}Ca + Complementary:
↑
Doubly magic
→ $E^* \sim 30 \text{ MeV}$
→ Higher fusion probability

Future discoveries with fusion

$t_{1/2} (^{257}\text{Fm}) = 100 \text{ days}$
 $t_{1/2} (^{254}\text{Es}) = 256 \text{ days}$



Predictions : SHE

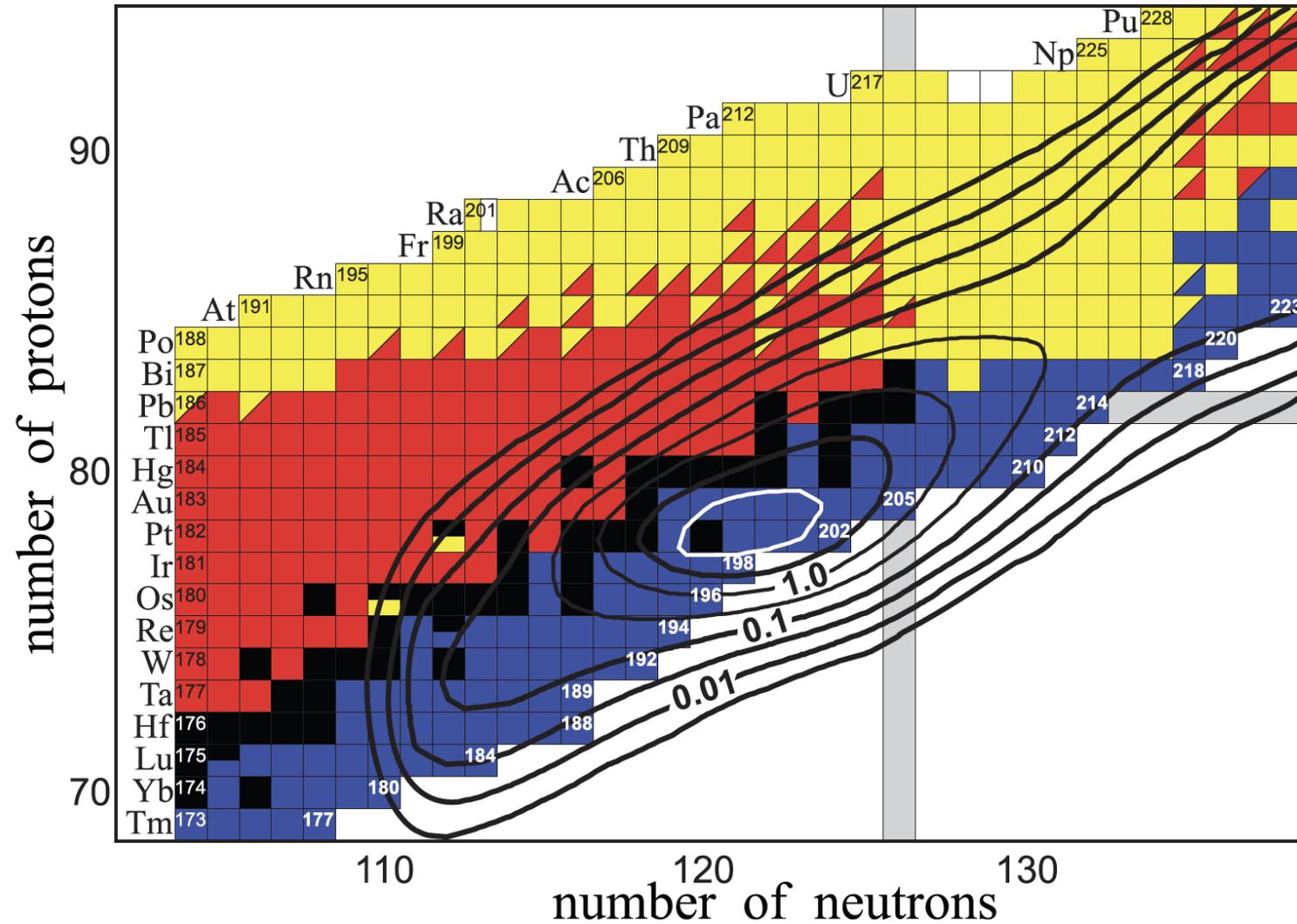


A. Karpov, V. Saiko; PPNL (2019)

Predictions : N=126

$^{238}\text{U} + ^{198}\text{Pt} : 6.55 \text{ MeV/u}$

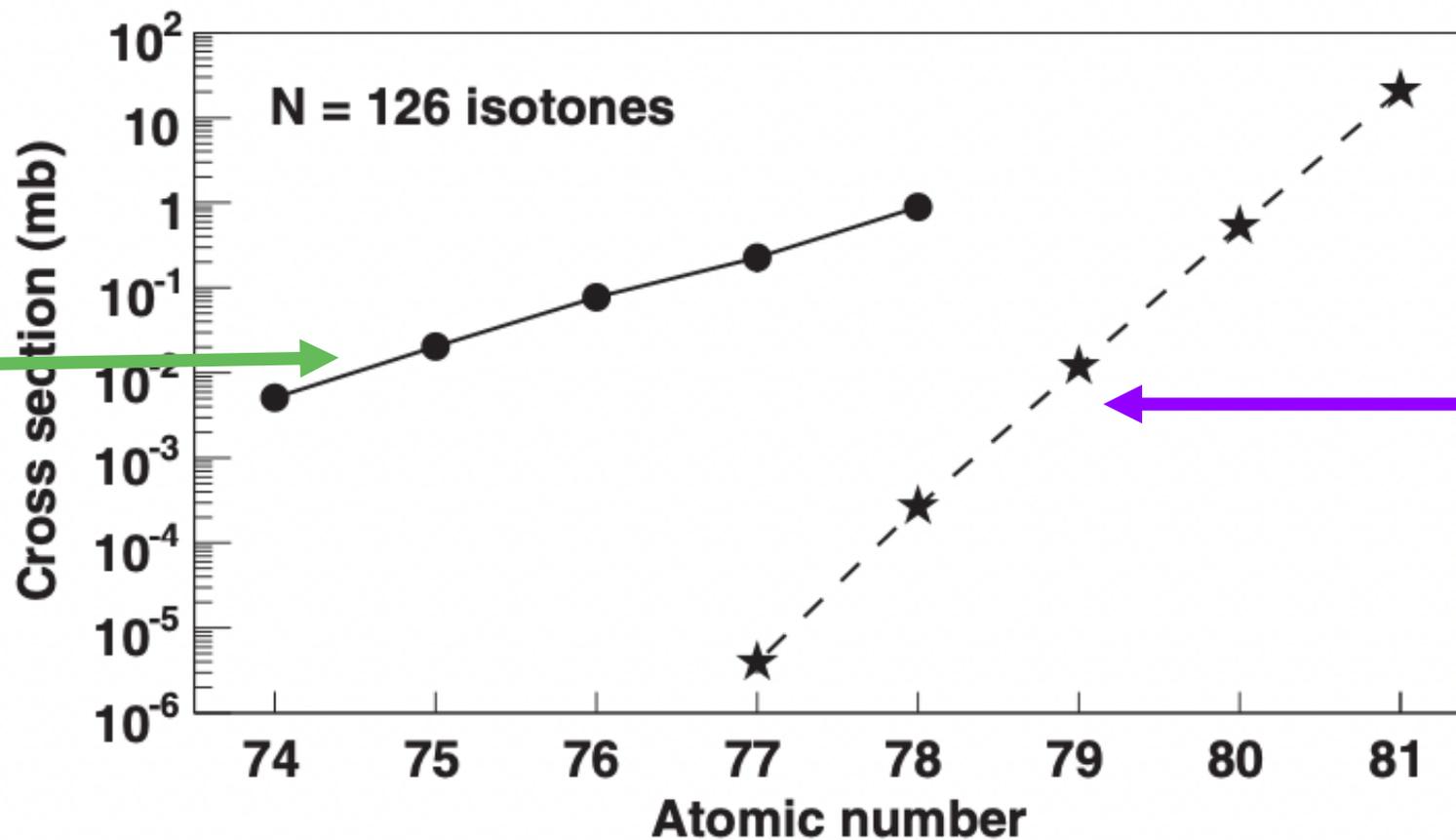
9.3 % above the barrier



MNT vs Fragmentation



MNT :
 $^{136}\text{Xe} + ^{198}\text{Pt}$
 $\sim 8 \text{ MeV / u}$
59 % above barrier

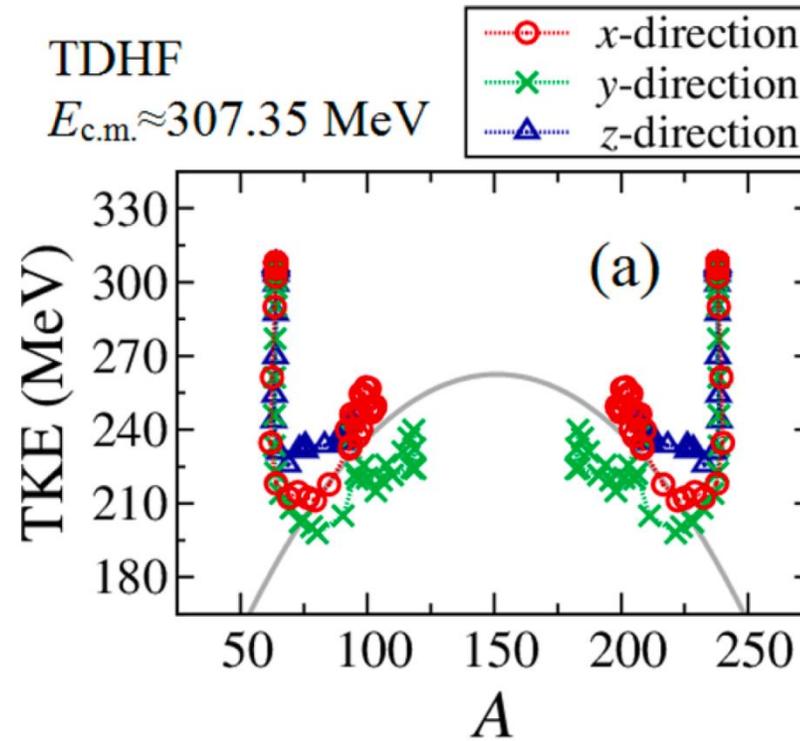


Fragmentation :
 $^{208}\text{Pb} + ^9\text{Be}$
1 GeV/u

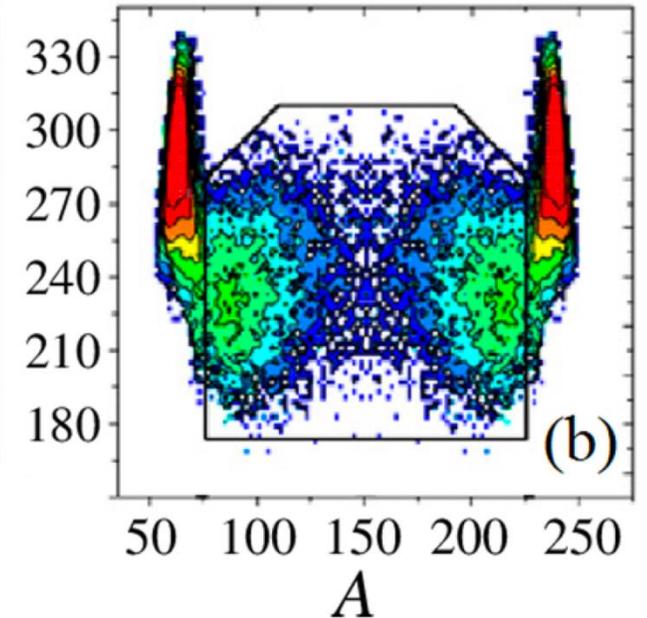
Y. X. Watanabe et. al.; PRL 115, 172503 (2015)

3D TDHF

- Novel approach for reactions between heavy partners
- Completely microscopic approach = more fundamental
- Each simulation = time-evolution of one reaction

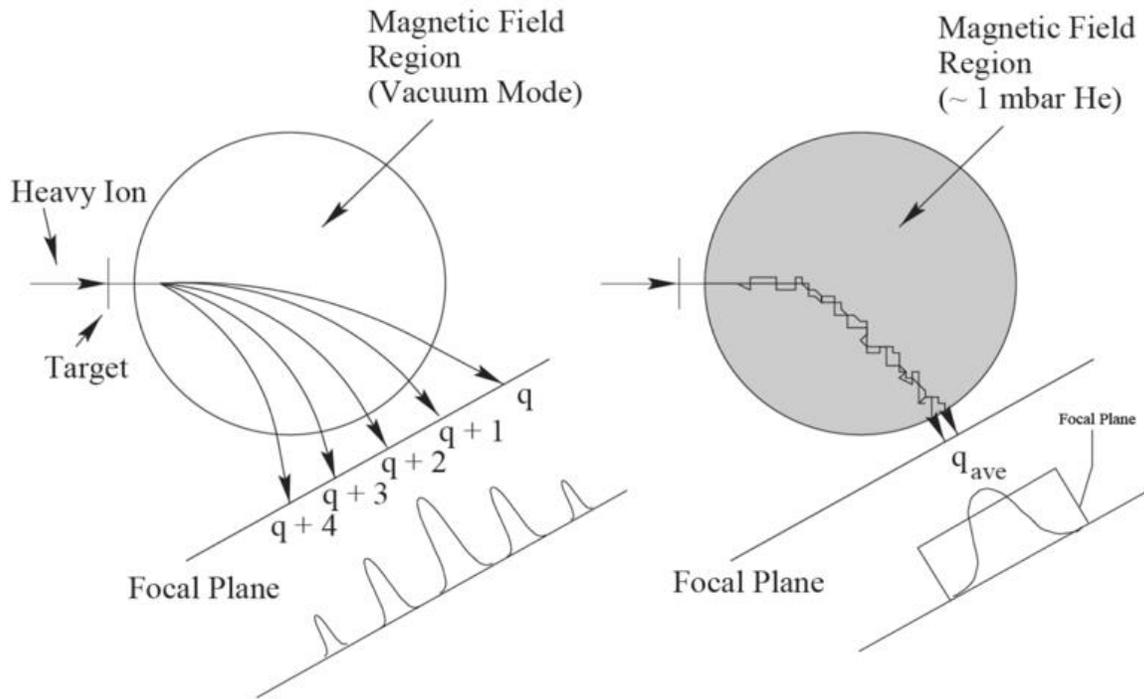


Expt. E.M. Kozulin et al.
 $E_{c.m.} \approx 301.05$ MeV



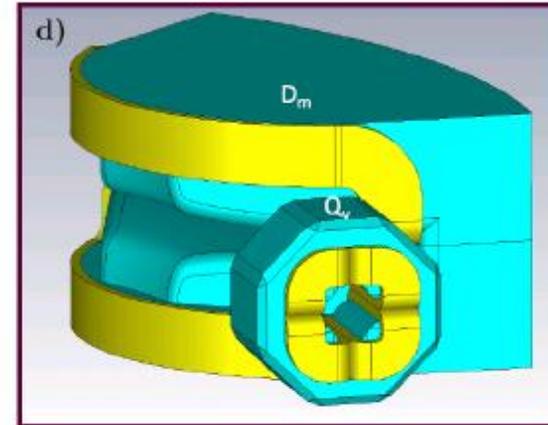
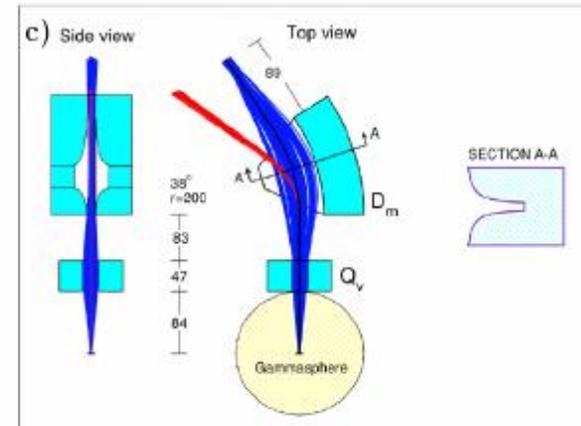
K. Sekizawa, K. Yabana; PRC 93 (216)

AGFA GFS

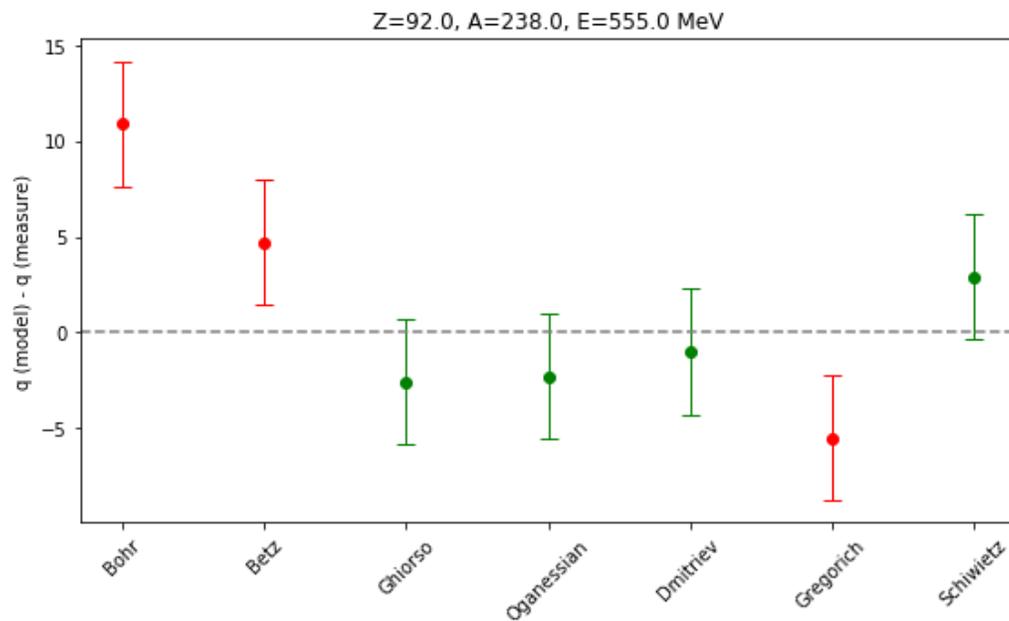
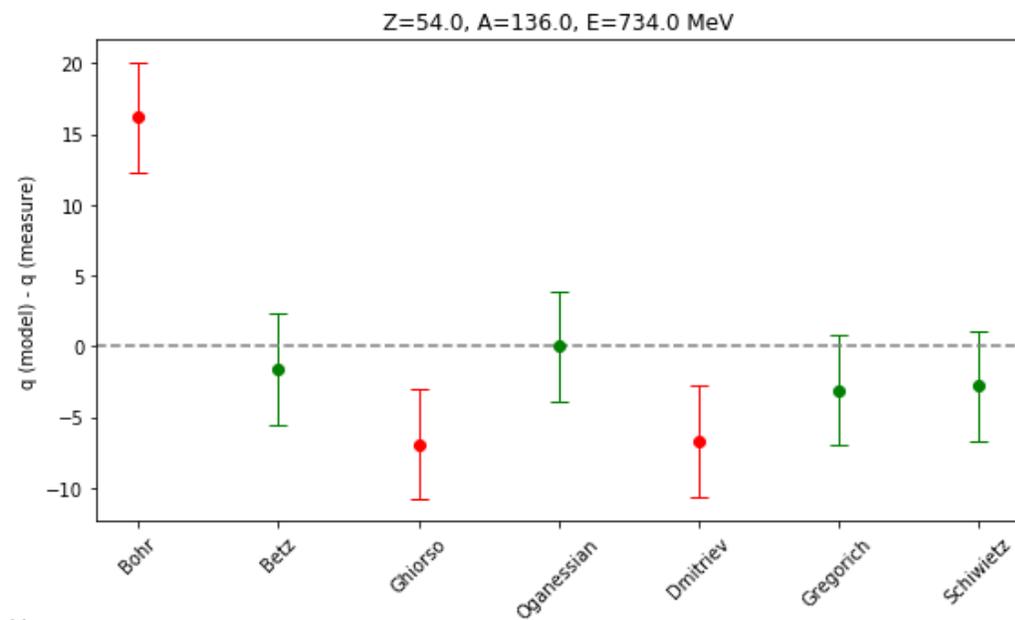
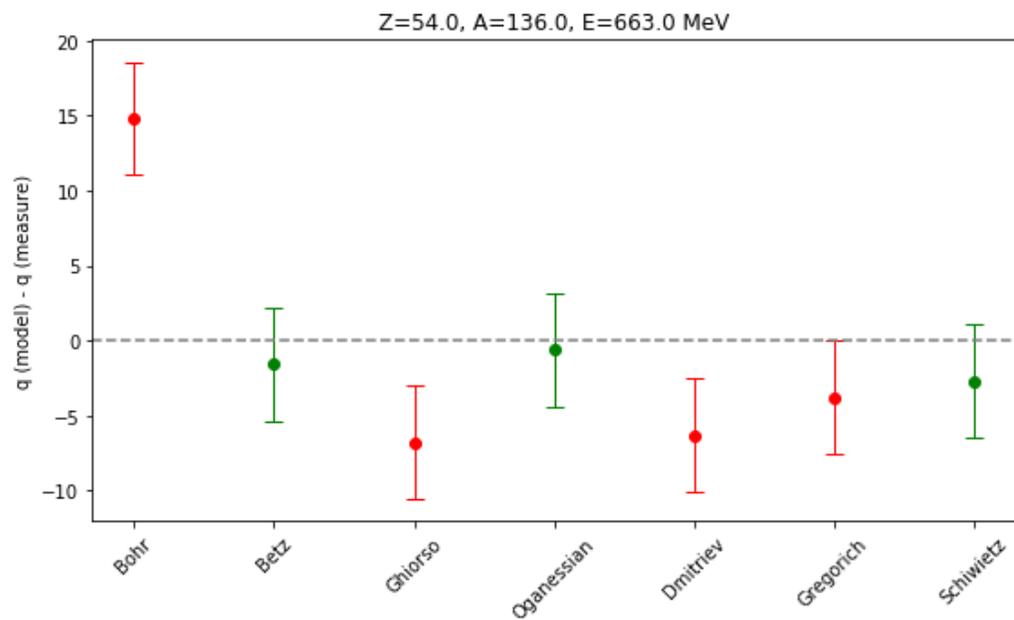


Greenlees, P; PhD thesis (University of Liverpool, 1999).

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

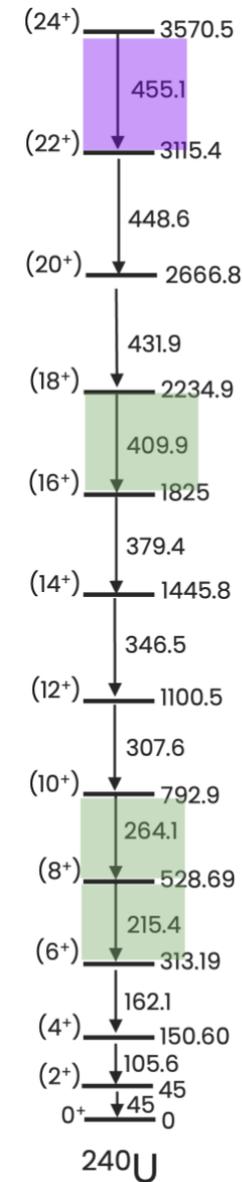
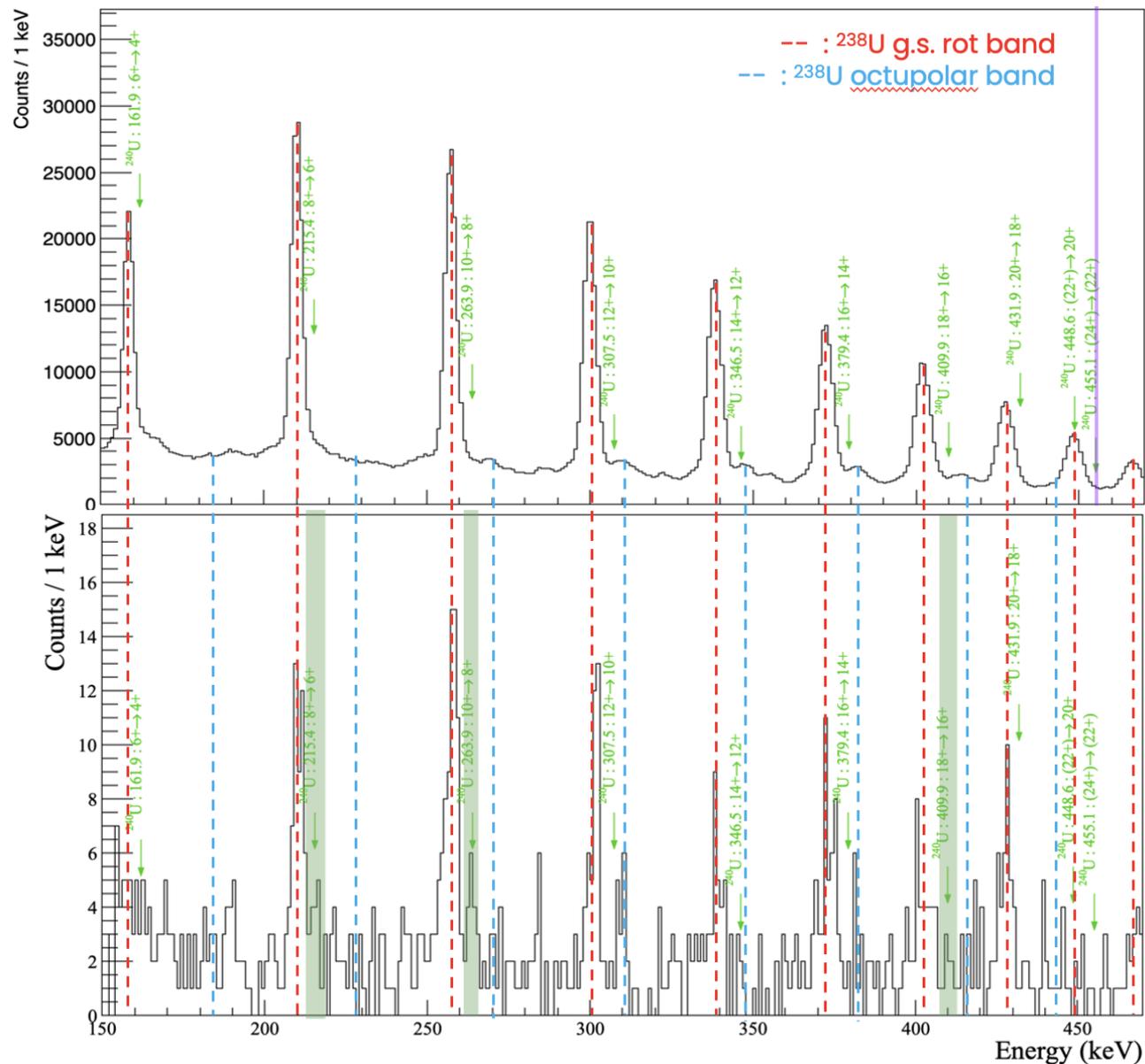


Magnetic rigidity : models



^{240}U : Matrix

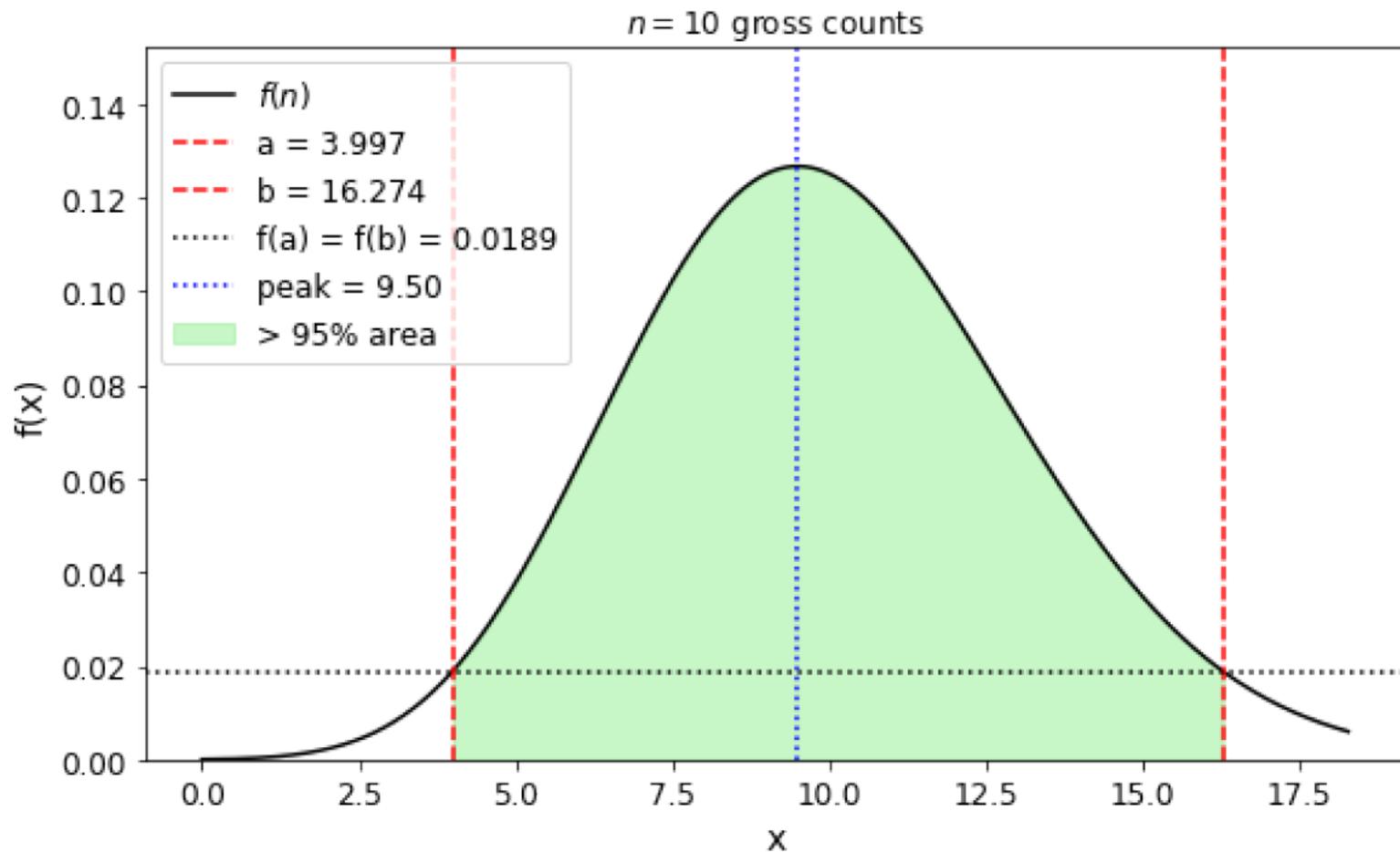
n B
13 5
20 10
7 3



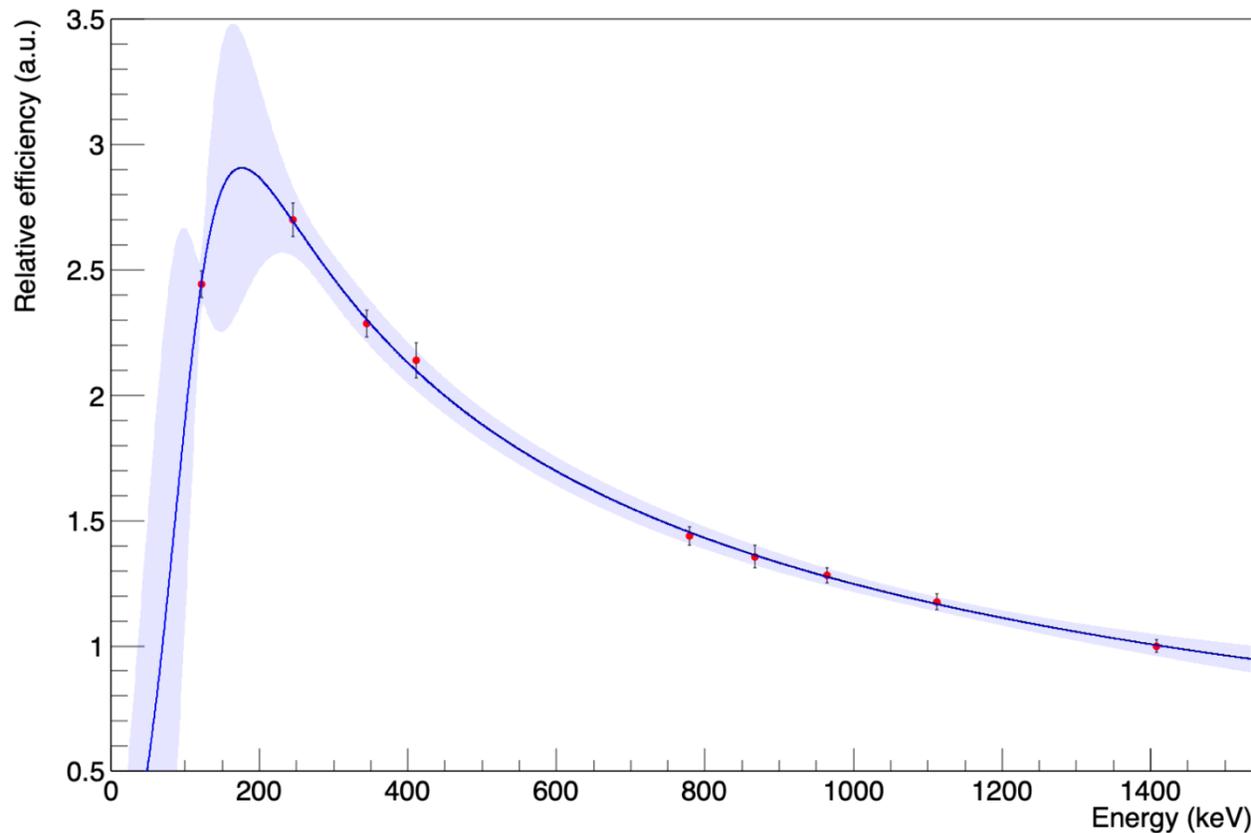
Poisson distribution

$$\sum_{k=A}^B \frac{(n)^k}{k!} e^{-n} \geq 0.95$$

$$\int_A^B \frac{n^x}{\Gamma(x+1)} e^{-n} dx \geq 0.95$$



GS : efficiency



Low-energy component: $x = \ln\left(\frac{E}{E_1}\right)$ with $E_1 = 100$ keV

Interaction parameter between the two energy regions

$$\varepsilon_{\text{rel}}(E) = K \cdot \exp\left((A + Bx + Cx^2)^{-G} + (D + Ey + Fy^2)^{-\frac{1}{G}} \right)$$

Scaling factor K

High-energy component: $y = \ln\left(\frac{E}{E_2}\right)$ with $E_2 = 1$ MeV

$$N_{\gamma\gamma,2} = \frac{\varepsilon_{\text{GS1}} \cdot \varepsilon_{\text{GS2}} \cdot \varepsilon_{\text{GS3}} \cdot \varepsilon_{\text{AGFA}} \cdot N_{\text{produced}} \cdot \Gamma_1 \cdot \Gamma_3}{(1 + \alpha_1)(1 + \alpha_2)(1 + \alpha_3)}$$

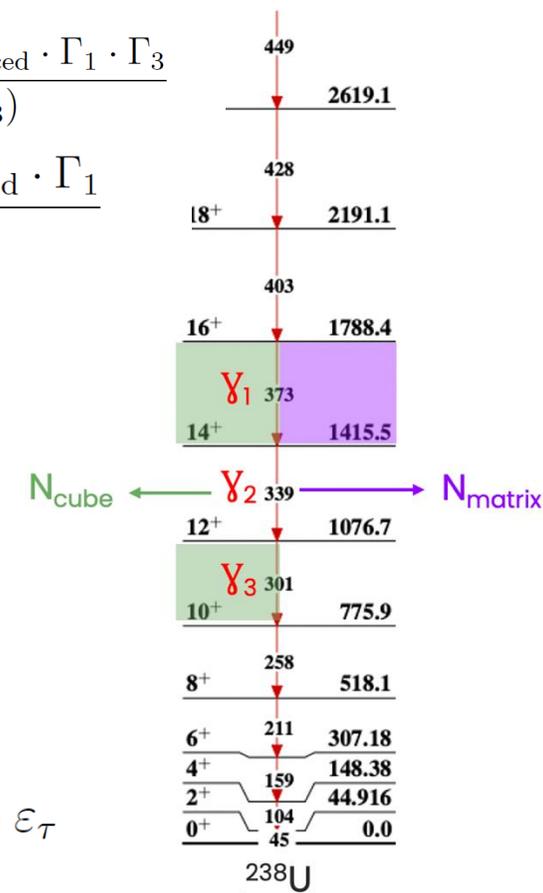
$$N_{\gamma\gamma,2} = \frac{\varepsilon_{\text{GS1}} \cdot \varepsilon_{\text{GS2}} \cdot \varepsilon_{\text{AGFA}} \cdot N_{\text{produced}} \cdot \Gamma_1}{(1 + \alpha_1)(1 + \alpha_2)}$$

$$\frac{N_{\text{detected},\gamma\gamma\gamma}}{N_{\text{detected},\gamma\gamma}} = \frac{\varepsilon_{\text{GS3}}}{(1 + \alpha_3) \cdot \Gamma_3}$$

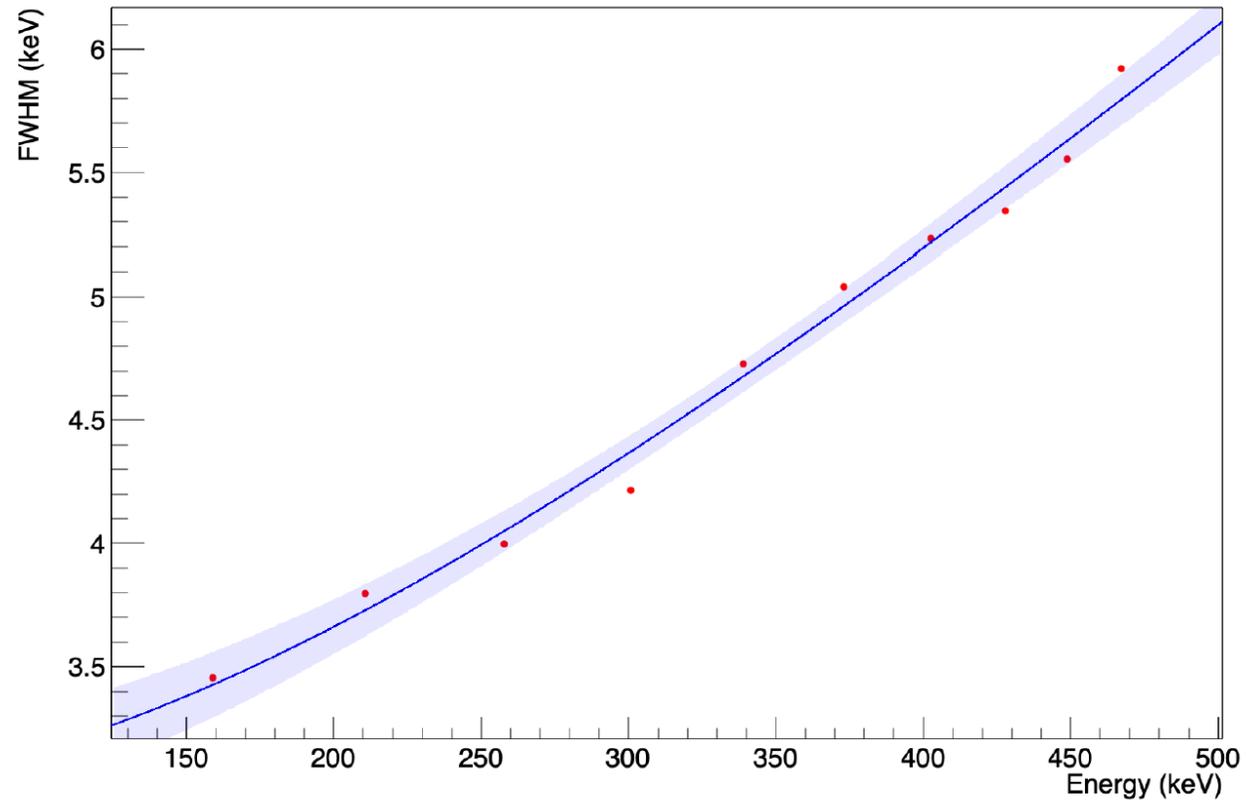
$$\Leftrightarrow \varepsilon_{\text{GS3}} = \frac{(1 + \alpha_3) \cdot \Gamma_3 \cdot N_{\text{detected},\gamma\gamma\gamma}}{N_{\text{detected},\gamma\gamma}}$$

$$\varepsilon_{\text{GS}} = \varepsilon_{\text{geo}} \cdot \varepsilon_{\text{int}} \cdot \varepsilon_{\tau}$$

9.25 % (1408 KeV)

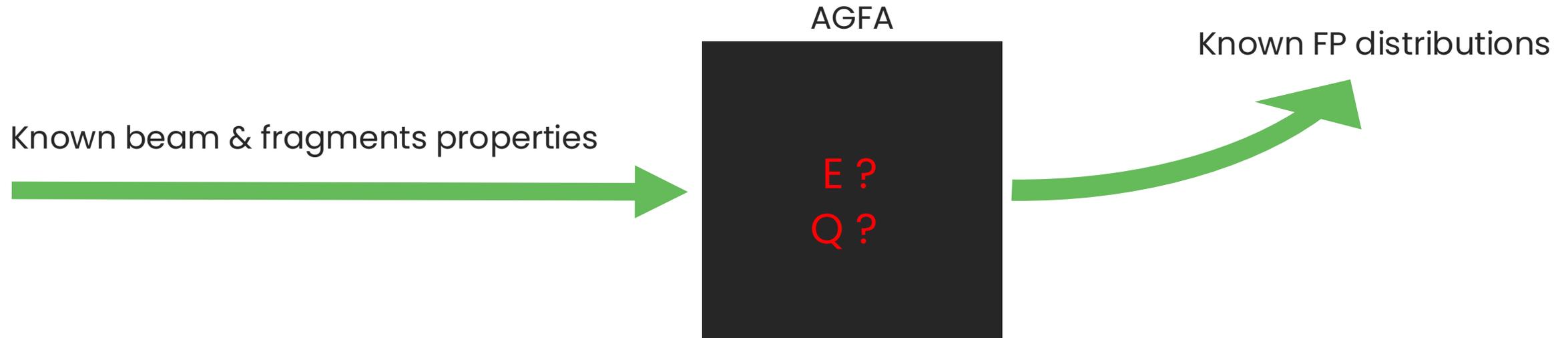


Gating efficiency



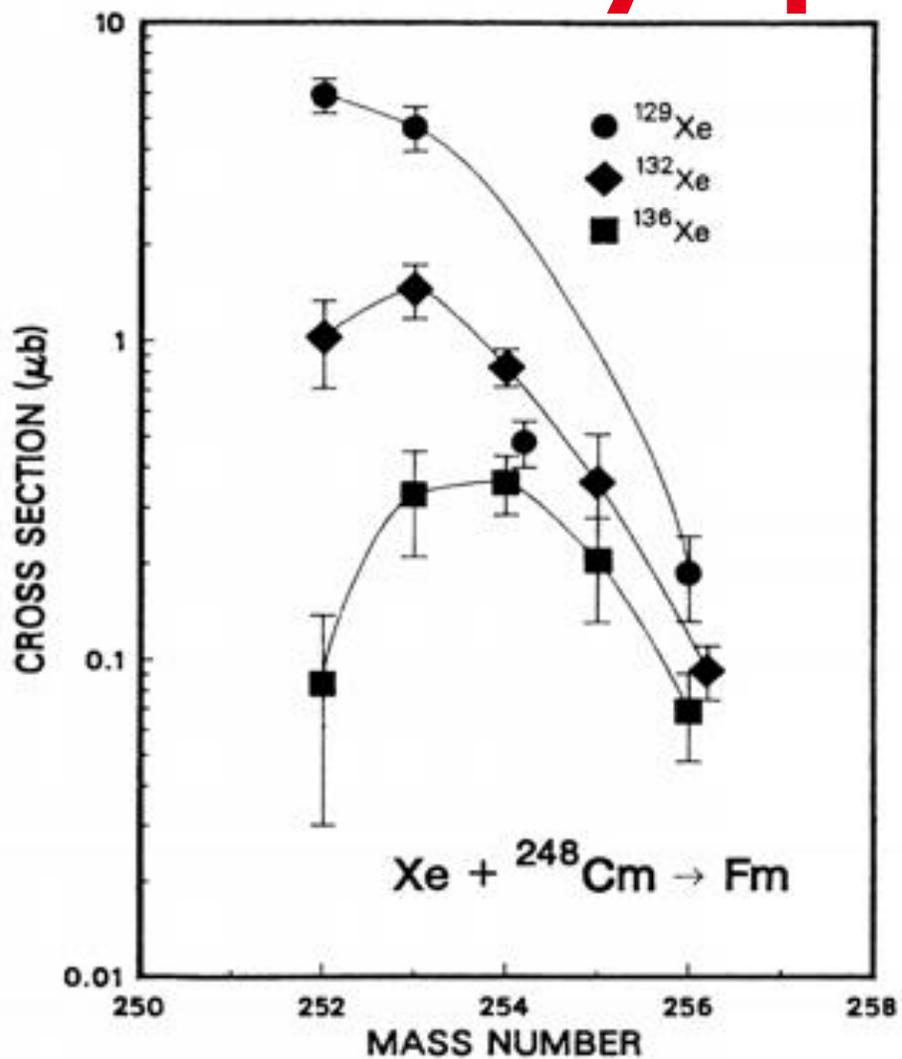
$$\Gamma = \frac{\int_{E_1}^{E_2} A \exp\left(-\frac{(E-E_0)^2}{2\sigma^2}\right) dE}{\int_0^{+\infty} A \exp\left(-\frac{(E-E_0)^2}{2\sigma^2}\right) dE} = \frac{1}{2} \left[\operatorname{erf}\left(\frac{E_2 - E_0}{\sqrt{2}\sigma}\right) - \operatorname{erf}\left(\frac{E_1 - E_0}{\sqrt{2}\sigma}\right) \right]$$

AGFA : Transmission

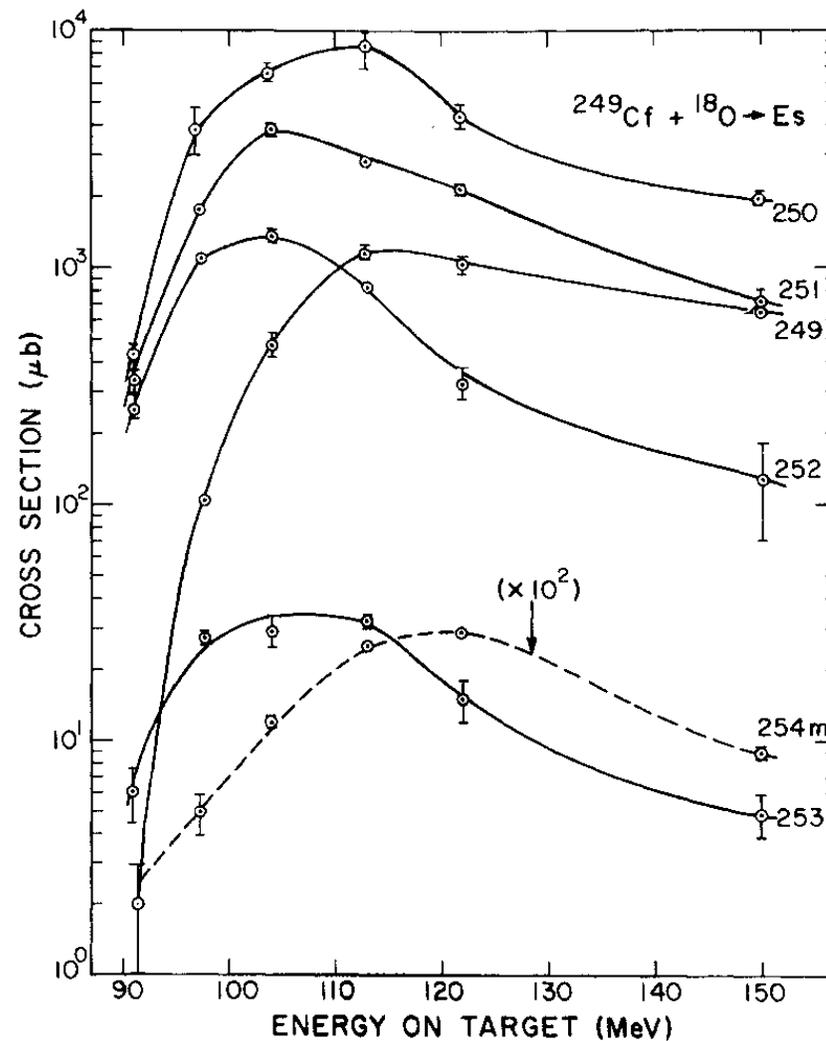


Adiabatic assumption $\rightarrow (E_{\text{start}}, Q_{\text{start}}) = (E_f, Q_f) \rightarrow$ Set parameters to retrieve the final distribution

Radiochemistry experiments



B. Welch et al. Phys. Rev. C Vol 35 (1987)



D. Lee et al. PRC 25 (1982) 286 : ${}^{16}\text{O}, {}^{18}\text{O}, {}^{20}\text{Ne}, {}^{22}\text{Ne} + {}^{248}\text{Cm}$
 D. Lee et al. PRC 27 (1983) 2656 : ${}^{18}\text{O} + {}^{248}\text{Cm}, {}^{249}\text{Cf}$
 K.J. Moody et al. PRC 33 (1986) 1315 : ${}^{18}\text{O}, {}^{86}\text{Kr}, {}^{136}\text{Xe} + {}^{248}\text{Cm}$
 M. Schädel et al. Phys. Rev. Lett. 48, 852 (1982): ${}^{238}\text{U} + {}^{248}\text{Cm}$
 A. Türler et al. PRC 46 (1992) 1364 : ${}^{40,44,48}\text{Ca} + {}^{248}\text{Cm}$

→ Chemical separation methods

→ isotope identification via radioactive decay

→ timescale of the fastest radiochemical separation techniques
 long lived isotope ≈ 10 s

→ Nuclei produced:
 $Z=101, N=157$

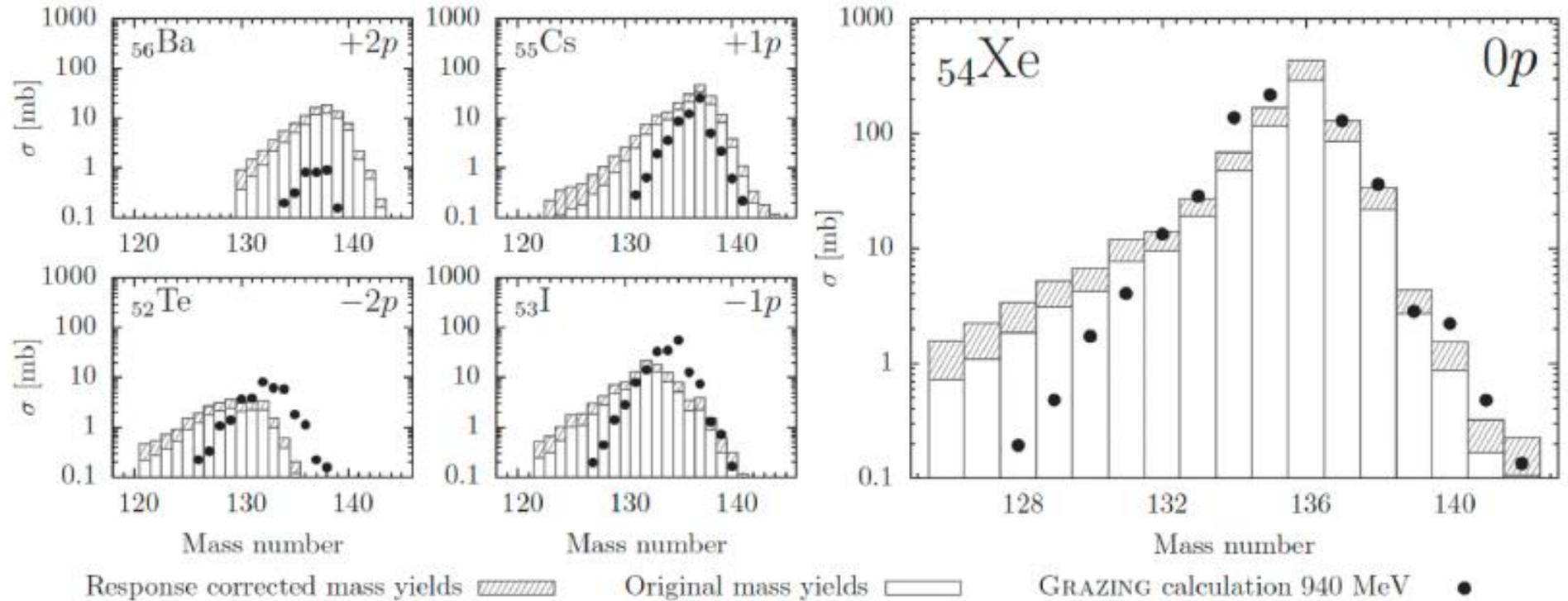
$^{136}\text{Xe} + ^{238}\text{U}$ at LNL : 7.35 MeV/u



36 % above the barrier

PRISMA at Grazing

Xe-like measured



A. Vogt et al.; PRC 92 (2) (2015)

Comparison with our experiment:

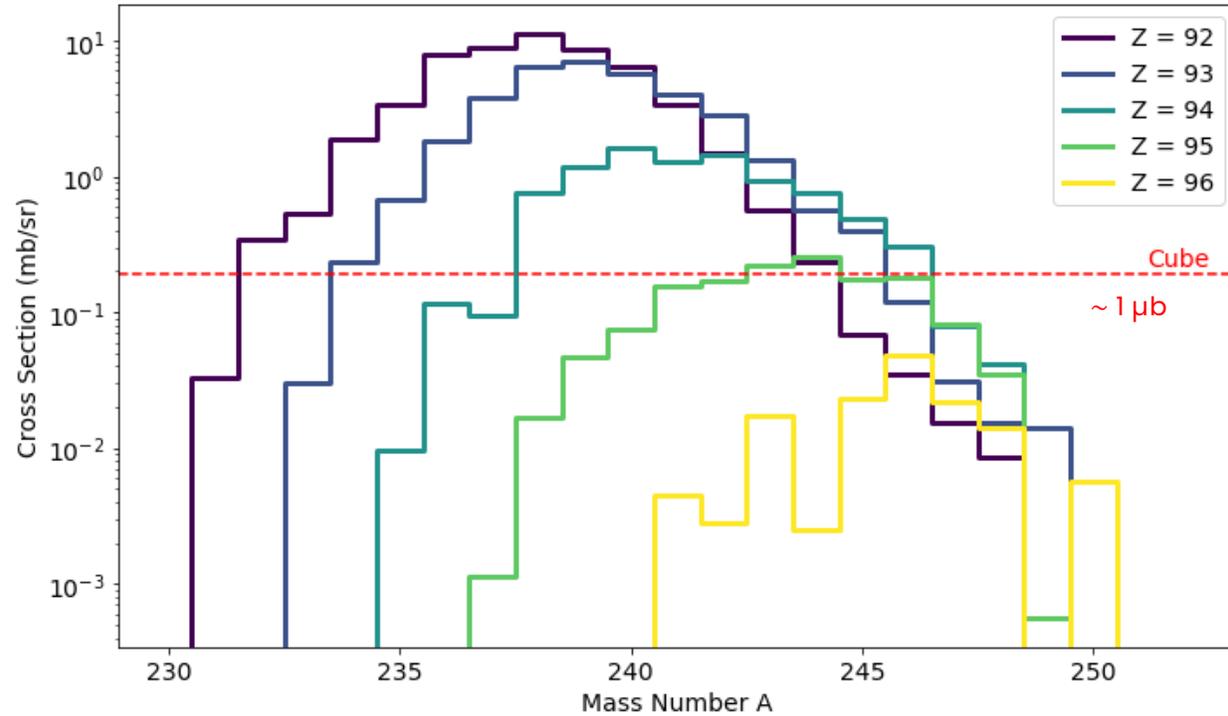
2n transfers \rightarrow cross-section $\sim >1000$ times higher in O.M.

6n transfers \rightarrow cross-section $\sim < 100$ times higher in O.M.

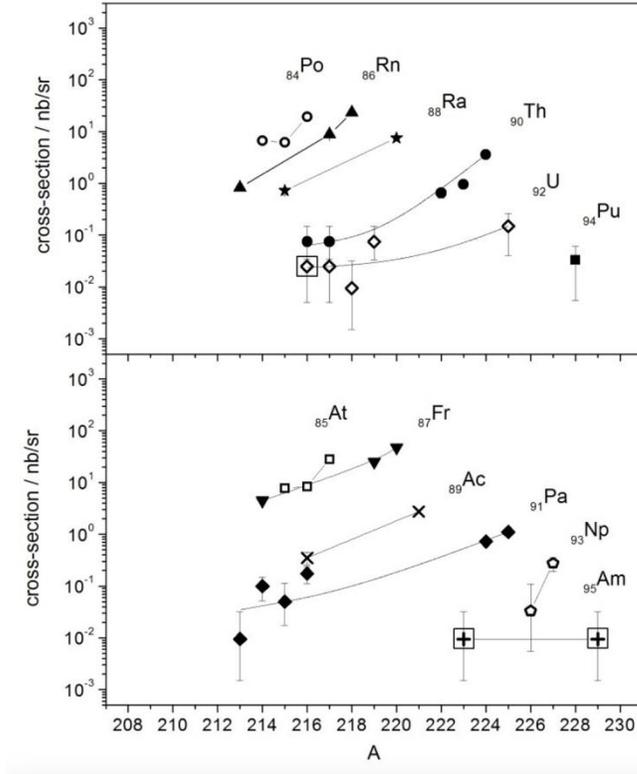
\rightarrow Larger transfers towards smaller angles?

$^{48}\text{Ca} + ^{248}\text{Cm}$ at GSI: 5.3 MeV/u

S. Heinz, et al. EPJA (2016) 52: 278



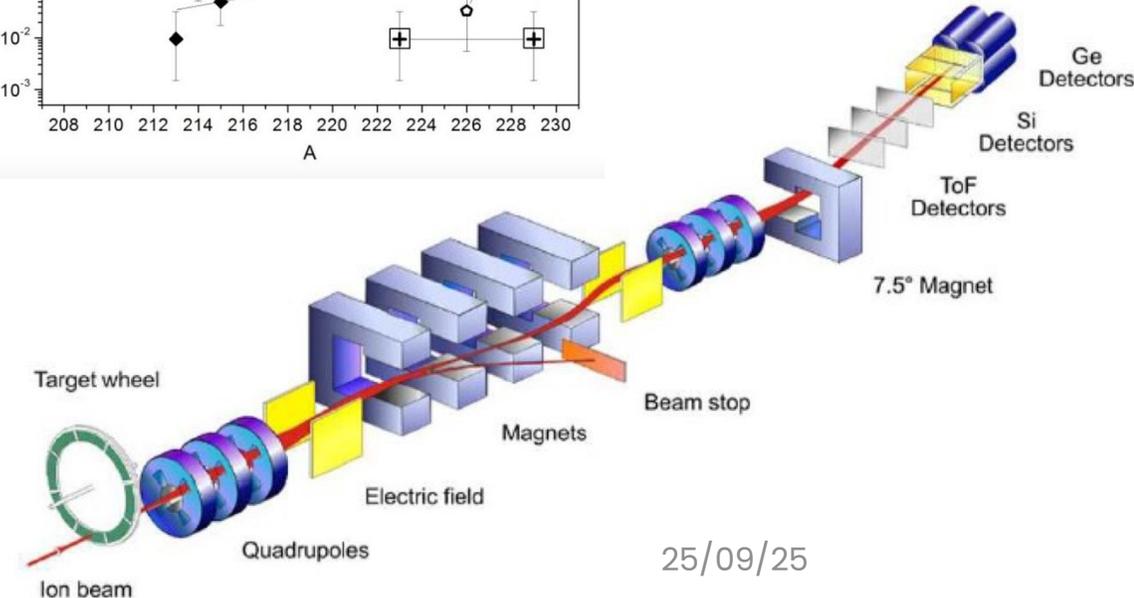
^{232}U : ~ 0.3 mb/sr
 Scaling rule : ~ 2 O.M. / 7n lost
 \rightarrow (below) $^{225}\text{U} \sim 100$ nb/sr



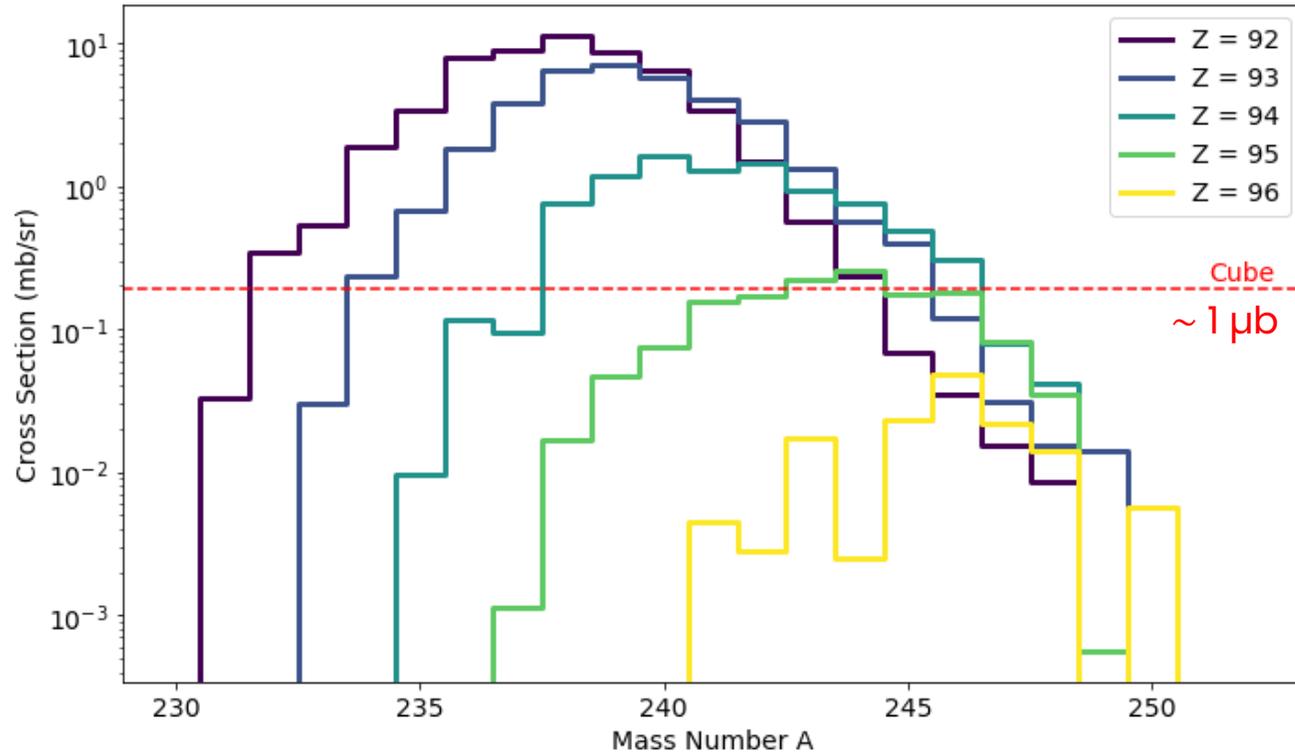
5 % above the barrier
 Grazing : 114°
 Heavy partner : 28°

^{225}U : ~ 0.2 nb/sr

Acceptance : $\sim 2^\circ$
 $\Delta v/v = 0.1$ FWHM



$^{50}\text{Ti} + ^{249}\text{Cf}$ at GSI: 6.1 MeV/u

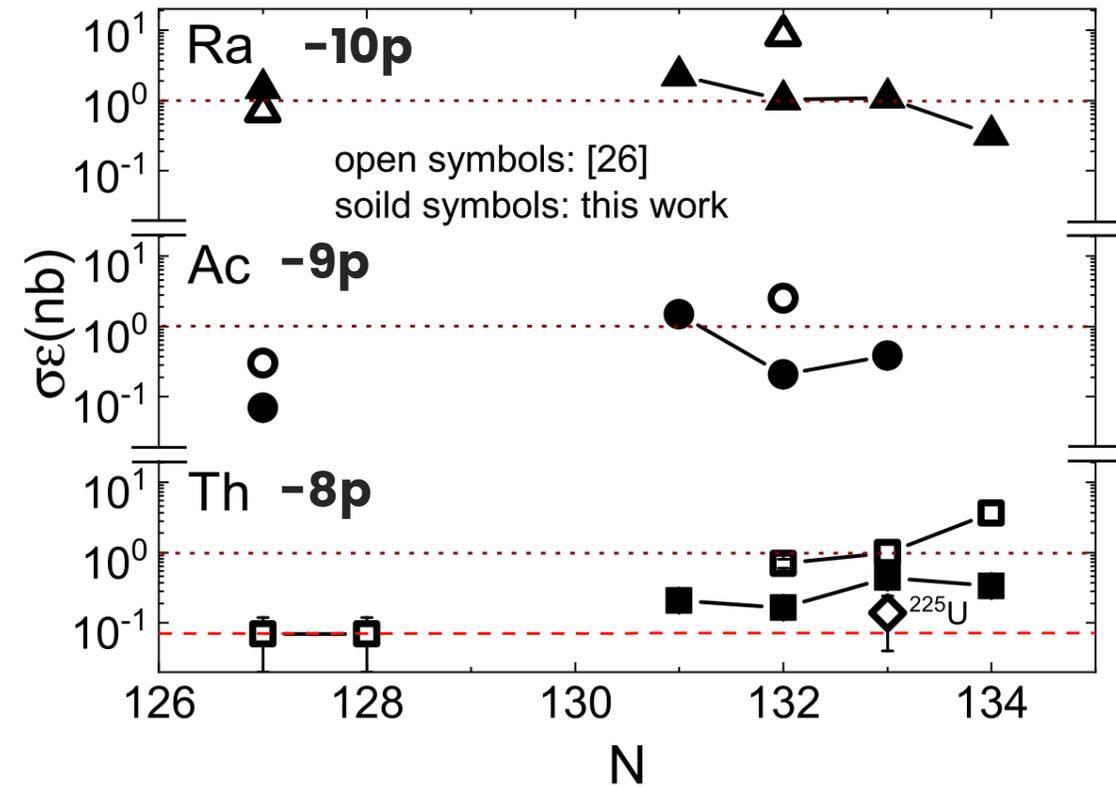


ε : $\sim 0.01\%$ for ^{223}Ac

Angular acceptance: 12 msr

$1 \text{ nb} * \varepsilon \rightarrow 83 \text{ nb/sr} * \varepsilon \rightarrow 8.3 \mu\text{b/sr}$ (Ac = -20n, -9p)

ANL: ^{249}Pu ? (+2p,+9n)

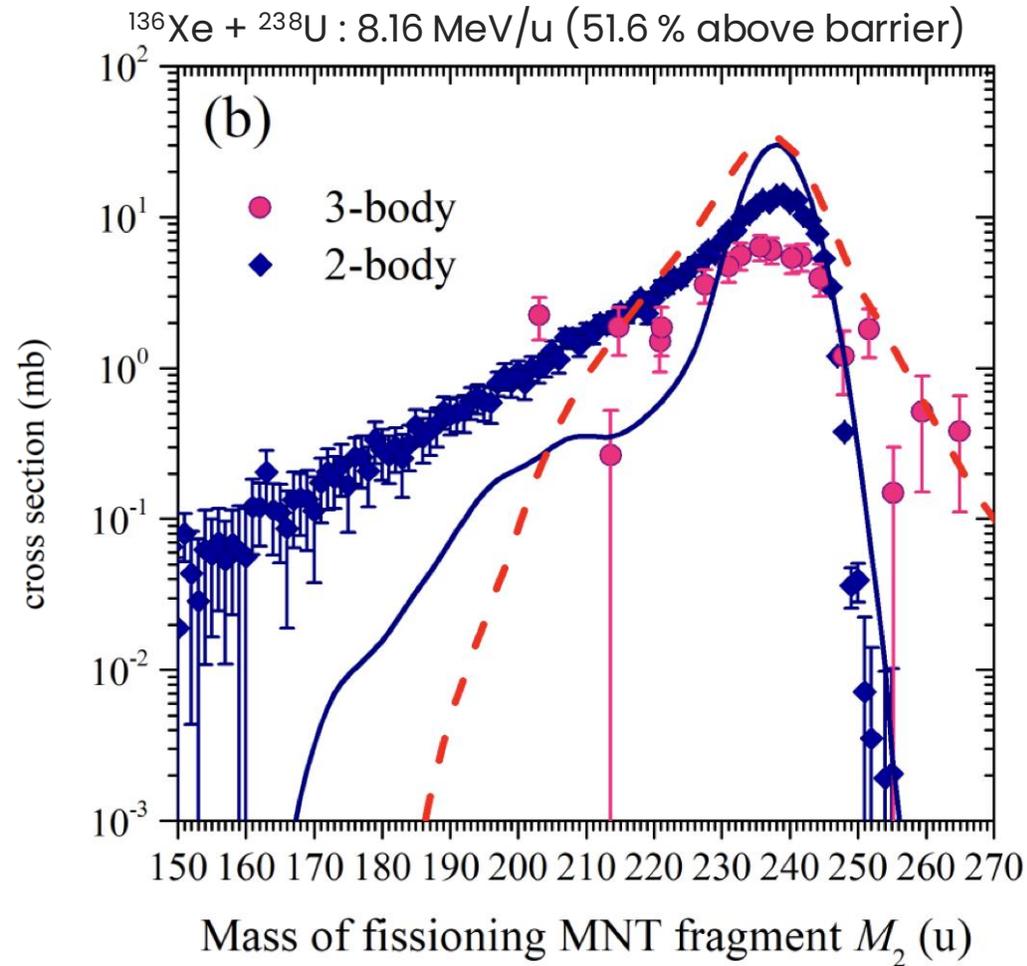


13 % above the barrier

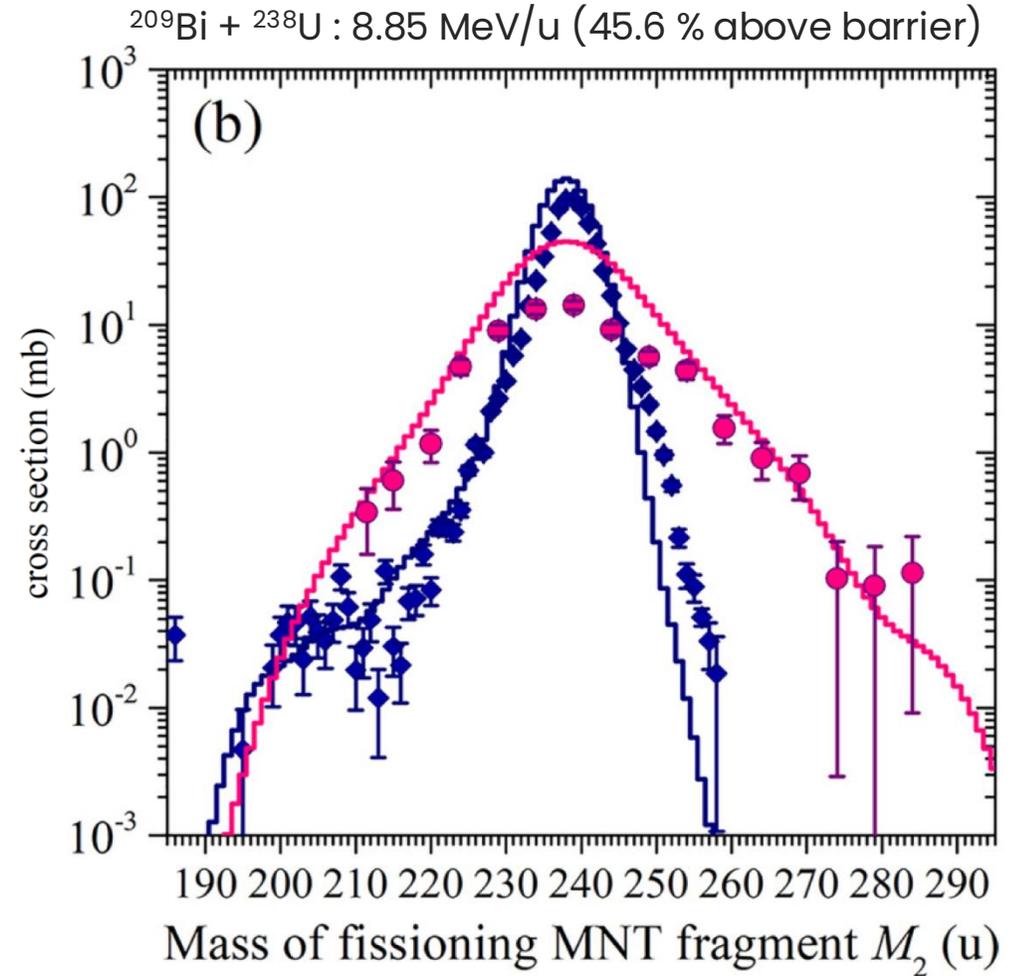
Grazing : 56.3°

Heavy partner : 57°

MNT at CORSET

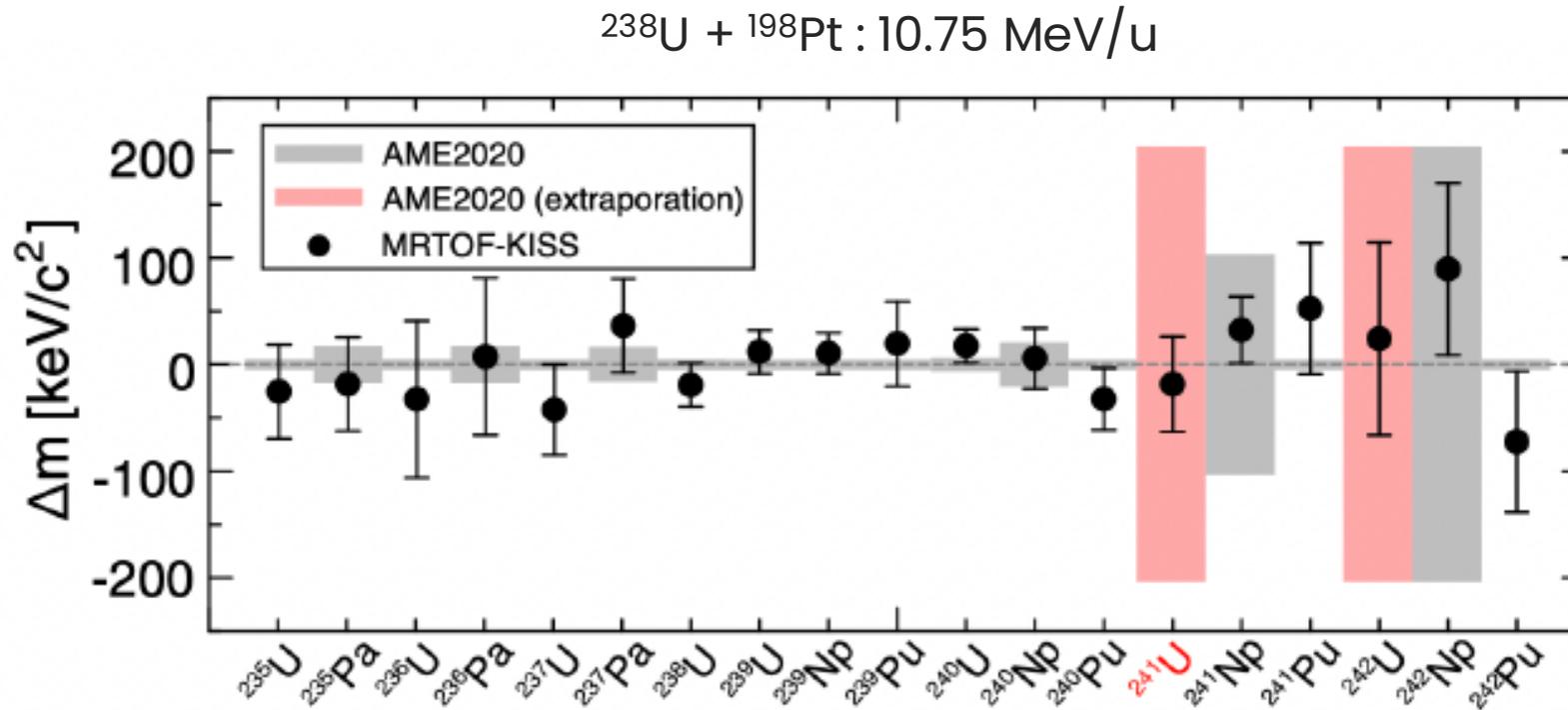


E. M. Kozulin et. al.; PRC 109 (2024)



I. V. Vorobiev et. al.; PRC 112 (2025)

MNT at KISS



T. Niwase et. al.; PRL 130 (2023)

81 % above barrier

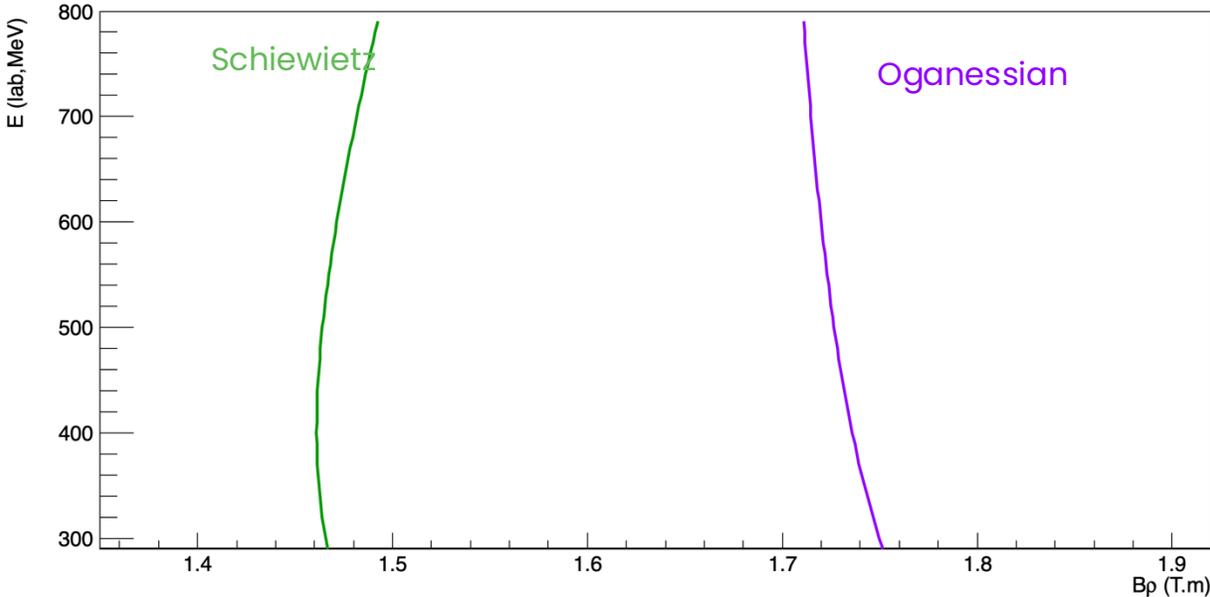
Gas-cell (KISS)

Low efficiency setup

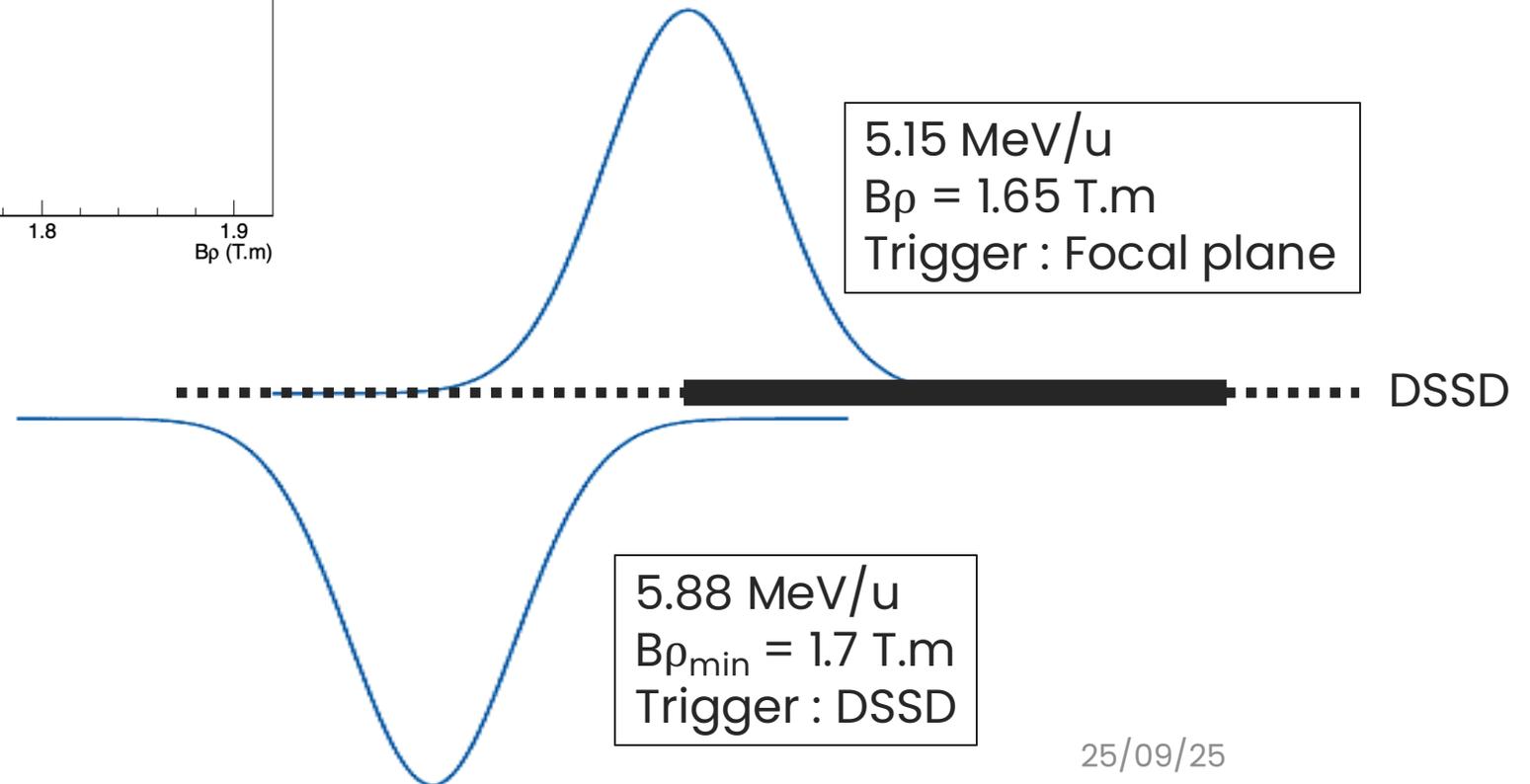
No MNT at 5.88 MeV/u



Magnetic rigidity distribution



- $B\rho$ scan
- No U-like identified (no CoulEx)
- Simulations : -30% CoulEx expected w.r.t 5.15 MeV/u data
M. Zielinska; private communication



Why no massive transfers at 5.15 MeV/u?

Scaling rule : +2p max / O.M & exp-max = +2

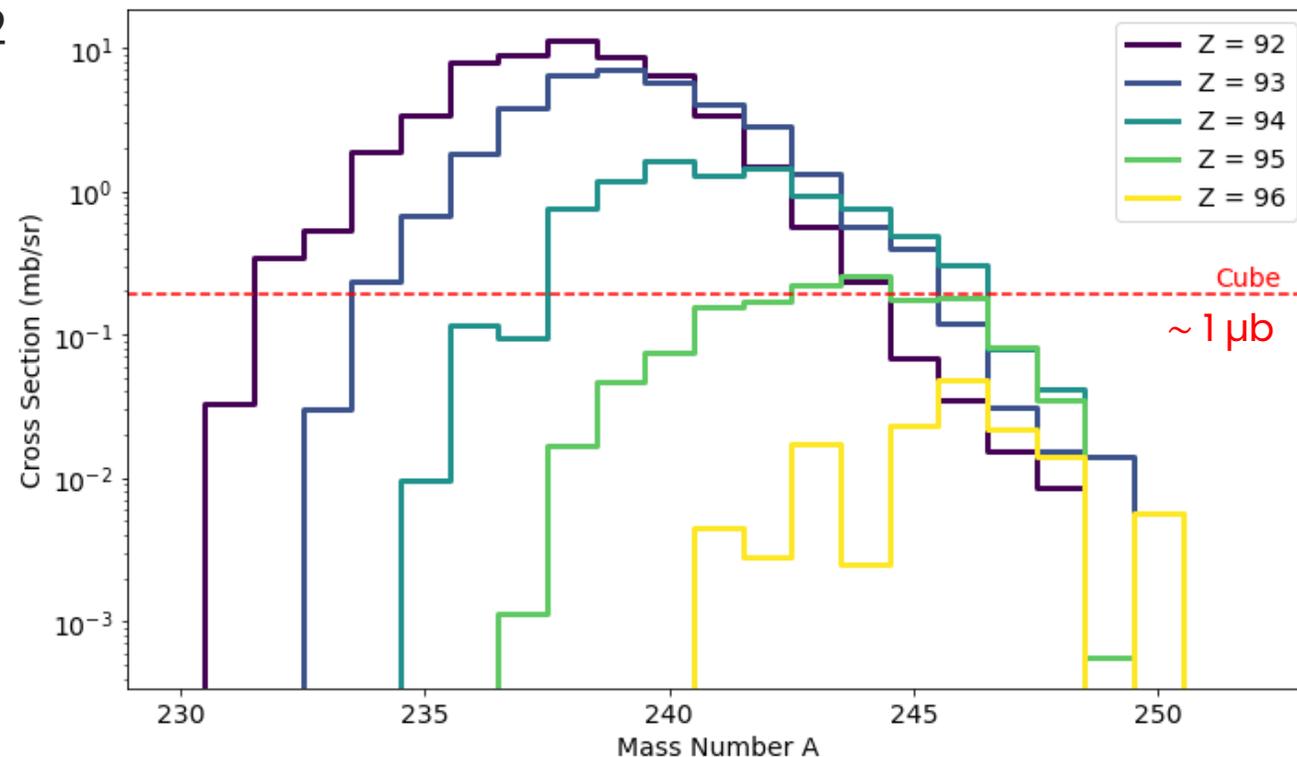
No CoulEx \rightarrow +4p max

Alpha decays \rightarrow +6p max

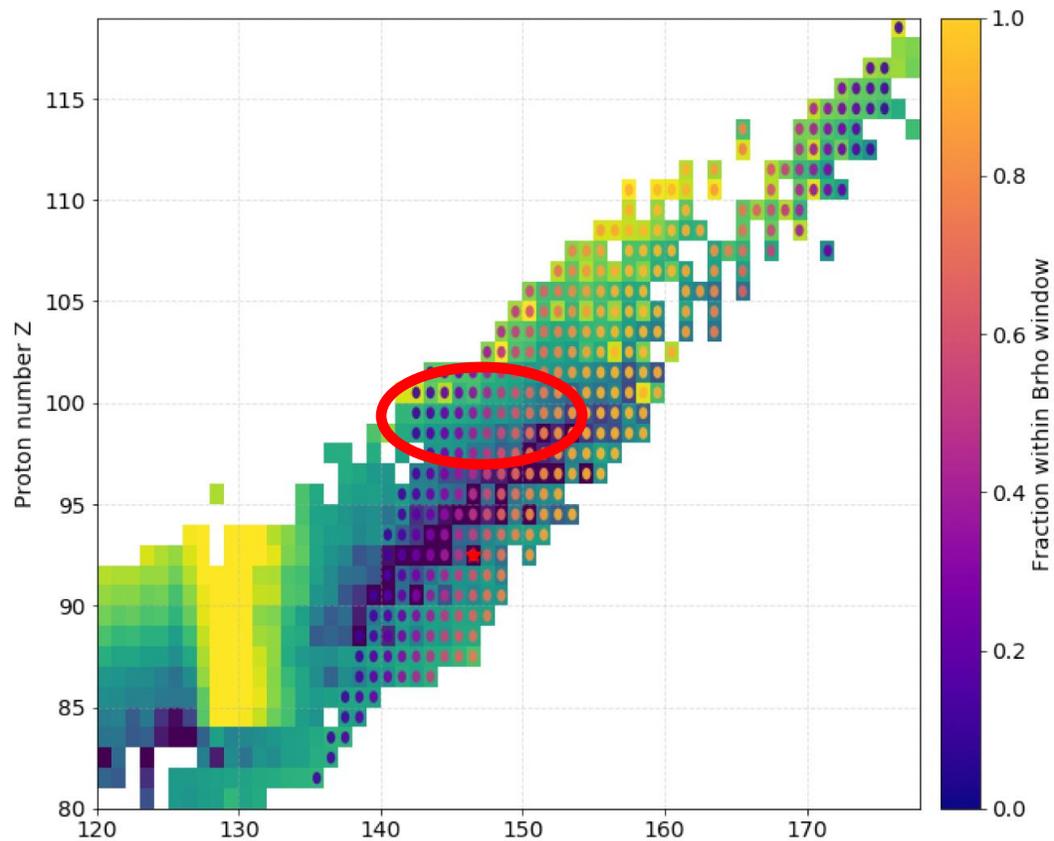
Too low energy :

5.15 MeV / u \rightarrow 4.7 % below barrier
(5.89 MeV / u \rightarrow 9 % above barrier)

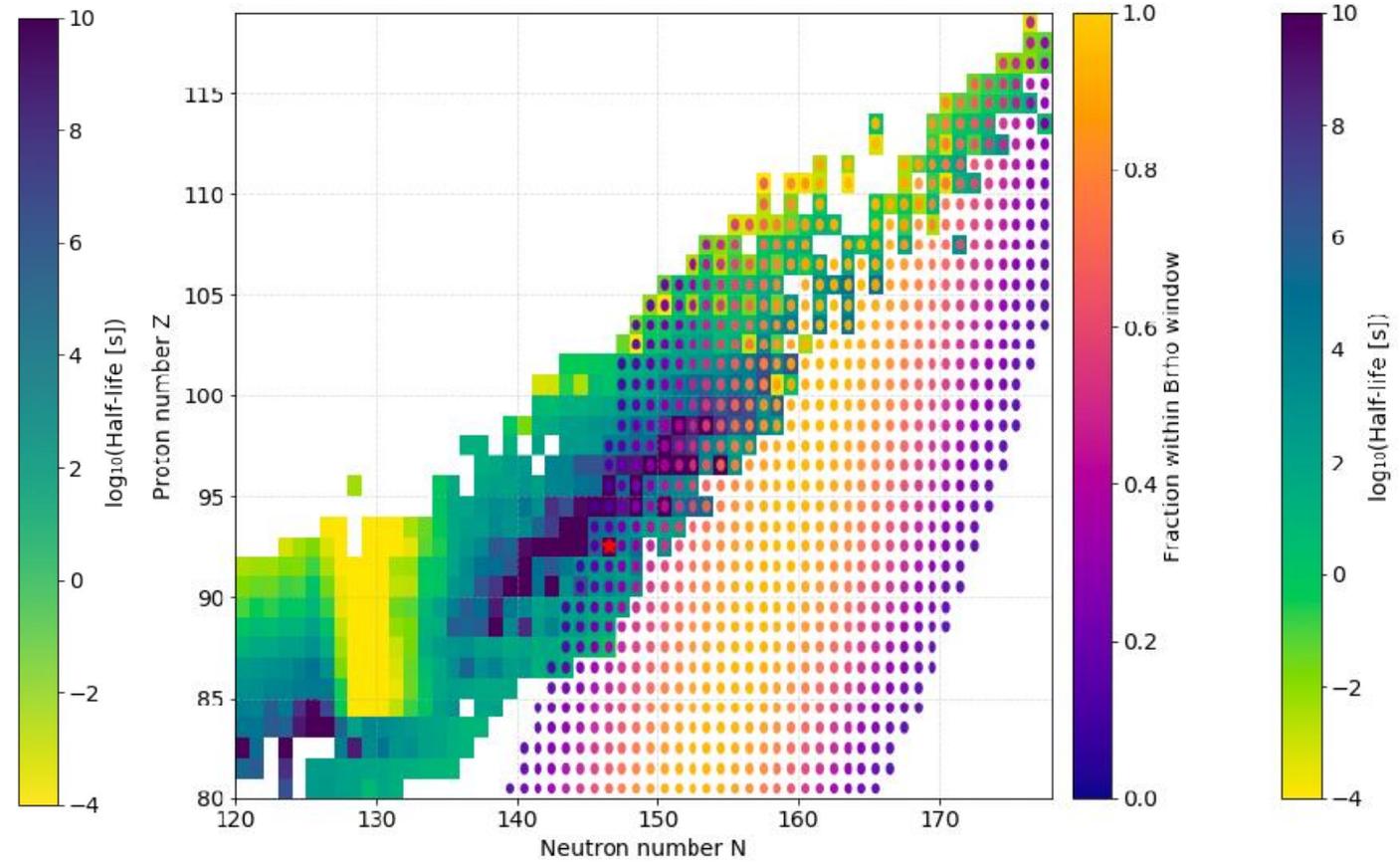
Not at optimum of the excitation function
 \rightarrow See $^{136}\text{Xe}+^{238}\text{U}$ at LNL for discussion



Decay spectroscopy ?



1.65 T.m



1.68 T.m

Max with α -decay : Fm ? (see massive transfers discussion)

Cross-section: octupole contribution

$$^{236}\text{U} : 10^+ \rightarrow 8^+ \text{ transition} \longrightarrow \sigma_{^{236}\text{U}}^{g.s.r} = 0.198 \text{ mb}$$

$$^{236}\text{U} : 11^- \rightarrow 9^- \text{ transition} \longrightarrow \sigma_{^{236}\text{U}}^{\text{octupole}} = 0.0597 \text{ mb}$$

$$\frac{\sigma_{^{236}\text{U}}^{\text{octupole}}}{\sigma_{^{236}\text{U}}} = 23\%$$

Ratio for ^{238}U (Coulex) : $\sim 10\%$

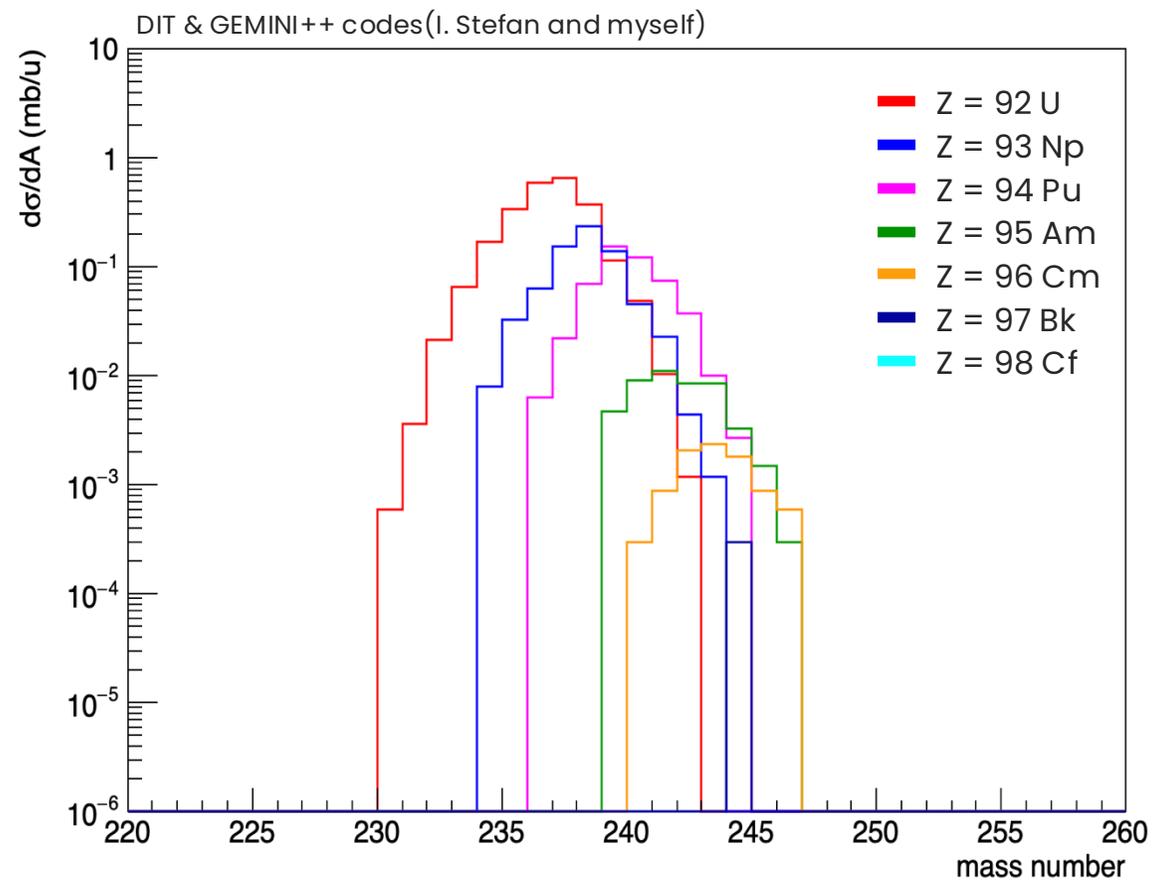
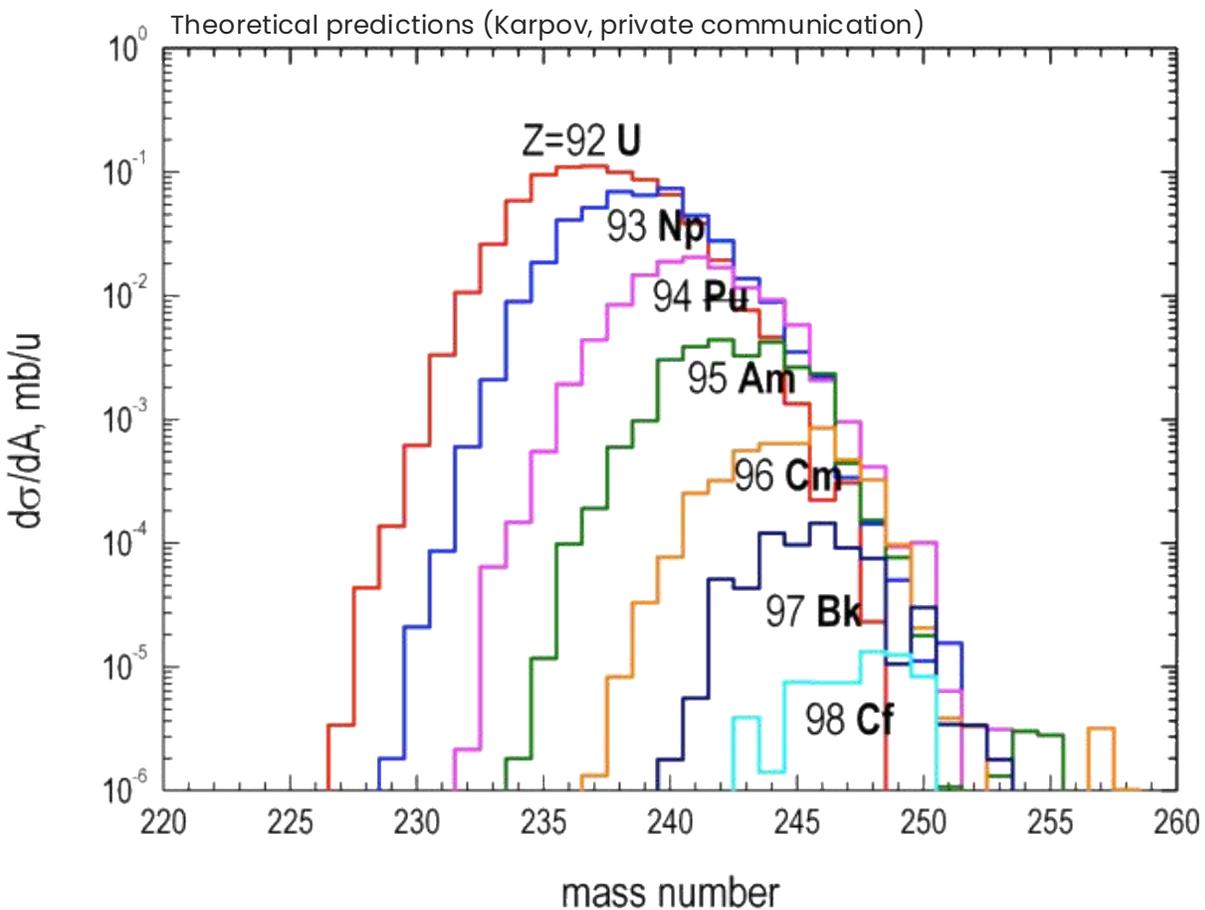
- Additional contribution from octupole smaller than uncertainties

- What are the spin distributions for both bands after MNT?

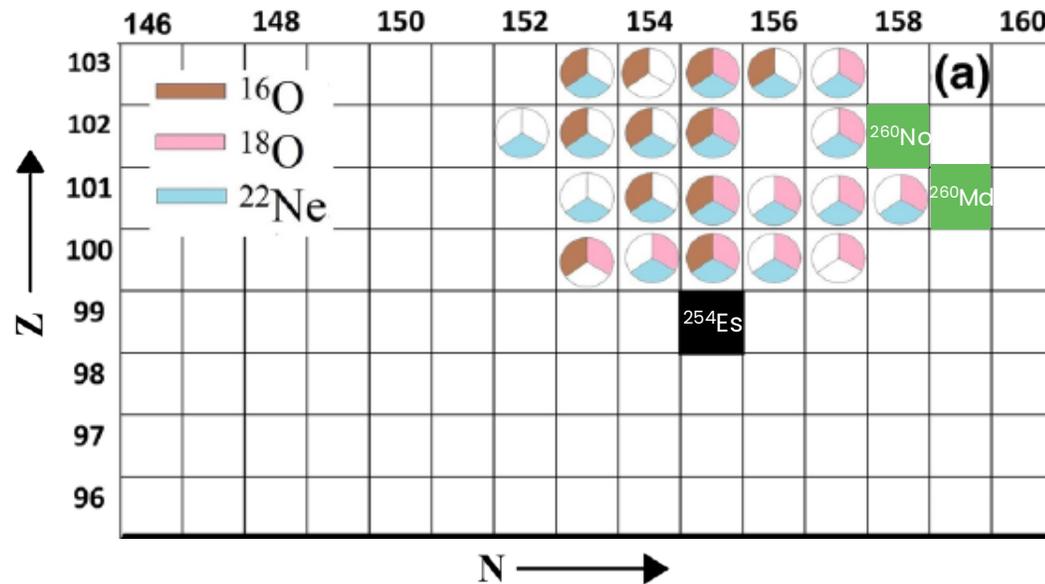
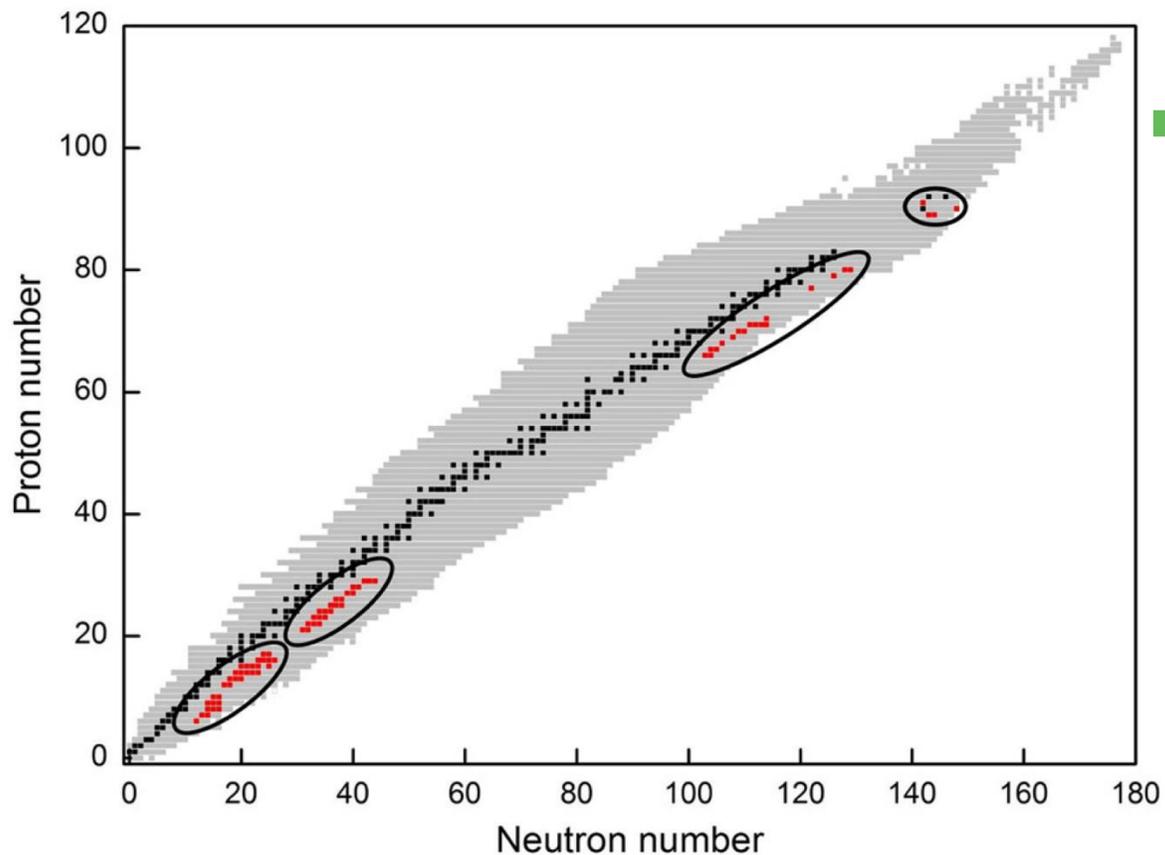
- How can the octupole component affect cross-sections?

→ Need for a dedicated experiment to measure spin distributions in both bands for various cases

5.88 MeV/u predictions



MNT : discovering neutron-rich isotopes

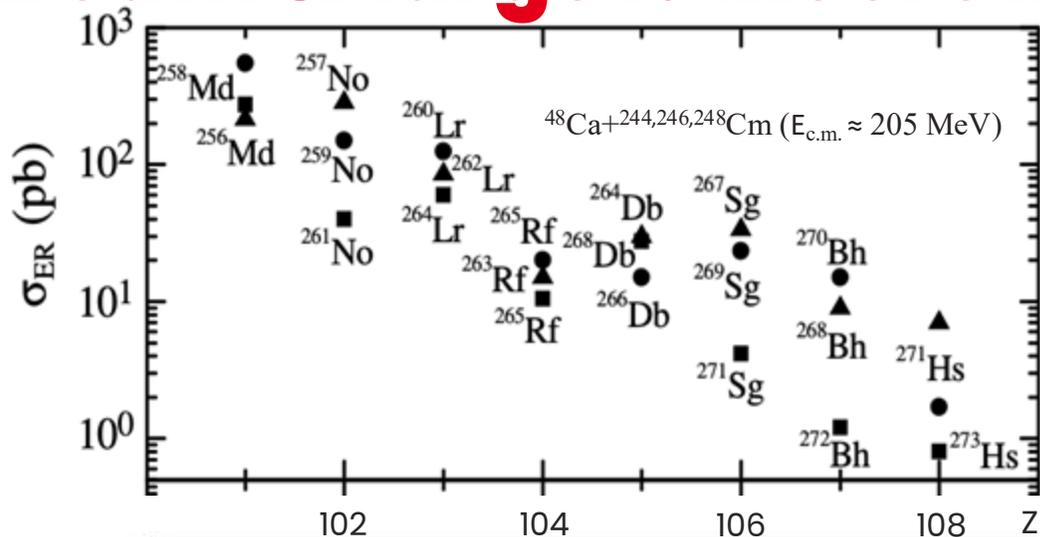


(mostly) neutron-rich discoveries all along the chart

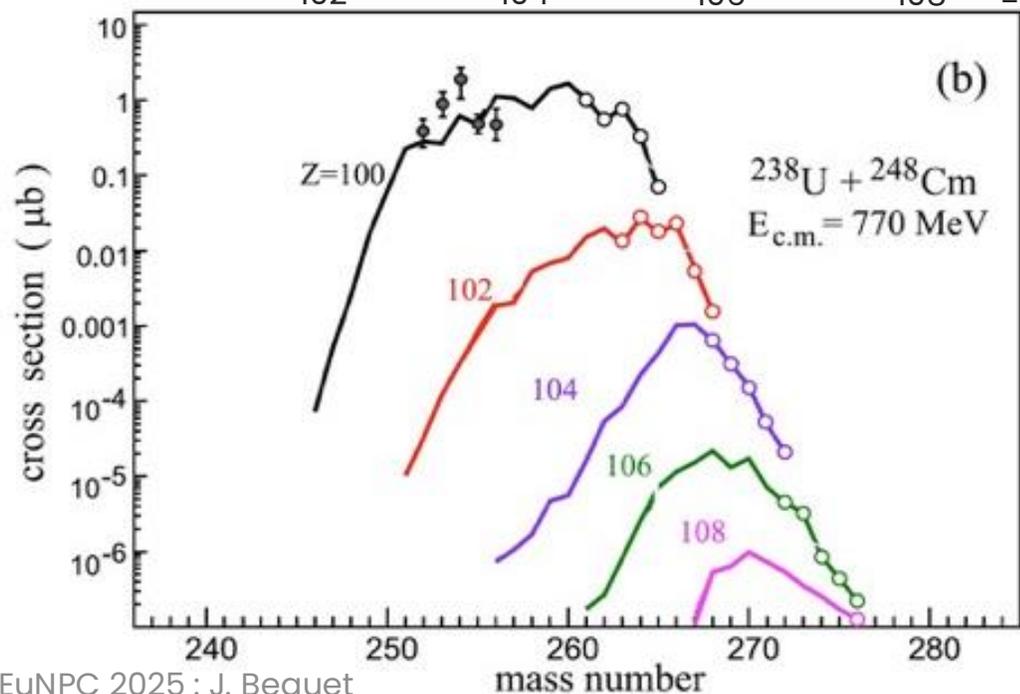
Adamian, G. G. et al. "How to extend the chart of nuclides?"; *Eur. Phys. J. A* 56.2 (2020)

Beam & target : theoretical predictions

G. G. Adamian, PRC 71, 034603 (2005)



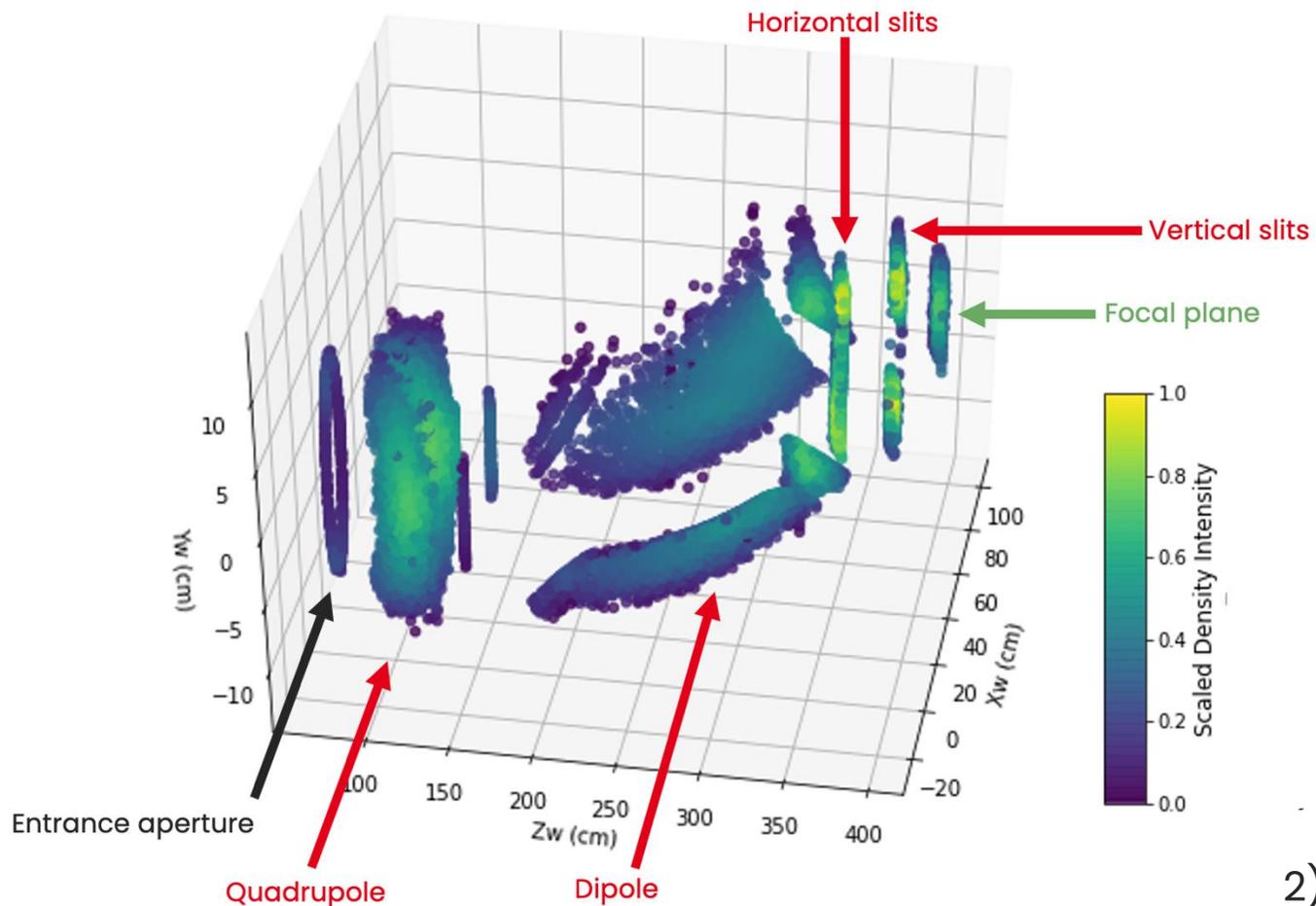
V. Zagrebaev, W. Greiner, NPA 944 (2015)



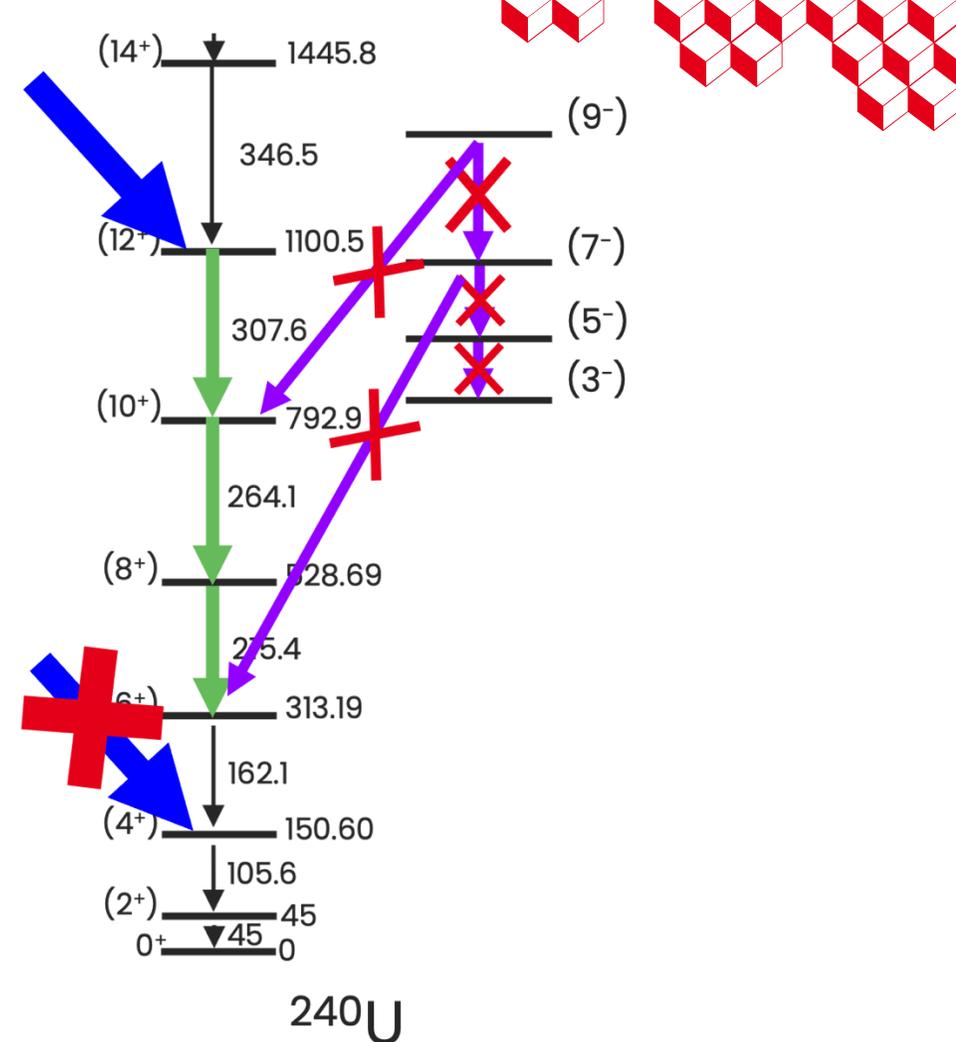
- Adamian et al. describe such reactions as the evolution of a di-nuclear system, using the **diffusion master equation** and diabatic internuclear potential.
- Light beams are favored: shell effect increases the survival probability of primary products.
- Zagrebaev & Greiner, then Karpov & Saiko, developed a model using **multidimensional Langevin equations** and an adiabatic internuclear potential to describe MNT.
- Heavier beams are favoured: large amount of available neutrons increase the probability to transfer enough to synthesise new neutron-rich isotopes.

Both models predict « reasonable » cross-sections for the production of superheavy nuclei for different reaction partners.

Assumptions:



1) Transmission evaluated with simulations

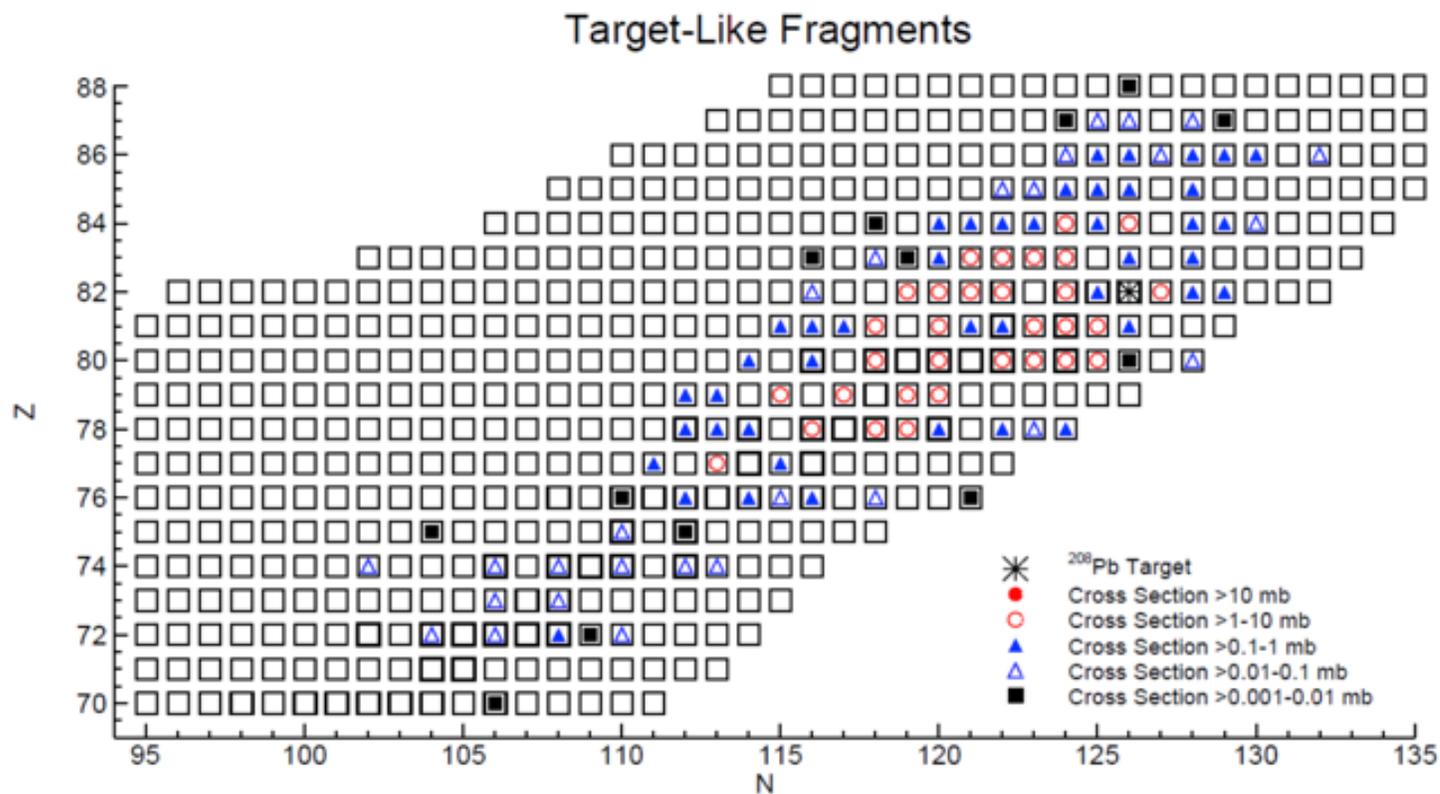


2) All transitions not in the g.s. rotational band are neglected

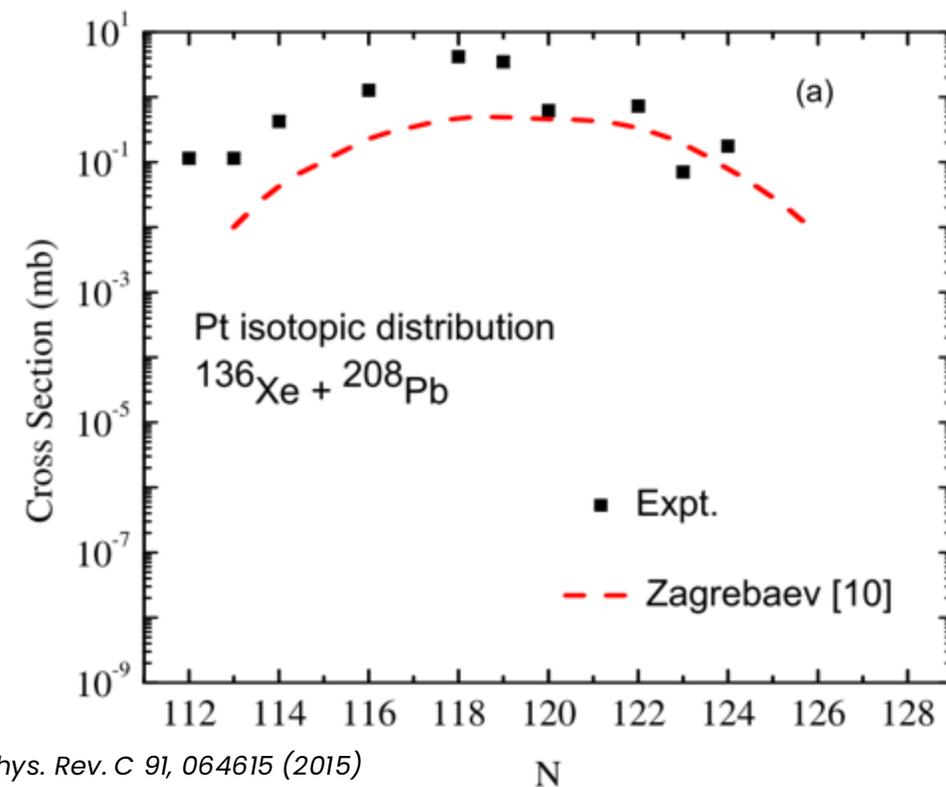
3) All products are at least excited up to the highest considered state in the triplet

Beam & target : validation

$^{136}\text{Xe} + ^{208}\text{Pb}$ 5.8 MeV/u with Gammasphere at ANL : beam stopped in a thick target



J.S. Barrett et al. Phys. Rev. C 91, 064615 (2015)



117 Pb-like products identified from Yb (Z=70) to Ra (Z=88)

The cross-section distribution follows the trend predicted by Zagrebaev

But result integrated over all angles and beam energies → **first step !**

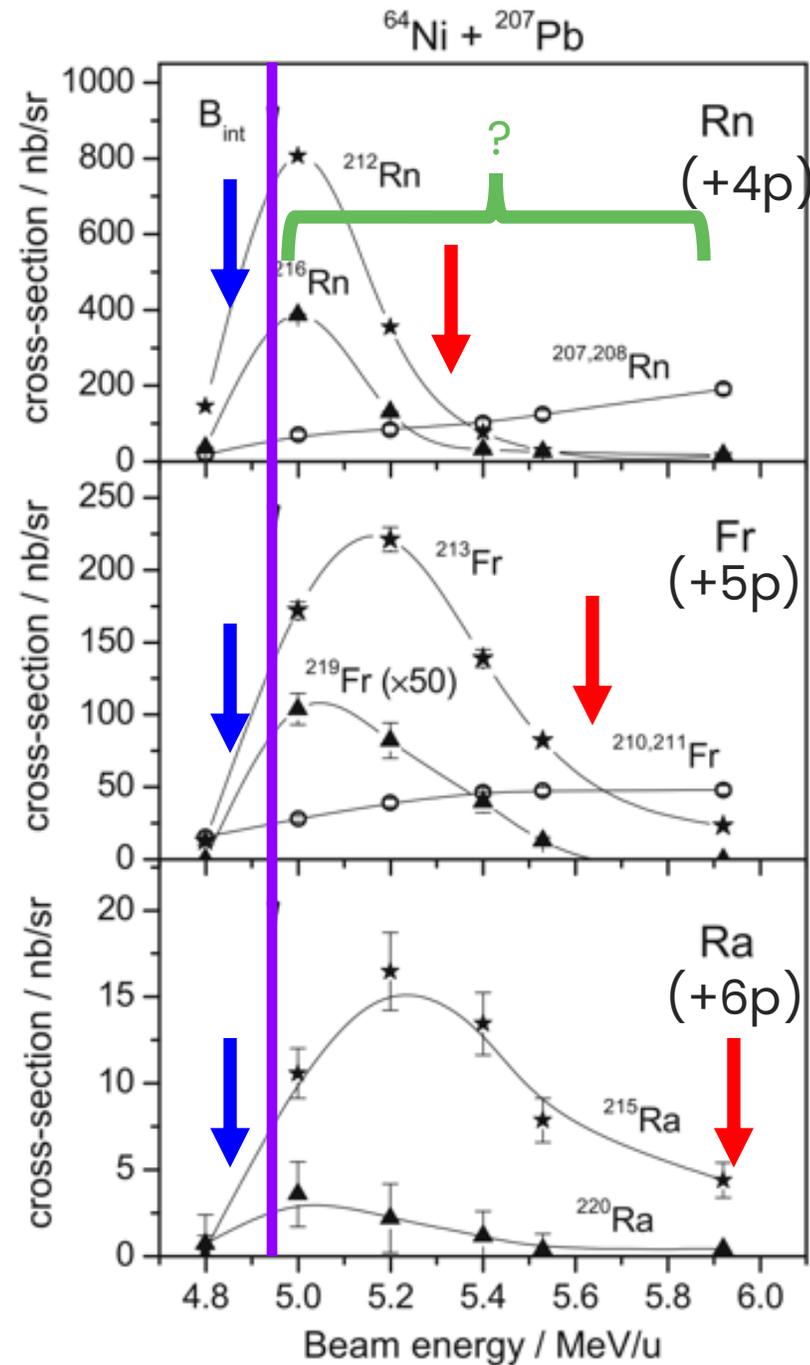
Near barrier reactions

Interaction barrier

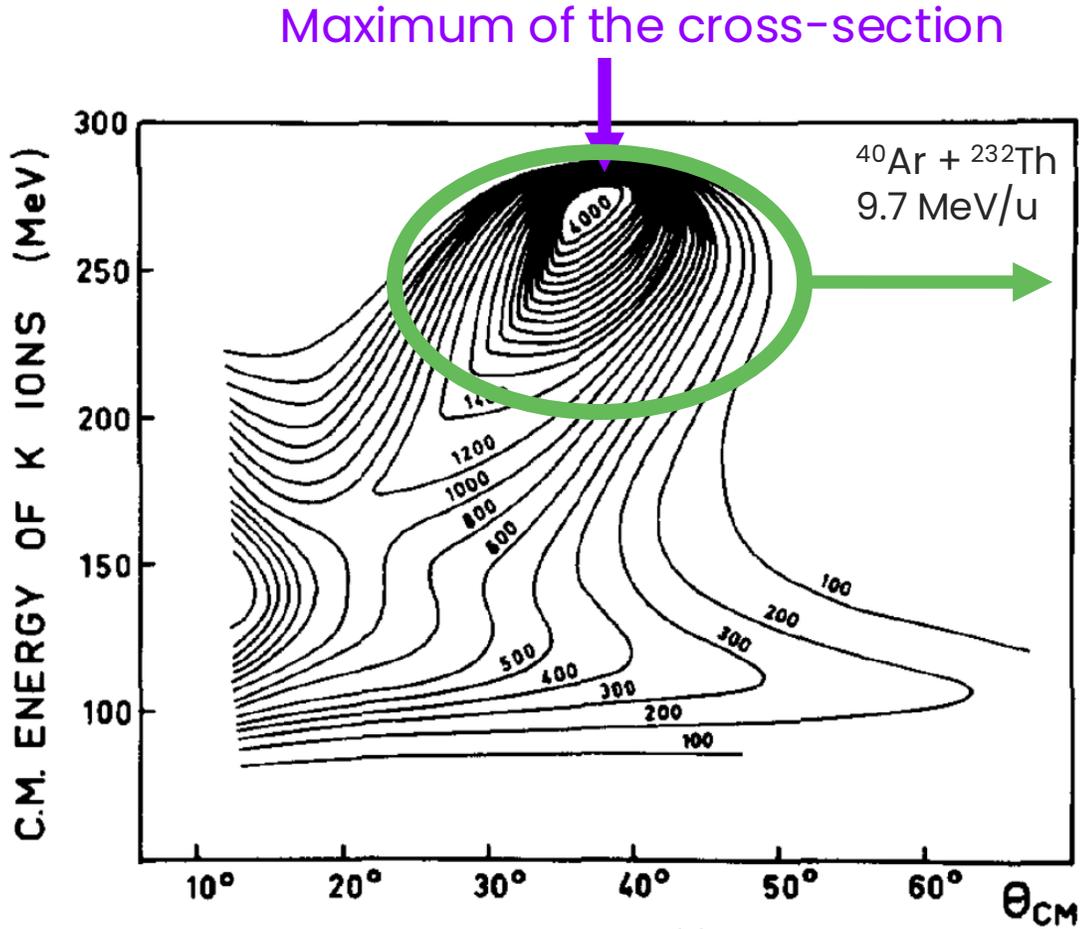
No Di-nuclear system

Products lost above a given energy

Optimal cross-section to find above the barrier



Angular distribution

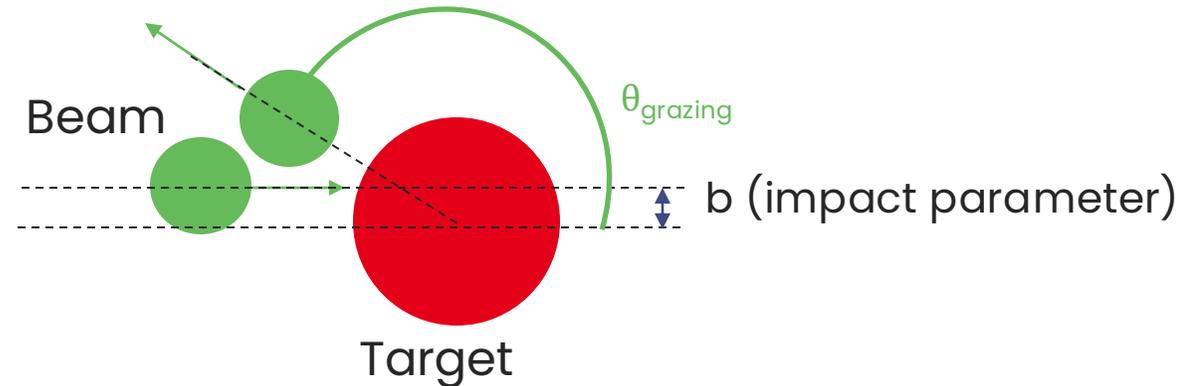
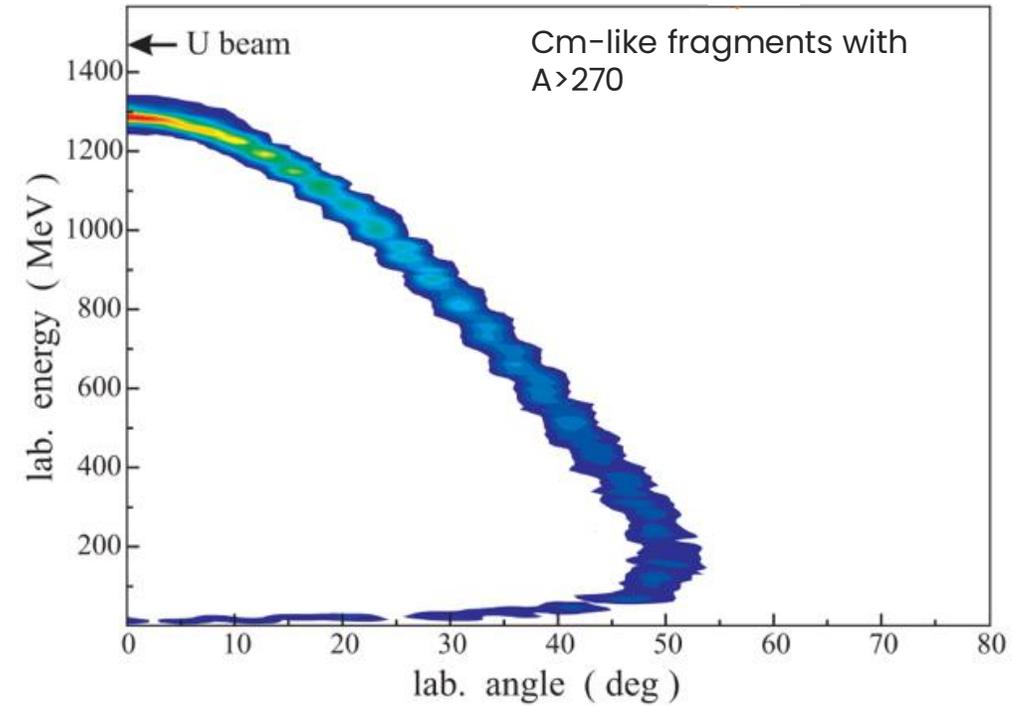


J. Wilczyński; PLB 47 (6), 1973.

Near-barrier → Central collisions

$^{238}\text{U} + ^{248}\text{Cm}$
6.1 MeV/u

V. Zagrebaev, W. Greiner; PRC 83 (2011)

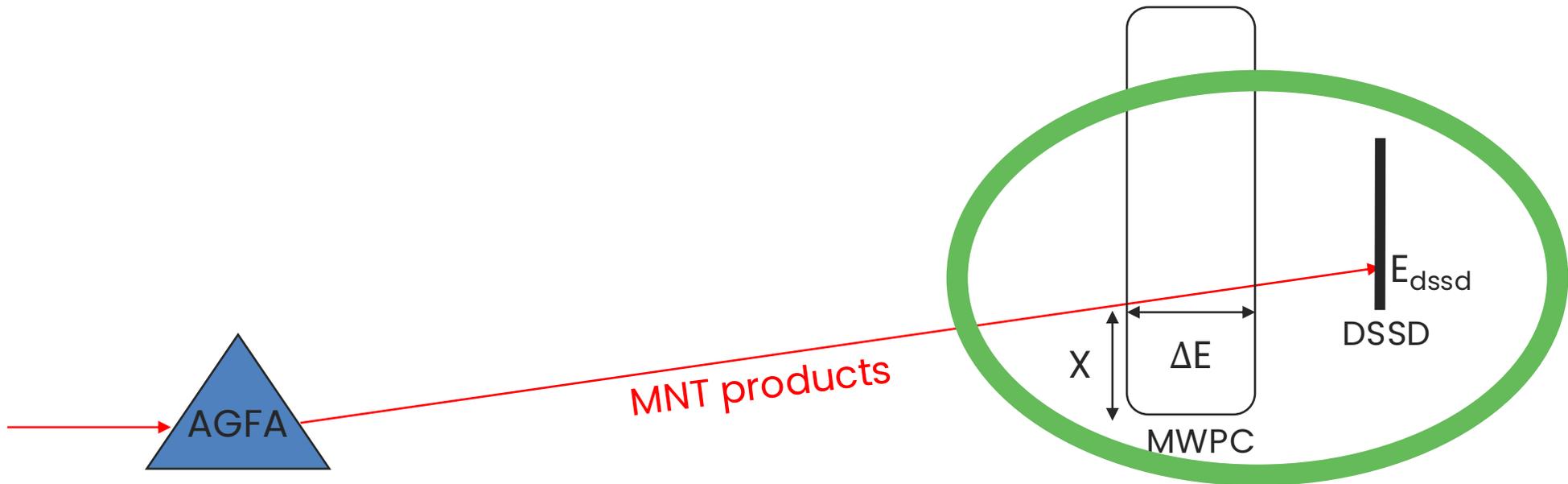
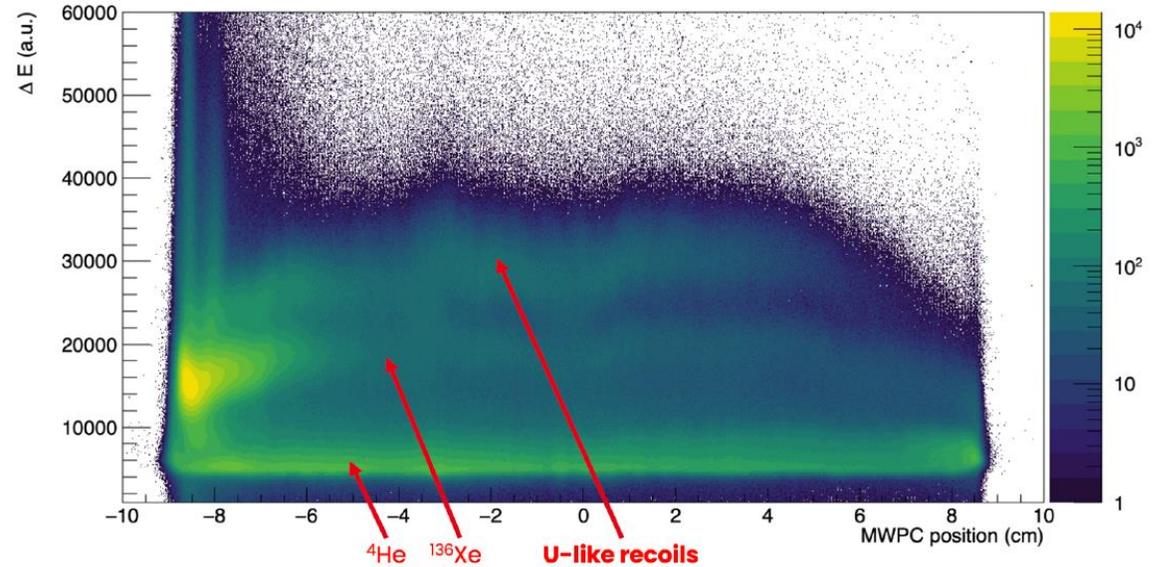


U-like nuclei selection

5 observables for this study:

- Energy loss in the PPAC
- Horizontal Position of nuclei in the PPAC (X)
- Implantation energy in the DSSD

Nuclei selection



U-like nuclei selection

5 observables for this study:

- Energy loss in the PPAC
 - Horizontal Position of nuclei in the PPAC (X)
 - Implantation energy in the DSSD
 - Time of flight (ToF) between nuclei entering the PPAC and the γ -rays they emitted in Gammasphere
- } γ -rays selection

