Dynamical deformation of the $^{136}Xe + ^{238}U$ system in sub-barrier multi-nucleon transfer reactions

Jonathan Bequet (GANIL)

Barbara Sulignano (CEA), Iulian Stefan (IJCLab), The #1930 ANL experiment collaboration

Zakopane 2026

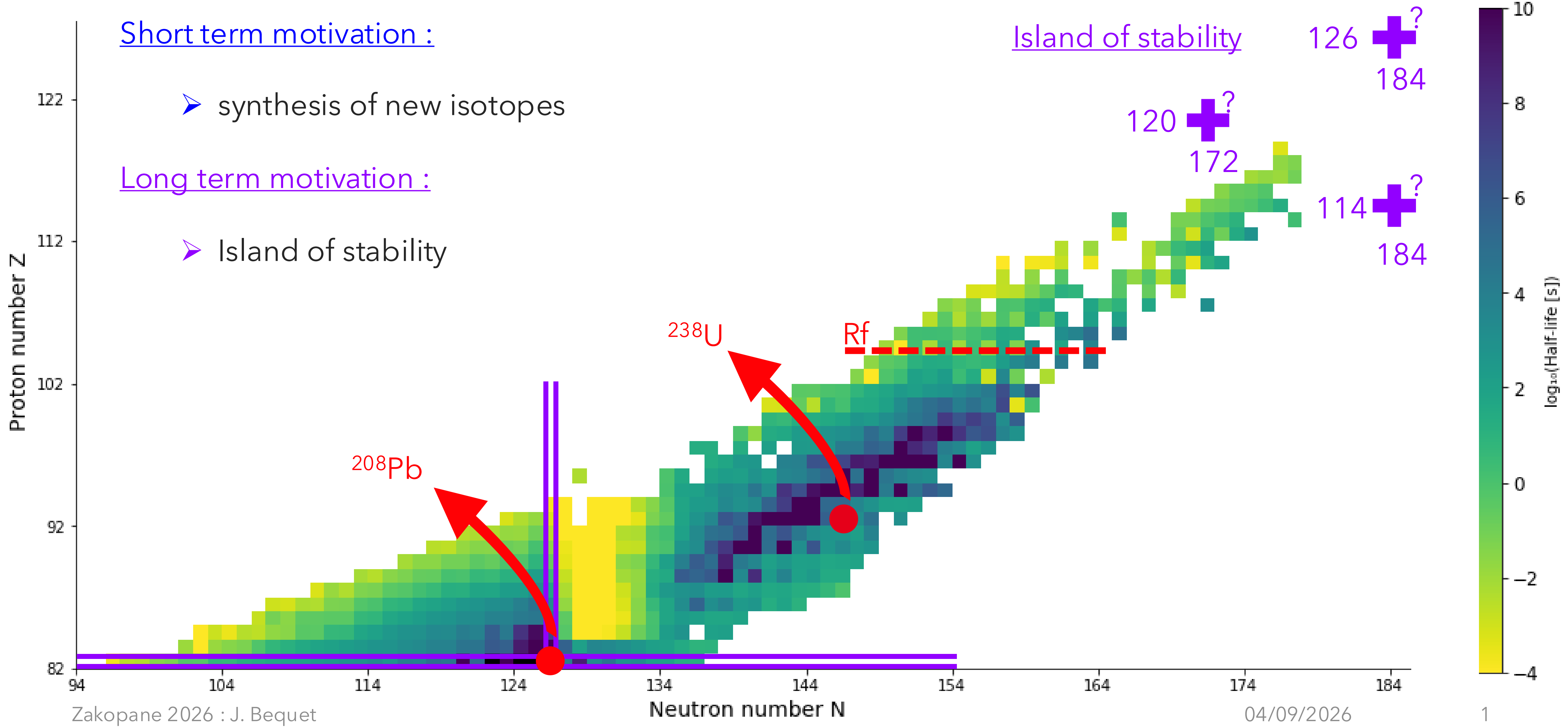
Motivation : the island of stability

Short term motivation :

- synthesis of new isotopes

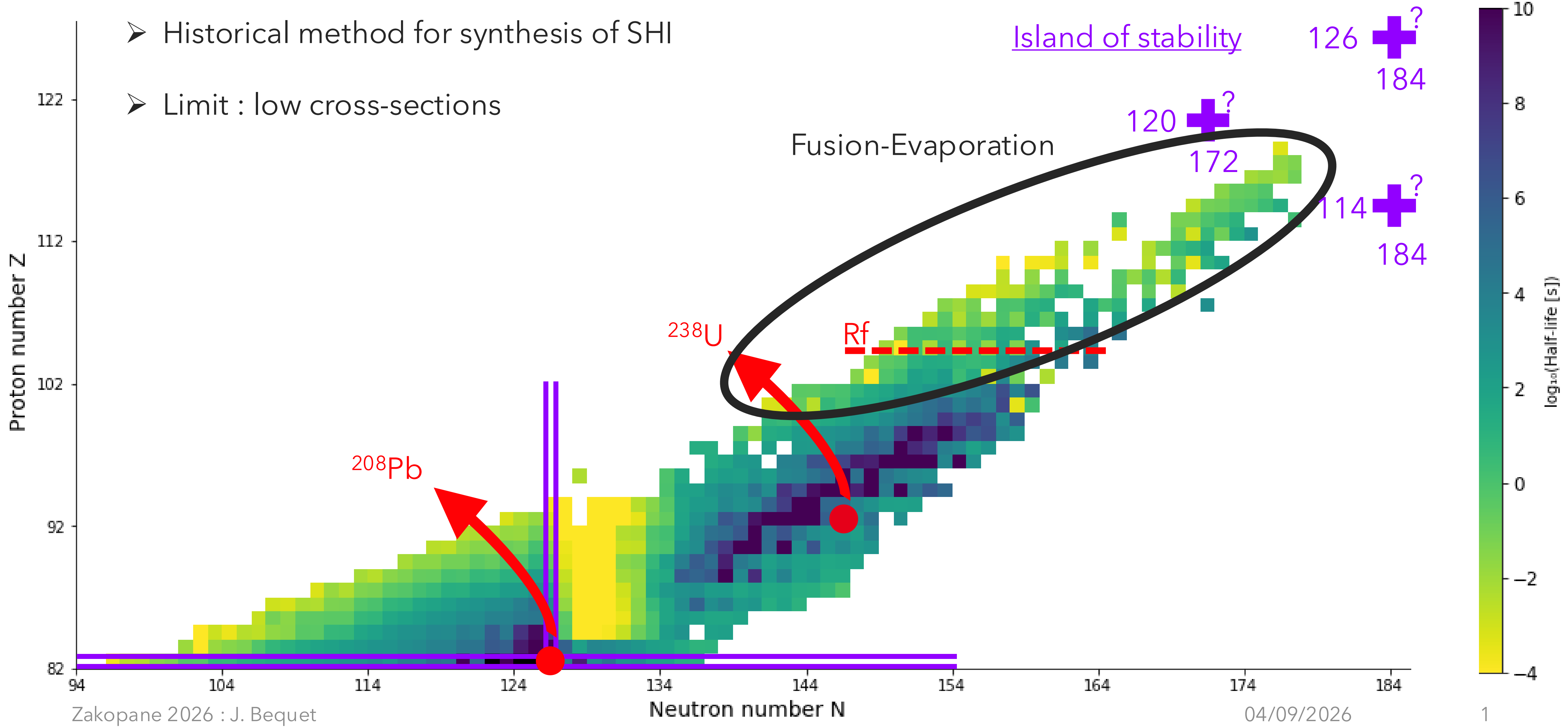
Long term motivation :

- Island of stability



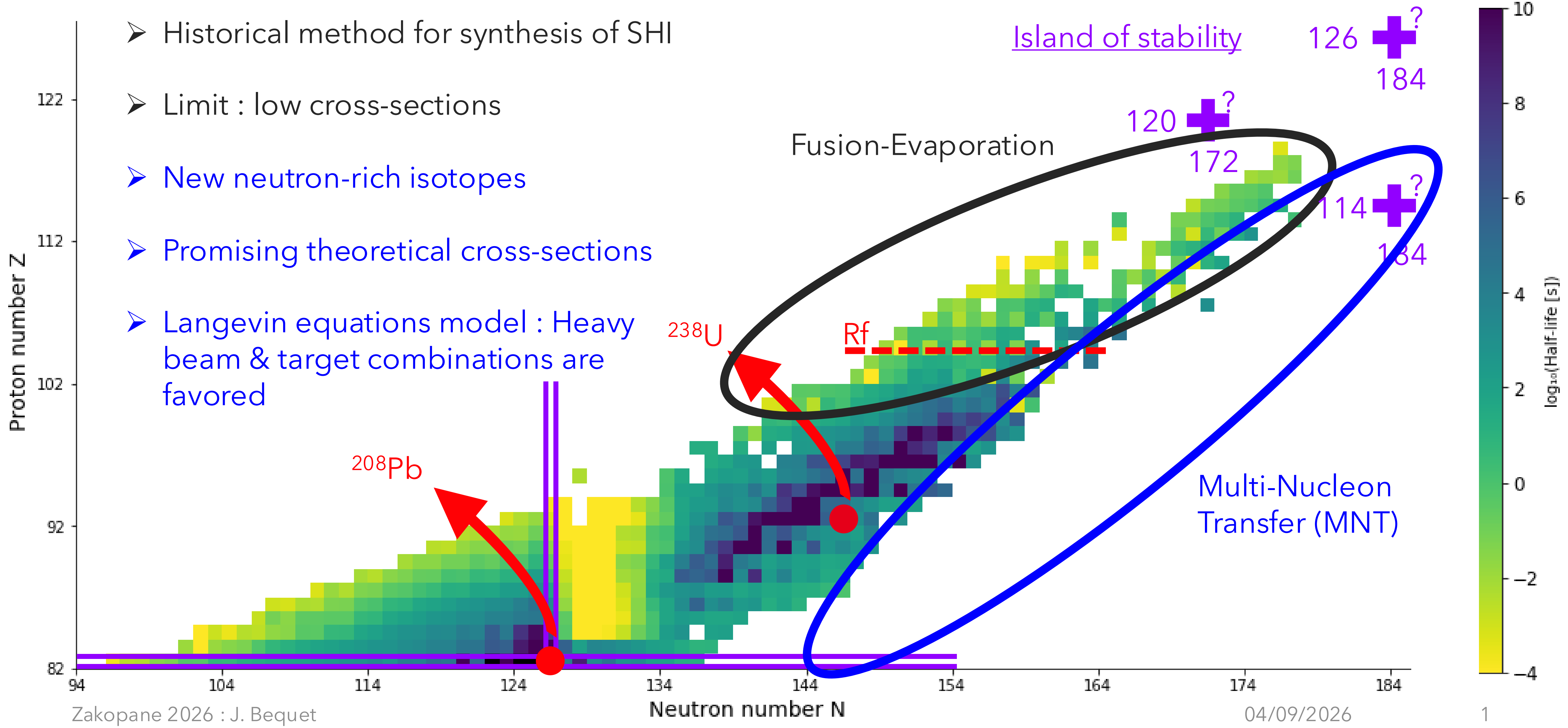
Motivation : the island of stability

- Historical method for synthesis of SHI
- Limit : low cross-sections



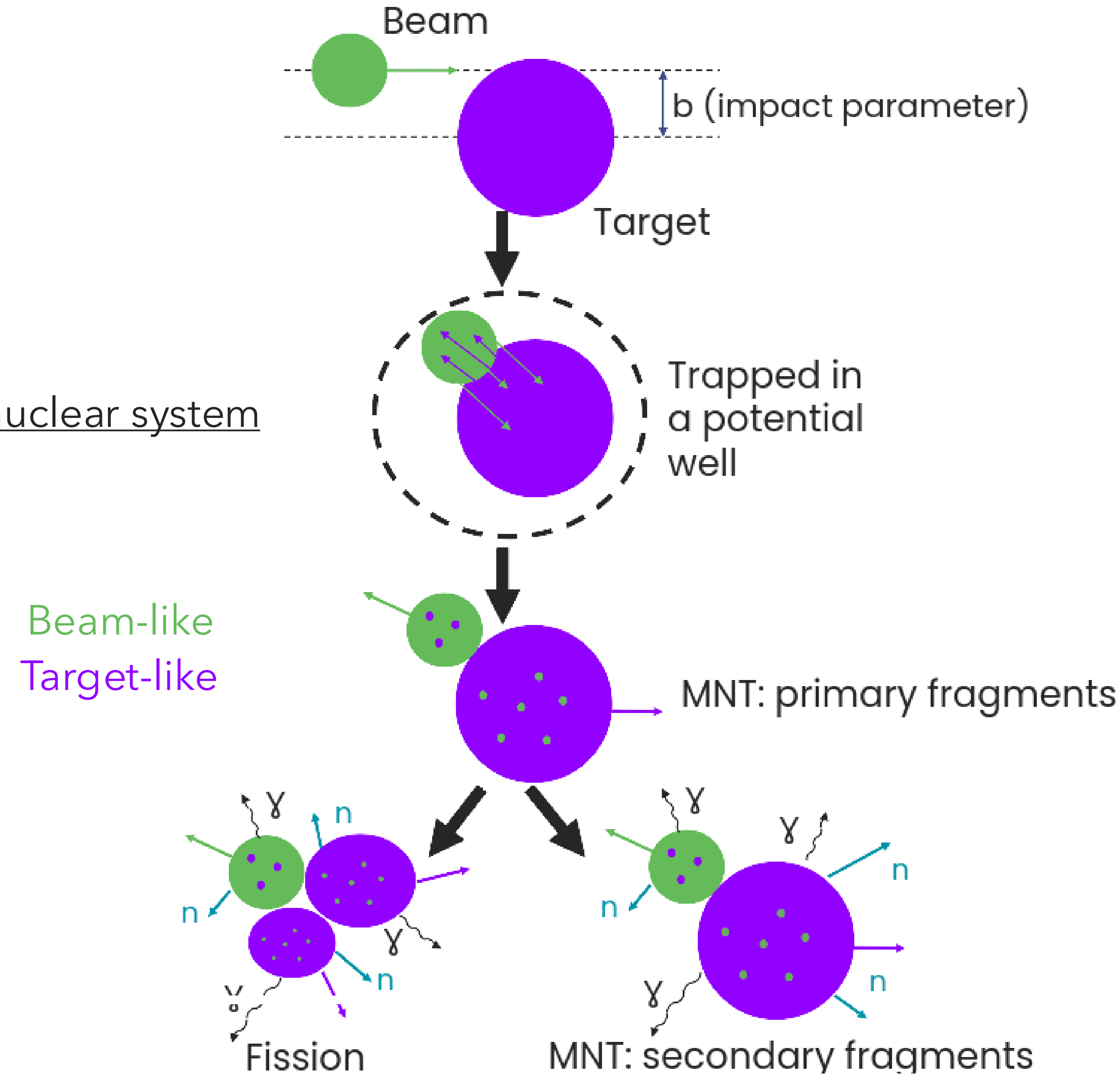
Motivation : the island of stability

- Historical method for synthesis of SHI
- Limit : low cross-sections
- New neutron-rich isotopes
- Promising theoretical cross-sections
- Langevin equations model : Heavy beam & target combinations are favored



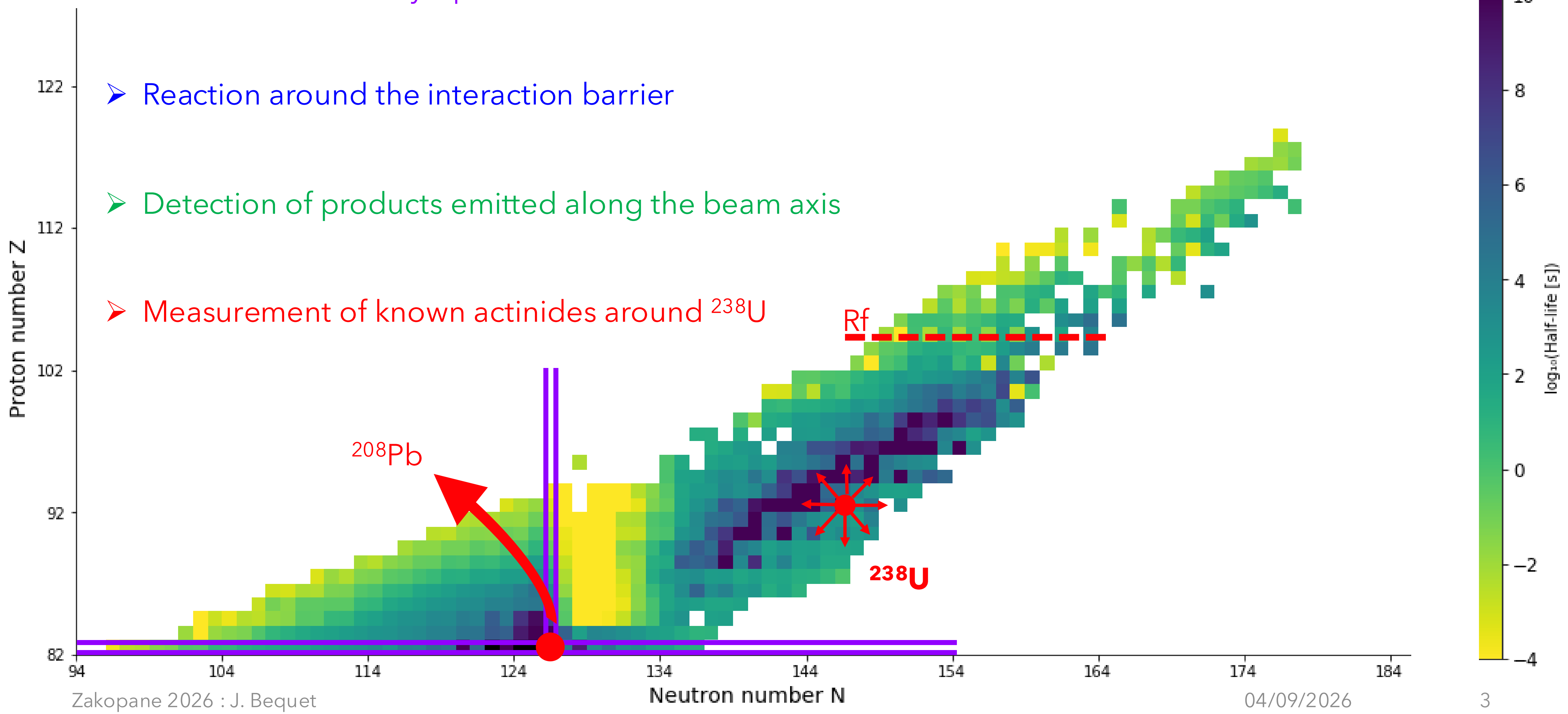
MNT : principles

Di-nuclear system



Physics case

- ^{136}**Xe+**^{238}**U** : « heavy » partners
- Reaction around the interaction barrier
- Detection of products emitted along the beam axis
- Measurement of known actinides around ^{238}U



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

Beam: ^{136}**Xe** at 5.15 and 5.89 MeV/u
Target: ^{238}**U** (U 350 µg/cm^2 + C 45 µg/cm^2)

^{136}Xe beam produced by ATLAS

^{238}U Target

Analyzed data:

→ 5.15 MeV/u
→ 11 h
→ 11 pnA
→ Bρ = 1.65 T.m
→ P_{AGFA} = 4 Torr
→ 72 HPGe in Gammasphere

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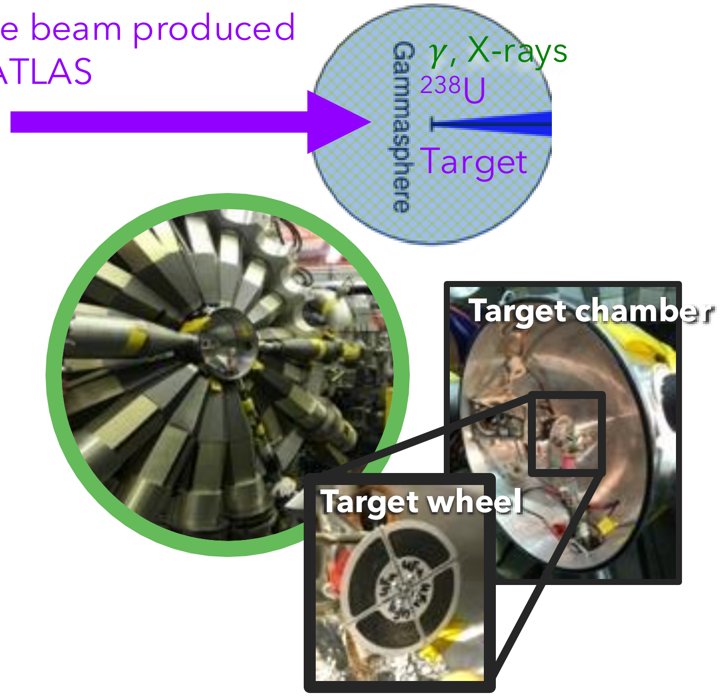

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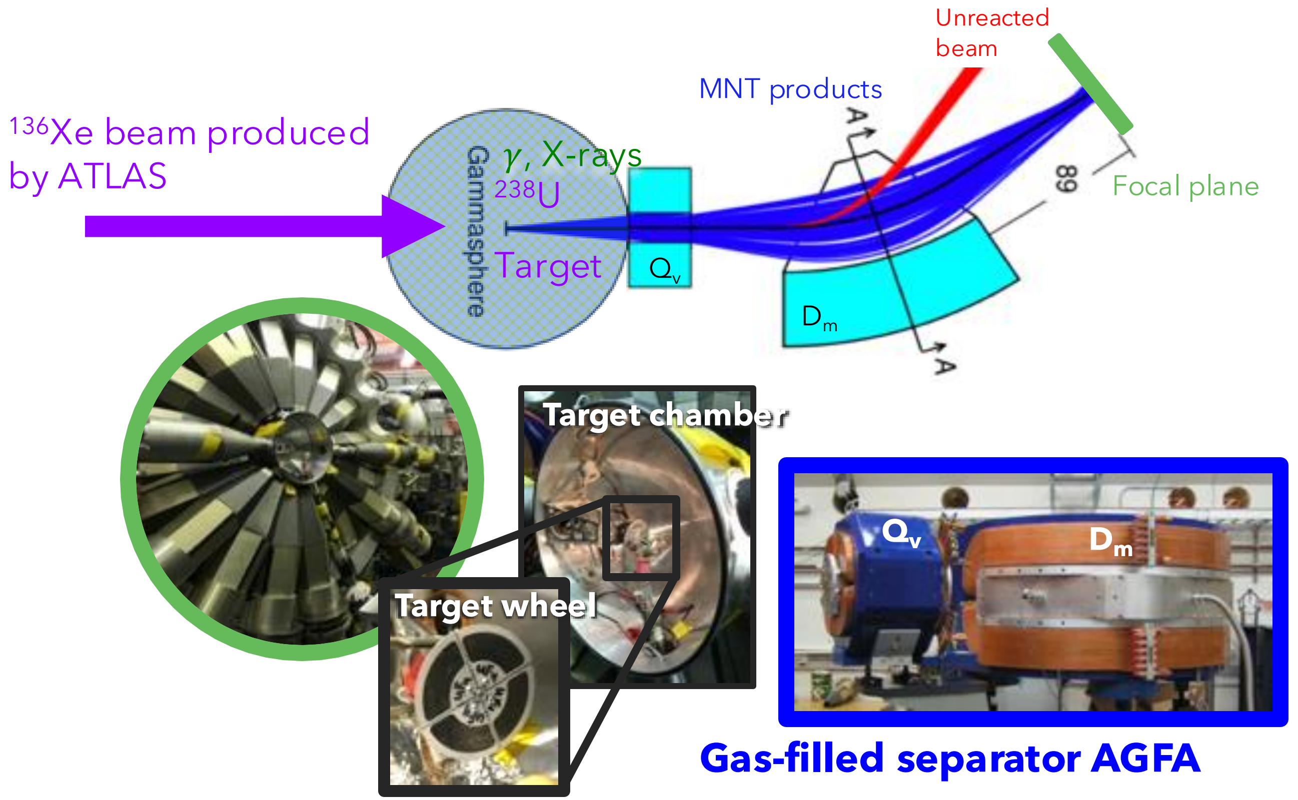

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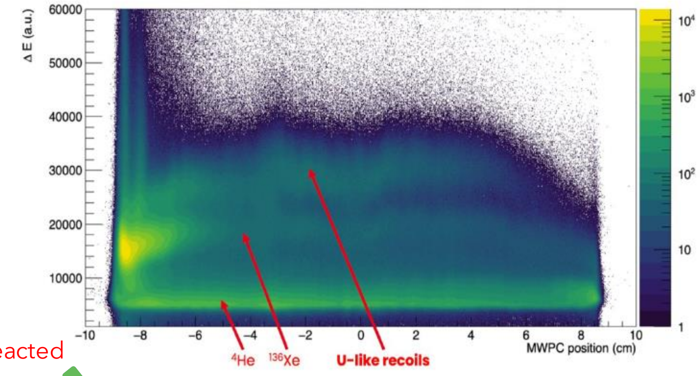

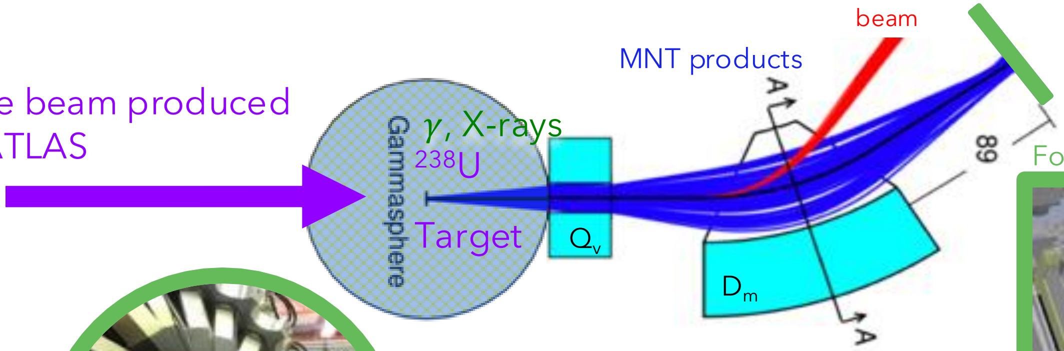

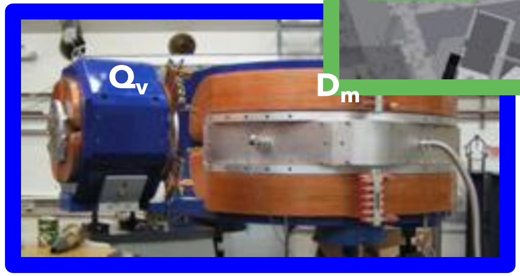

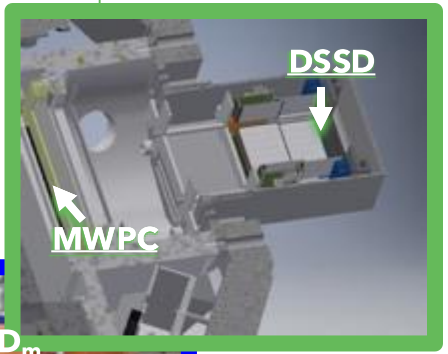

Focal plane

Gas-filled separator AGFA

Analyzed data:

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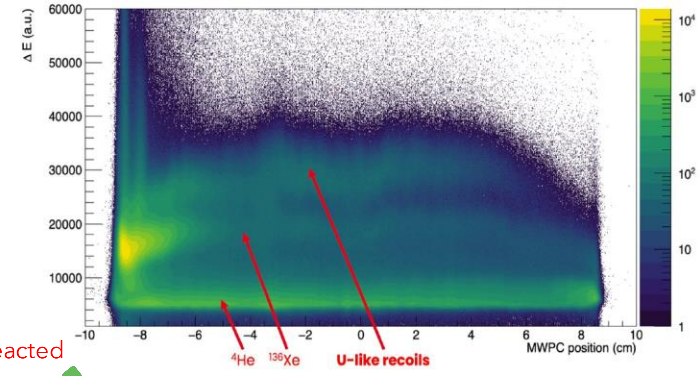

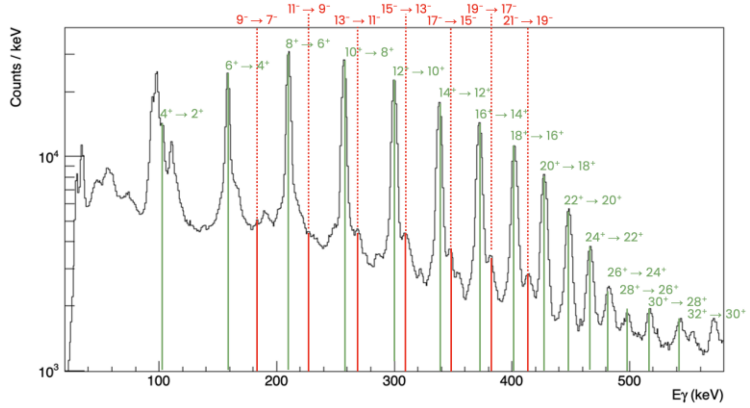

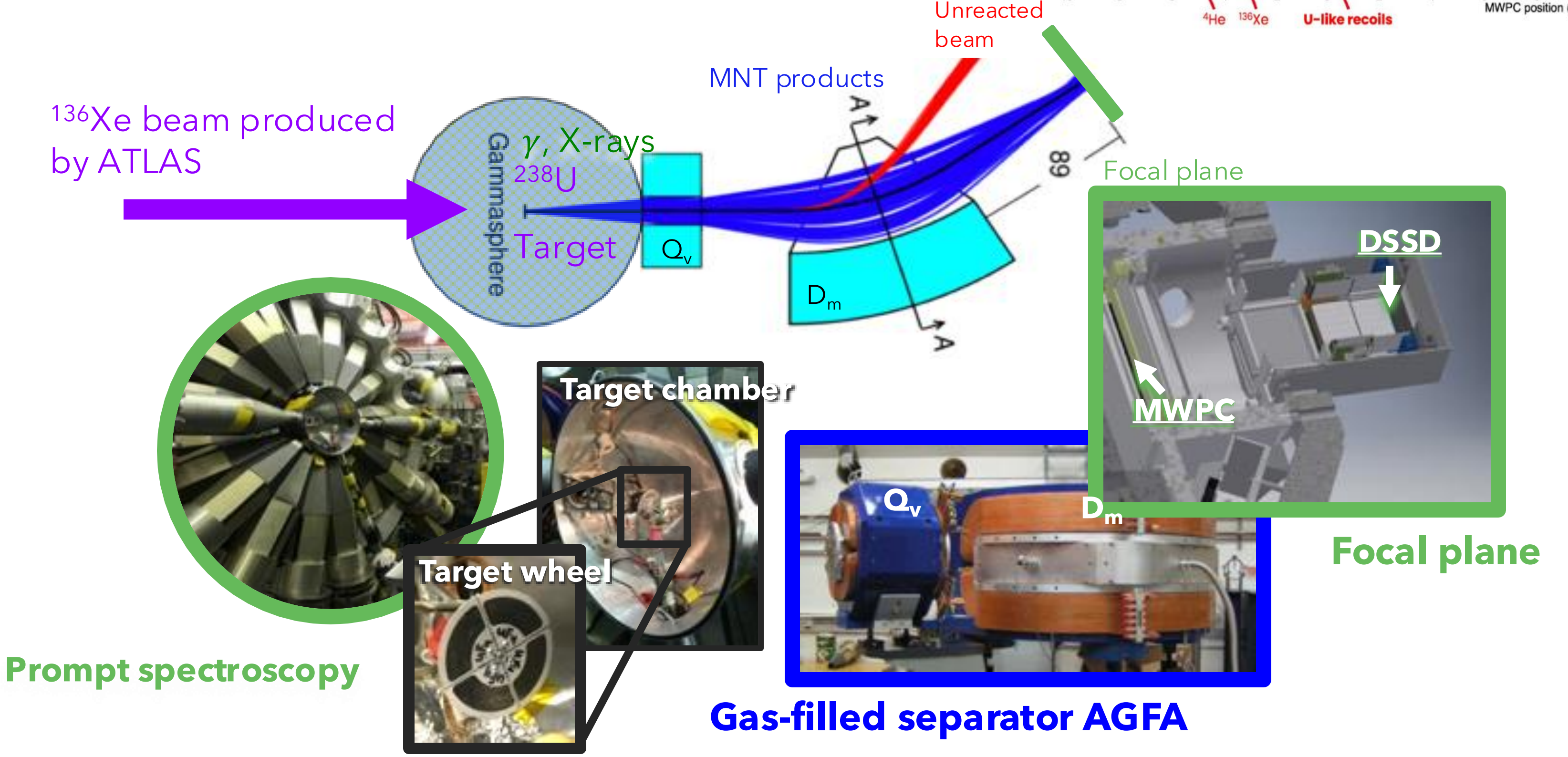

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^{240}U : From identification to measurement

Poisson statistics :

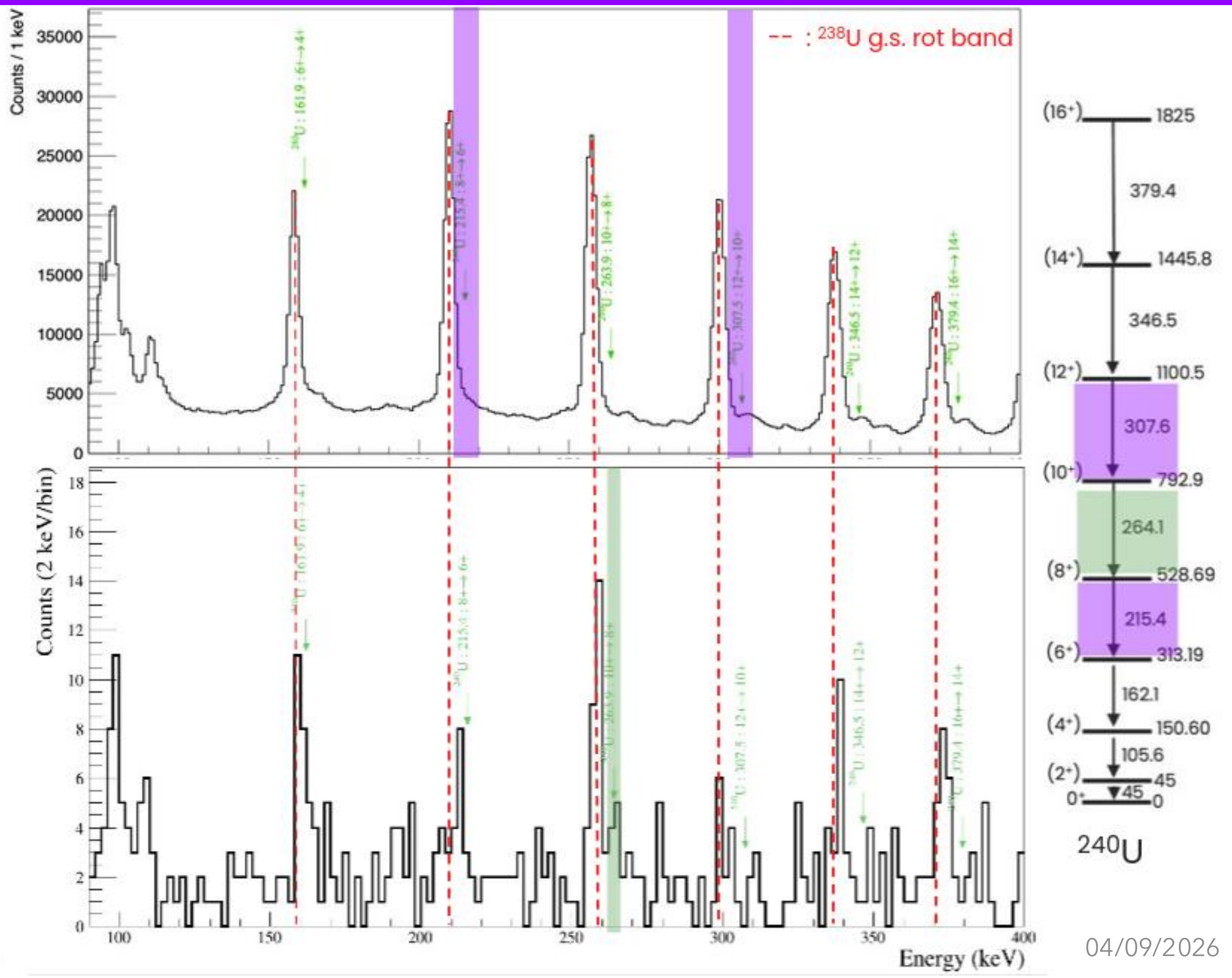
- Probability that the peak is not completely made of background :

  99,93%

- True number of counts in a 95% confidence interval using a Bayesian approach* :

  [2.78 , 13.22]

*: *obtained distribution propagated through the calculation with MC simulations*



Cross-sections extraction

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

$N_{produced}$:

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

N_{beam} :

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

N_{target} :

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

Cross-sections extraction

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

Isotope	α_1	α_2	α_3	$N_{\gamma 2}$	ε_1 (%)	ε_2 (%)	ε_3 (%)	Γ_1	Γ_3	N_{prod}	$\sigma(\mu\mathrm{b})$ (95% C.L.)
^{240}U	0.569(8)	0.282(4)	0.174(3)	7.7	9.6(7)	8.9(6)	8.3(5)	0.981(6)	0.963(5)	81767	$92\pm^{129}_{57}$
^{236}U(rot)	0.598(9)	0.297(5)	0.183(3)	6.0	9.6(8)	9.0(6)	8.4(5)	0.655(12)	0.408(7)	255363	$274\pm^{65}_{25}$
^{236}U(oct)	0.764(11)	0.363(5)	0.144(2)	4.3	9.8(9)	9.2(6)	8.0(5)	0.964(14)	0.960(4)	77050	$64\pm^{122}_{46}$
^{234}U	2.14(3)	0.734(11)	0.367(6)	5.8	9.7(12)	9.2(8)	8.6(6)	0.990(6)	0.988(3)	237651	$183\pm^{47}_{13}$
^{232}U	0.546(8)	0.279(4)	0.177(3)	2.0	9.5(7)	8.9(6)	8.3(5)	0.627(9)	0.802(9)	45474	$54\pm^{137}_{46}$

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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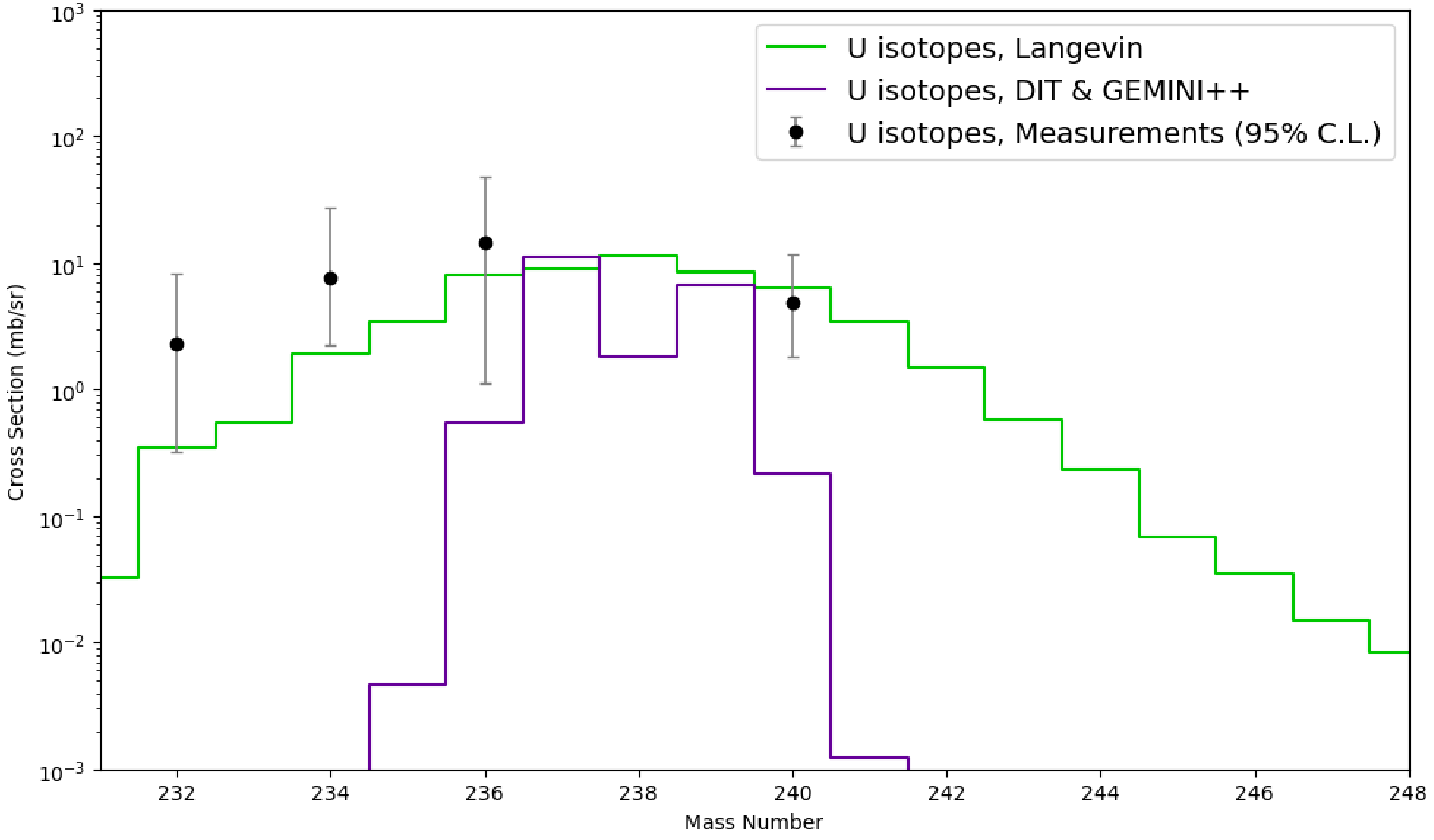

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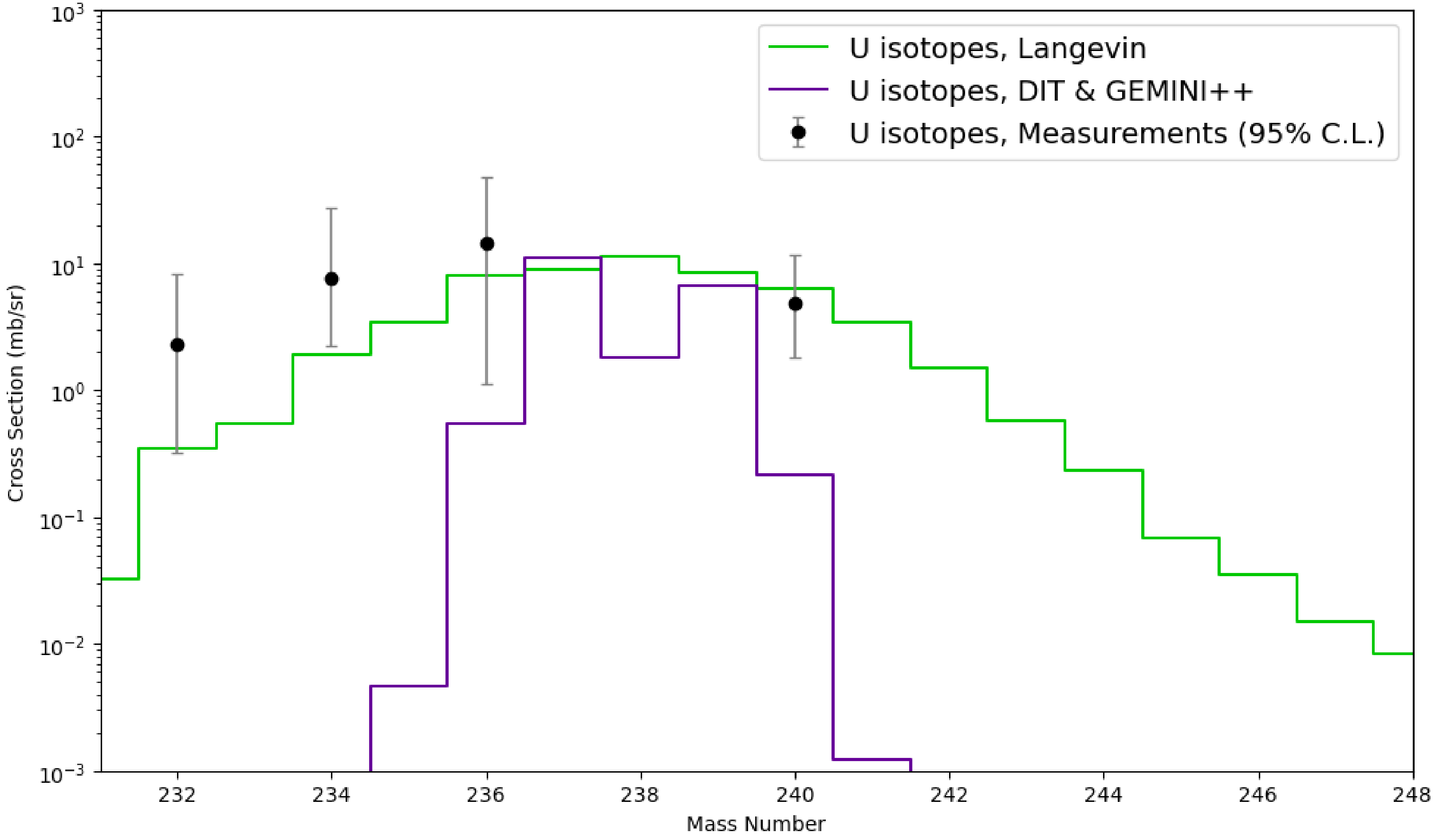

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completely fails for this physics case

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overall agreement with measurements

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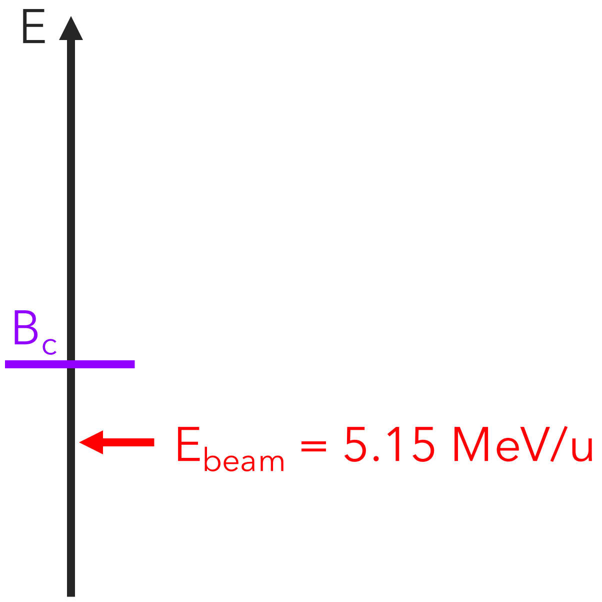
- Purely spherical nuclei
  → B_C = 5.29 MeV/u



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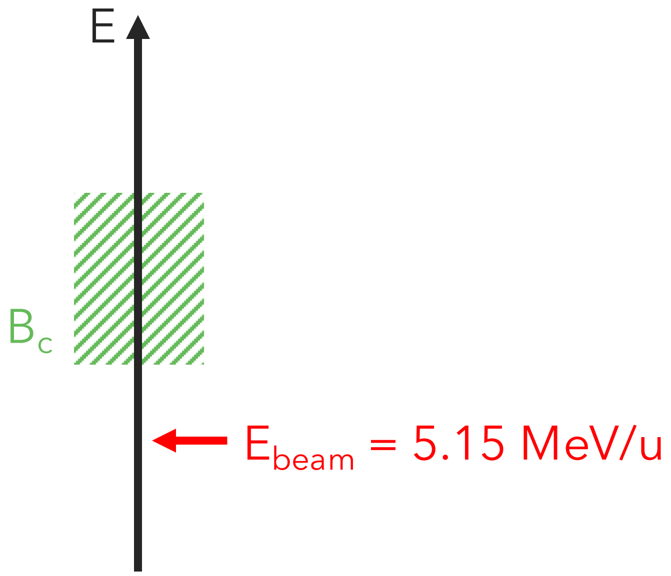
Langevin equations model :

- Deformations & relative orientations accounted for
  → $B_C \in$ [5.28, 5.68] MeV/u



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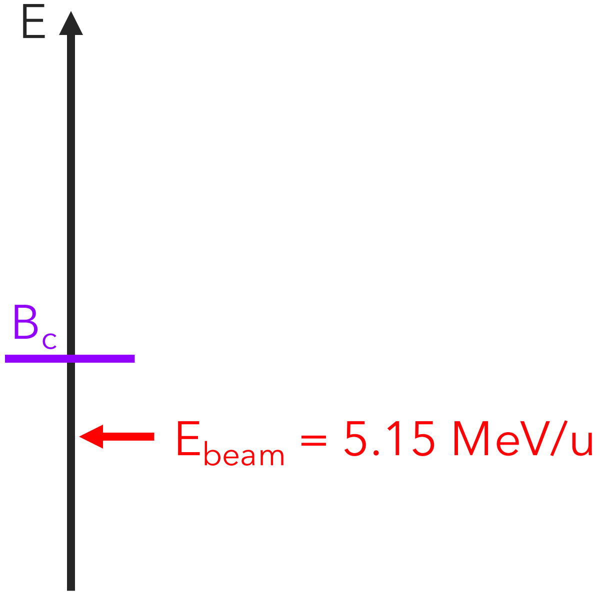
Cross-sections : Uranium isotopes at 5.15 MeV/u

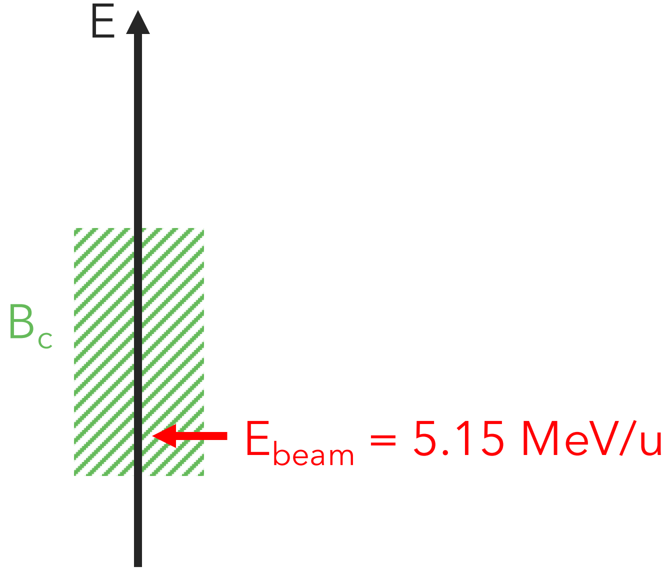
DIT & GEMINI++ :

- Purely spherical nuclei
  → B_C = 5.29 MeV/u
- Statical nuclear properties during the interaction



Langevin equations model :

- Deformations & relative orientations accounted for
  → $B_C \in [5.28, 5.68]$ MeV/u
- Dynamical deformation of nuclei while approaching



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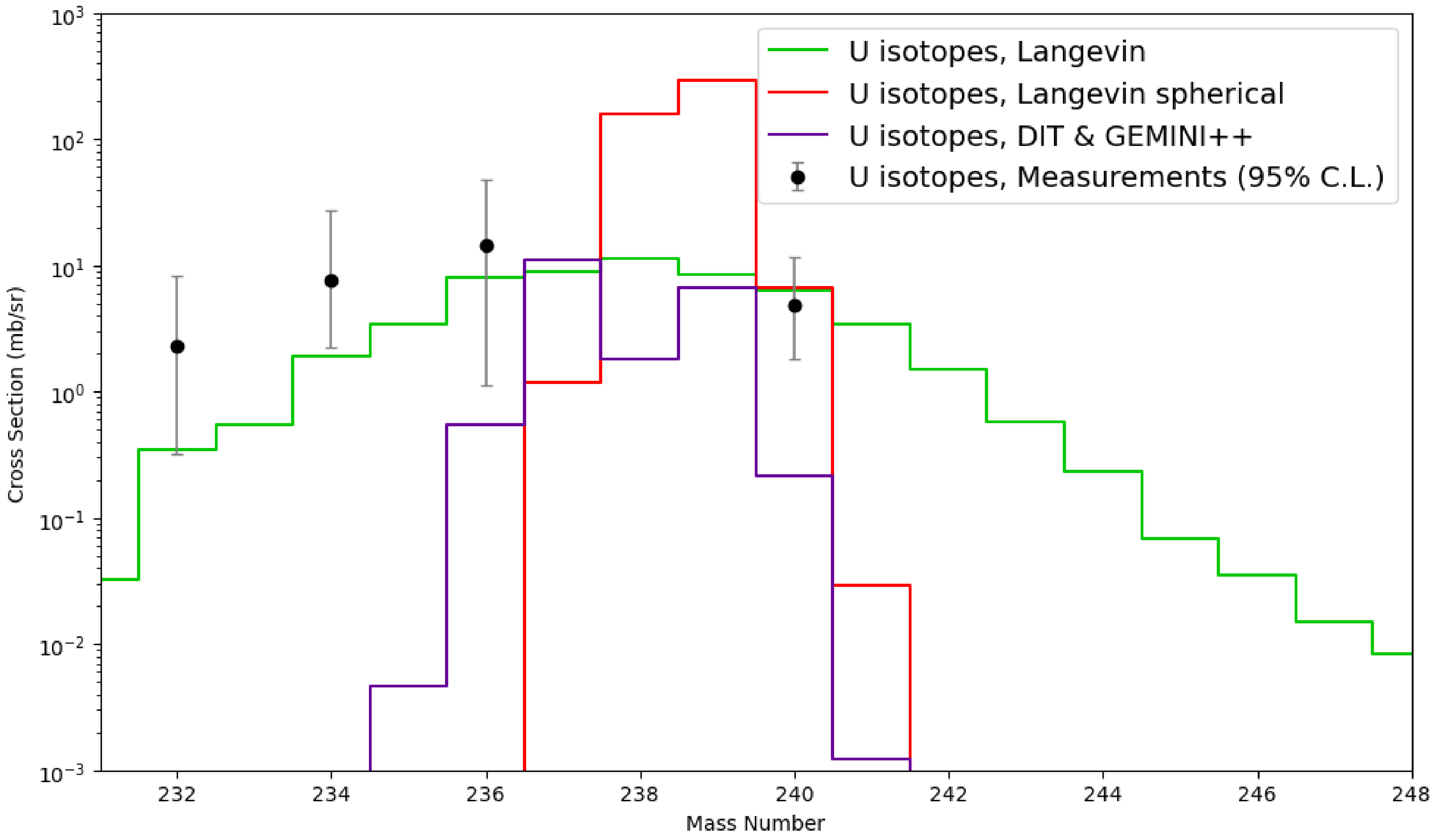

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Langevin equations model:

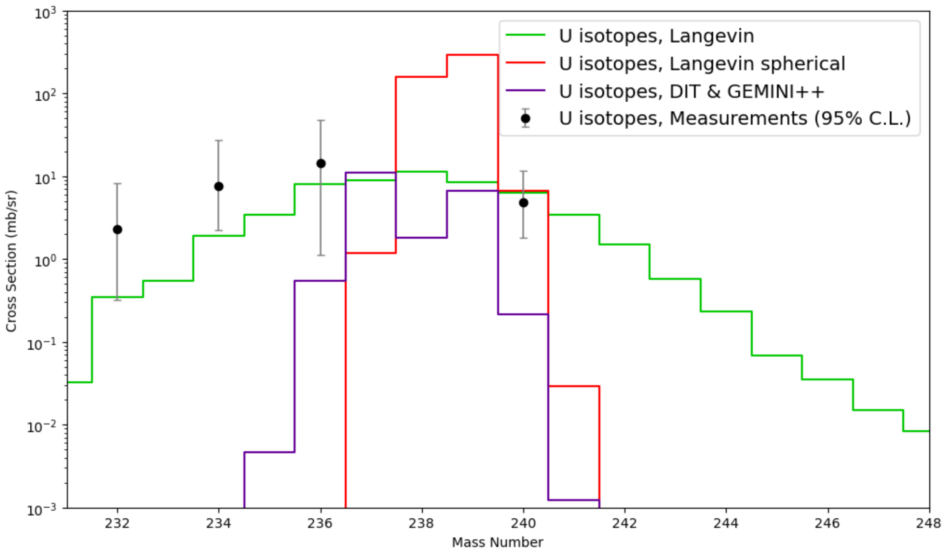
overall agreement with measurements

Signature of the dynamical deformation of nuclei

Conclusion

Successes :

- MNT neutron-transfer channels observed using $^{136}Xe + ^{238}U$
- Extracted cross-sections confirm Langevin equations model predictions
- Dynamical deformation of the nuclei indirectly observed



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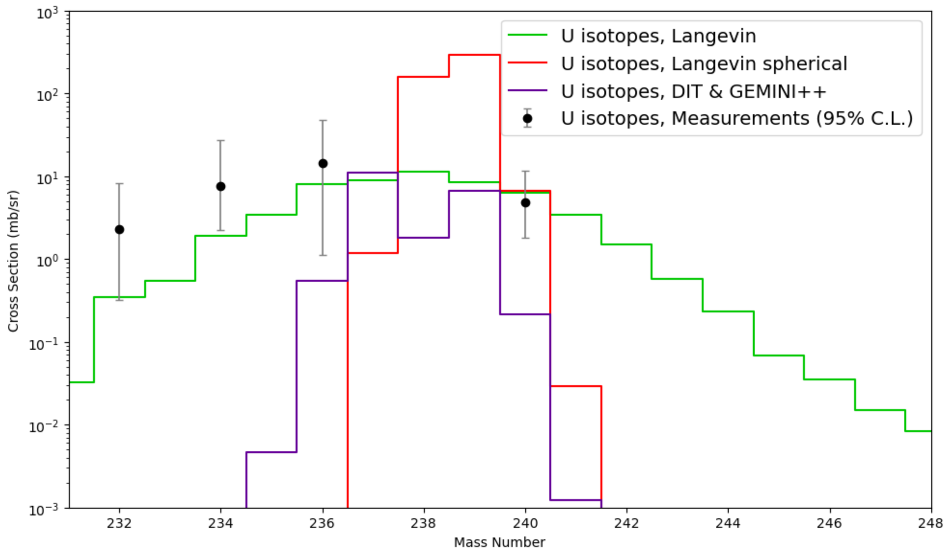


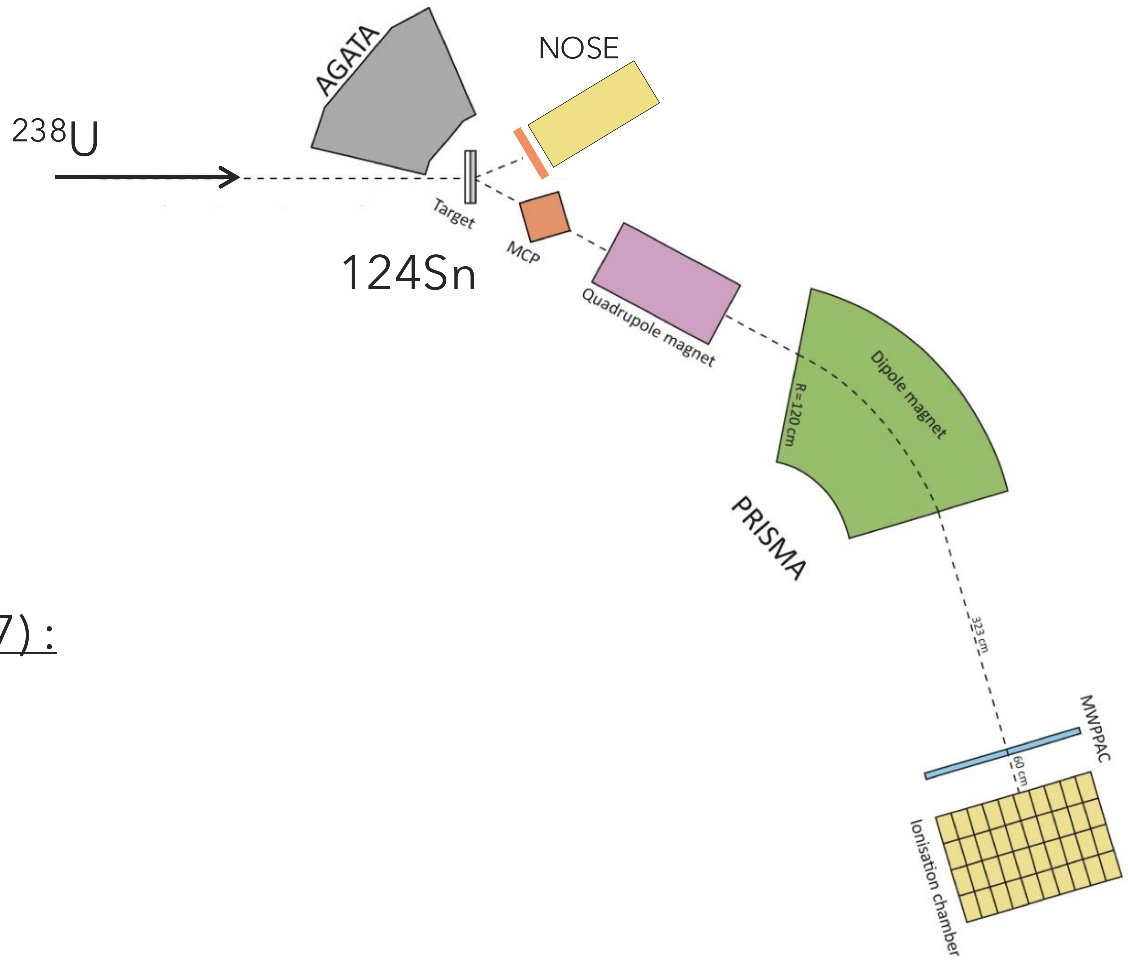
Limitations :

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

Outlooks : next experiments

^{238}U + ^{124}Sn at 6.2 MeV/u with AGATA at LNL (July 2026) :

M. Coguic & L. Busak



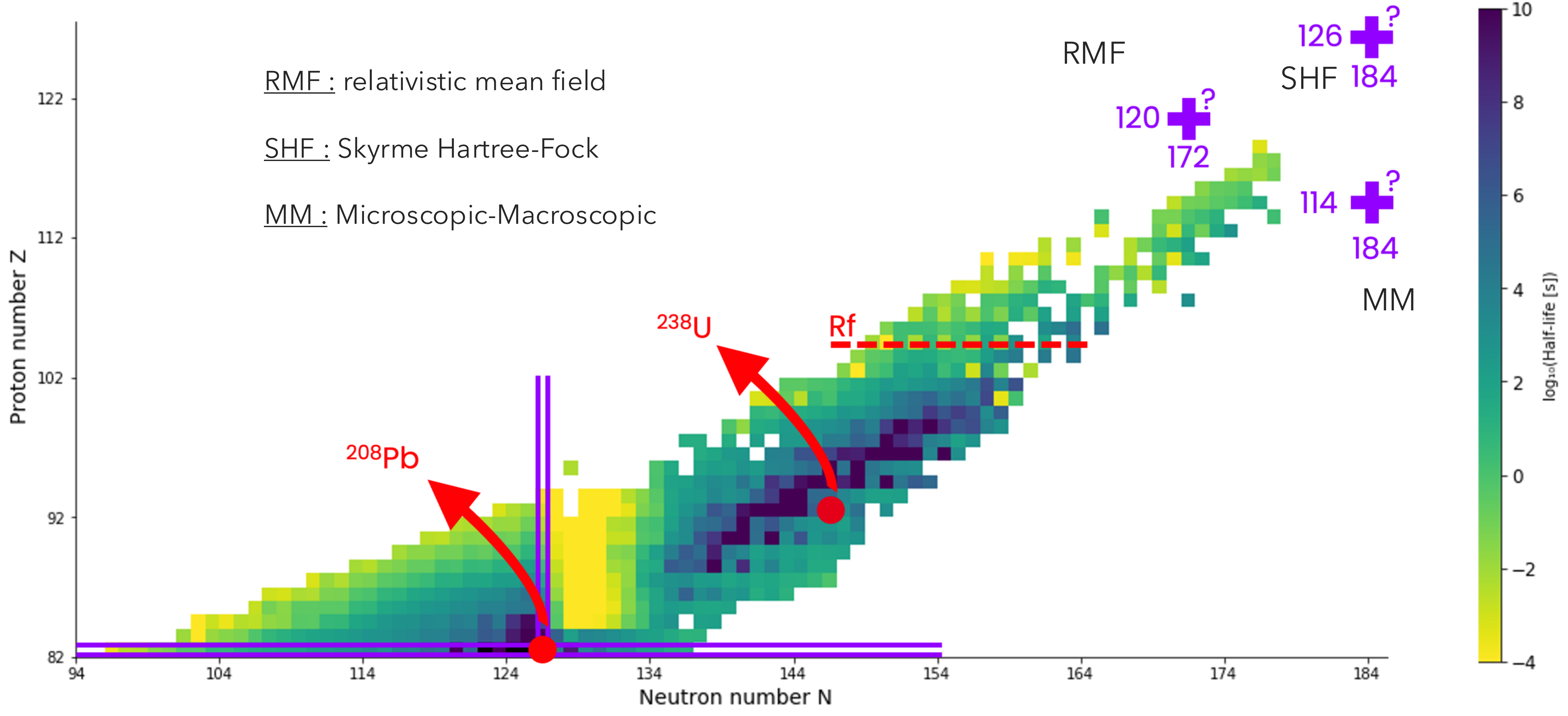
- Isotopic identification of Sn-like in Prisma
- Correlated U-like partner in NOSE
- γ spectroscopy of both with AGATA

^{232}Th + ^{96}Zr at 6 MeV/u with VAMOS at GANIL (Spring 2027) :

- Same principle
- Focus on the deep-inelastic part of the reaction

Thank you for your attention

Island of stability



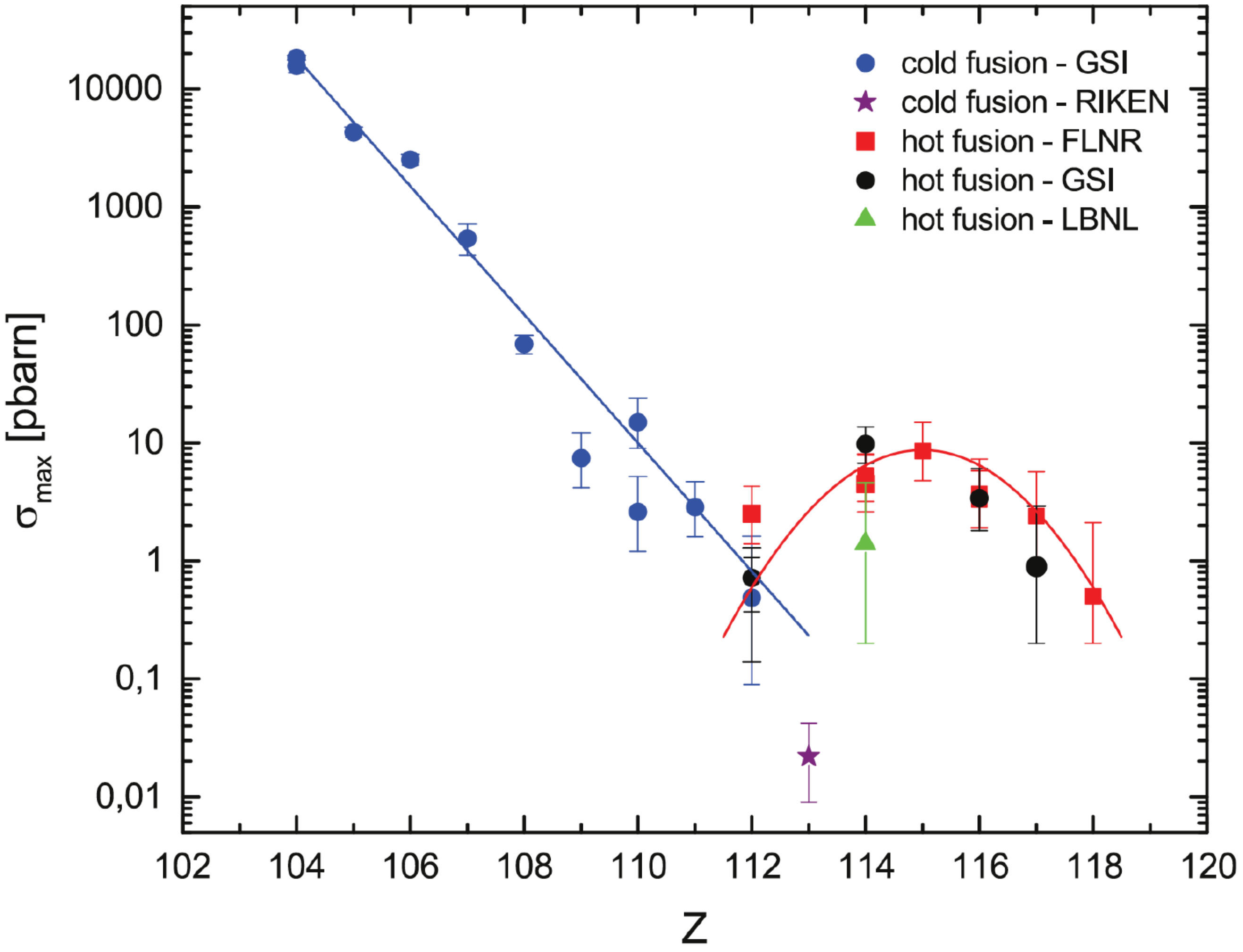
Hot & cold fusion

Cold Fusion

Complementary + ^{208}Pb

Doubly magic

→ E* ~ 10 MeV



D. Ackermann & Ch. Theisen; PS (2017)

Hot Fusion

^{48}Ca + Complementary:

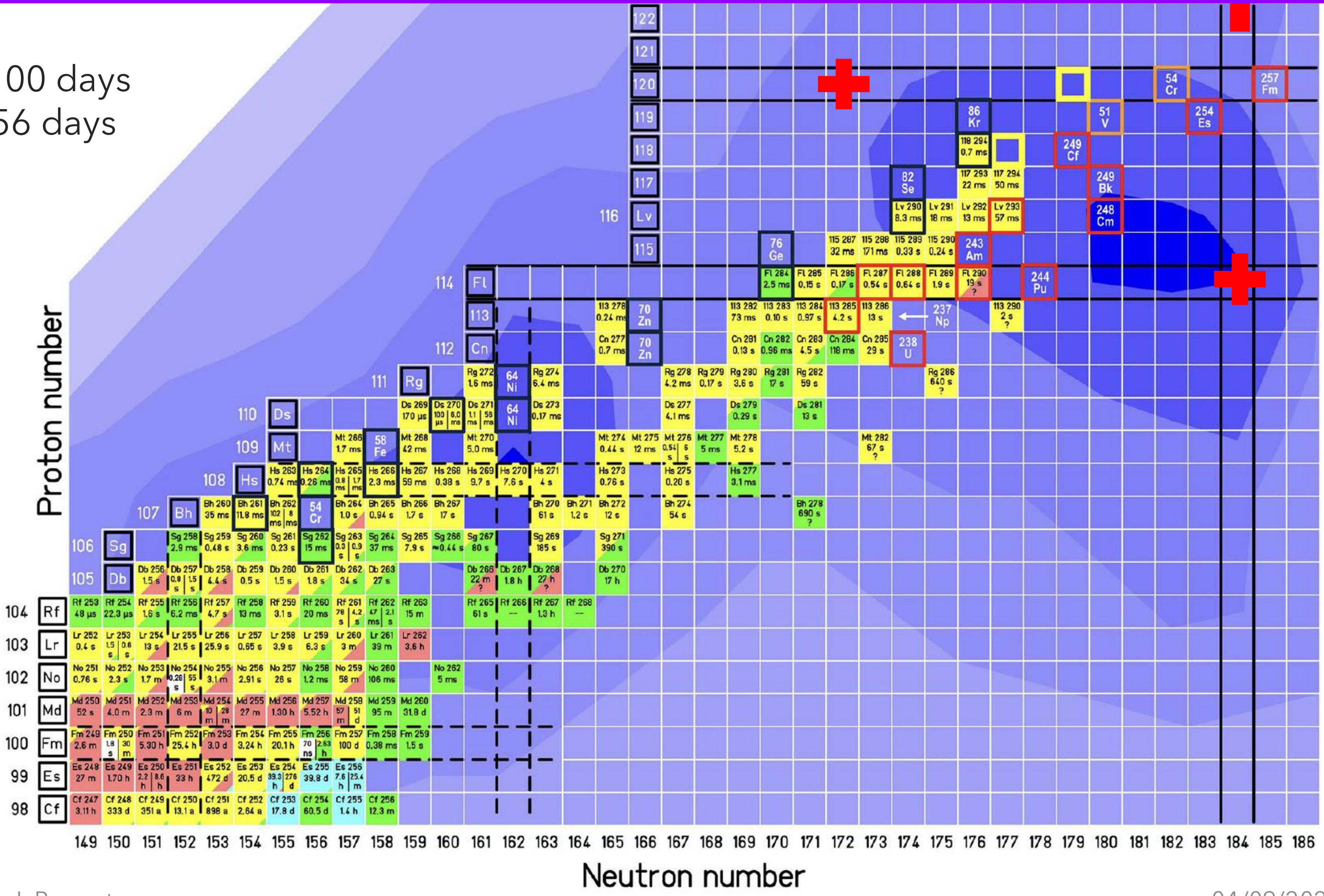
Doubly magic

→ E* ~ 30 MeV

→ Higher fusion probability

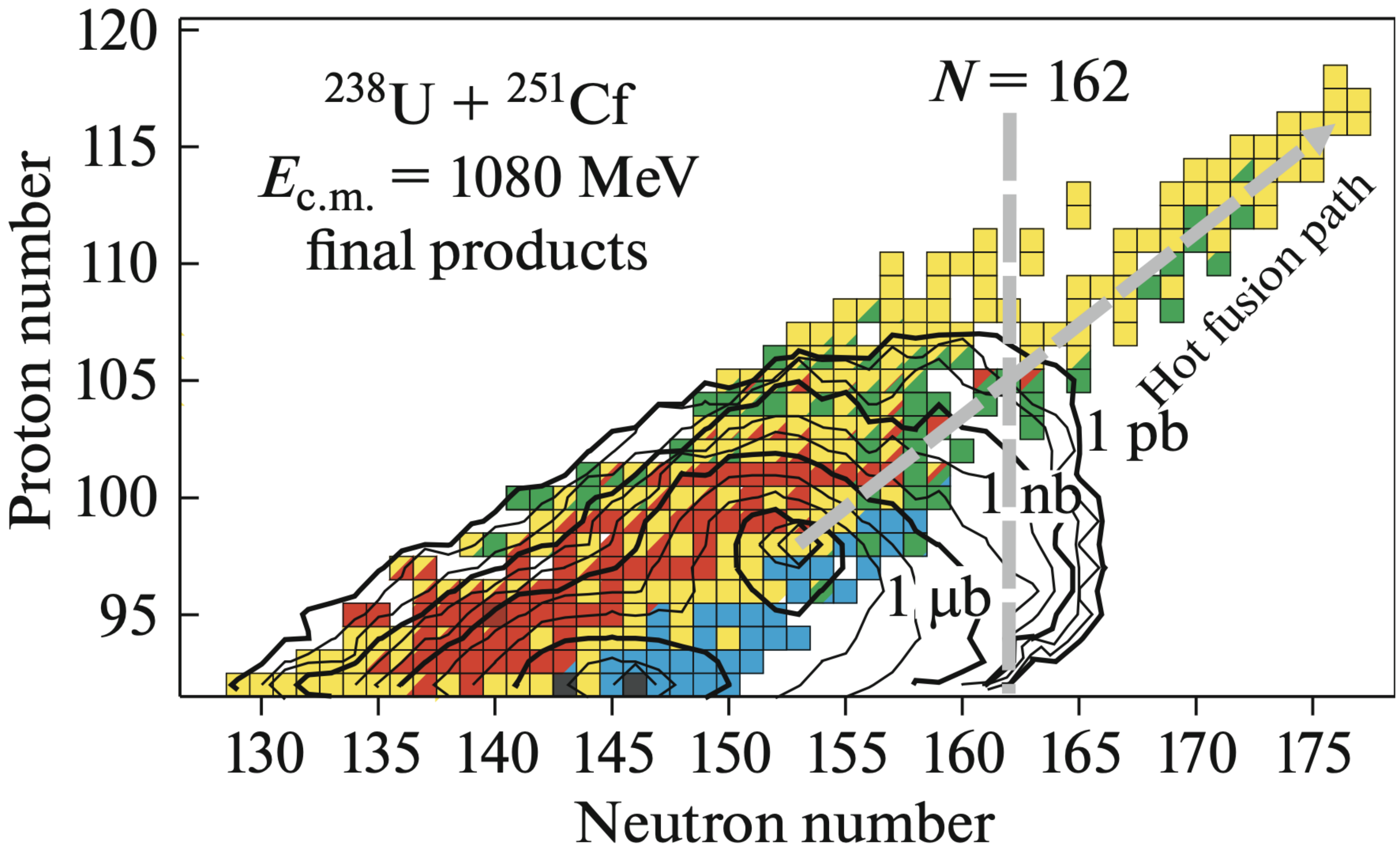
Next steps with fusion

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



S. Hofmann et. al.; EPJA (2016)

MNT predictions for SHI

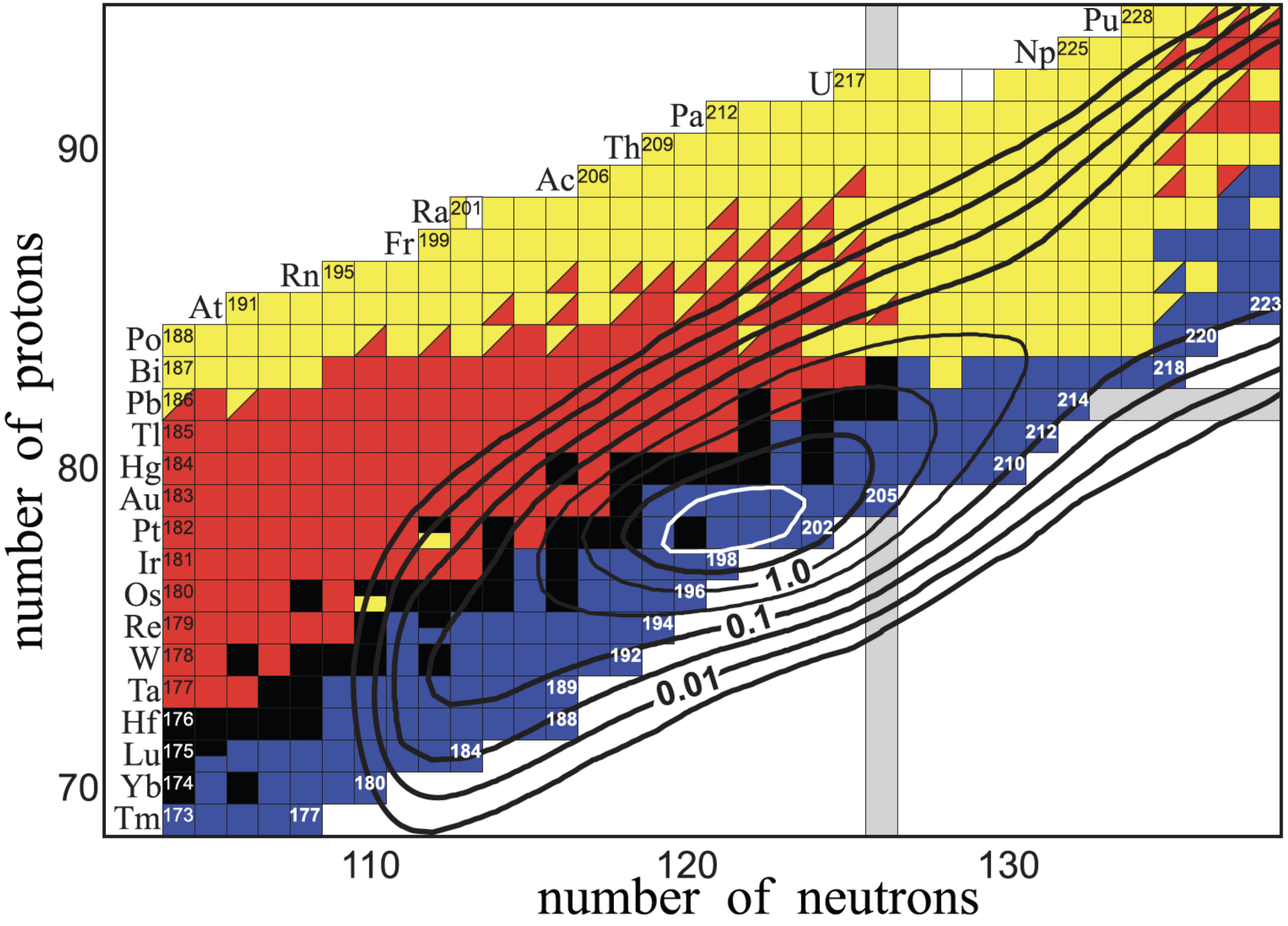


A. Karpov, V. Saiko; PPNL (2019)

MNT predictions for N = 126

9.3 % above the barrier

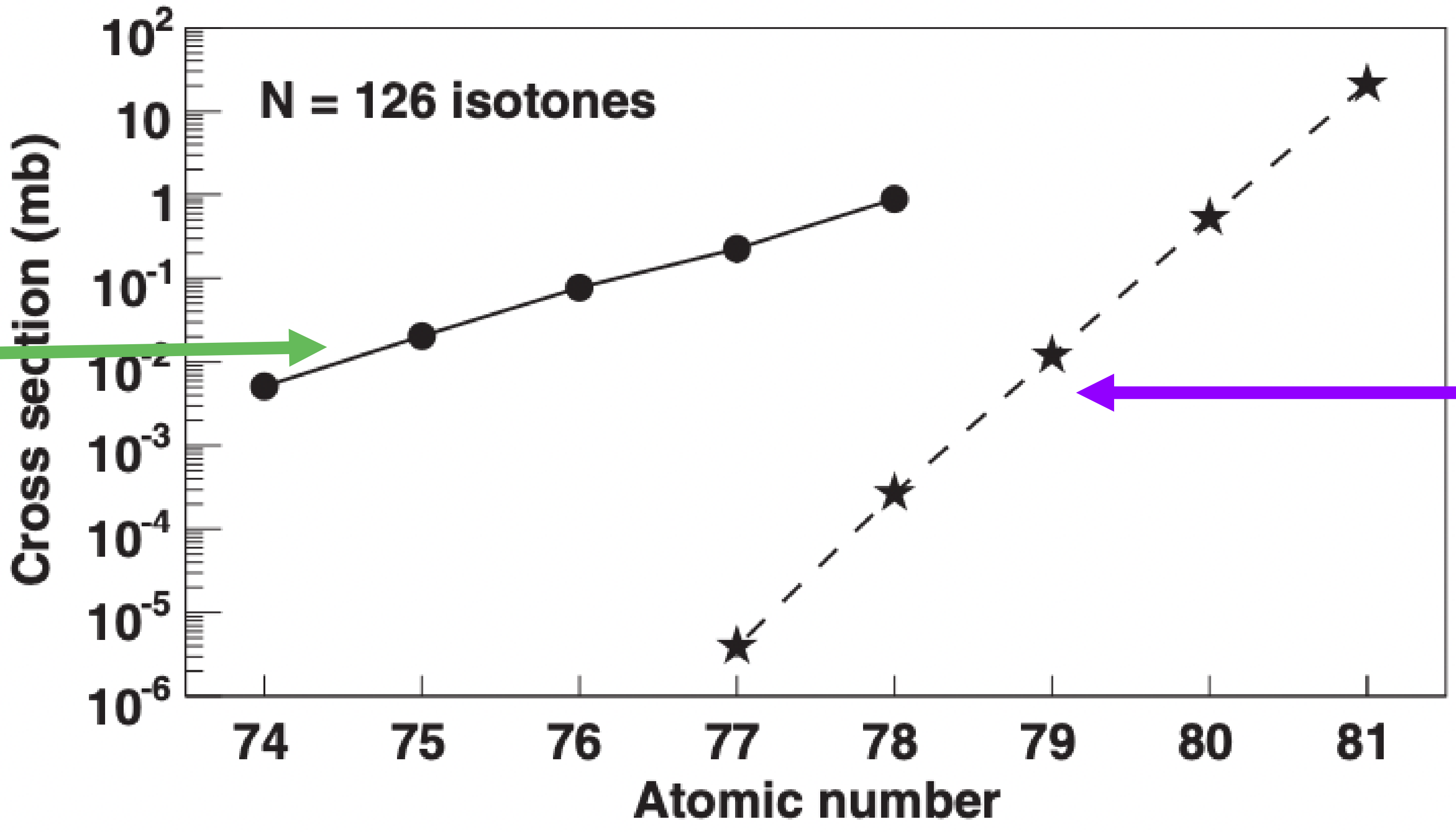
$^{238}U + ^{198}Pt$: 6.55 MeV/u



V.I. Zagrebaev, W. Greiner; PRC 87 (2013)

MNT vs fragmentation

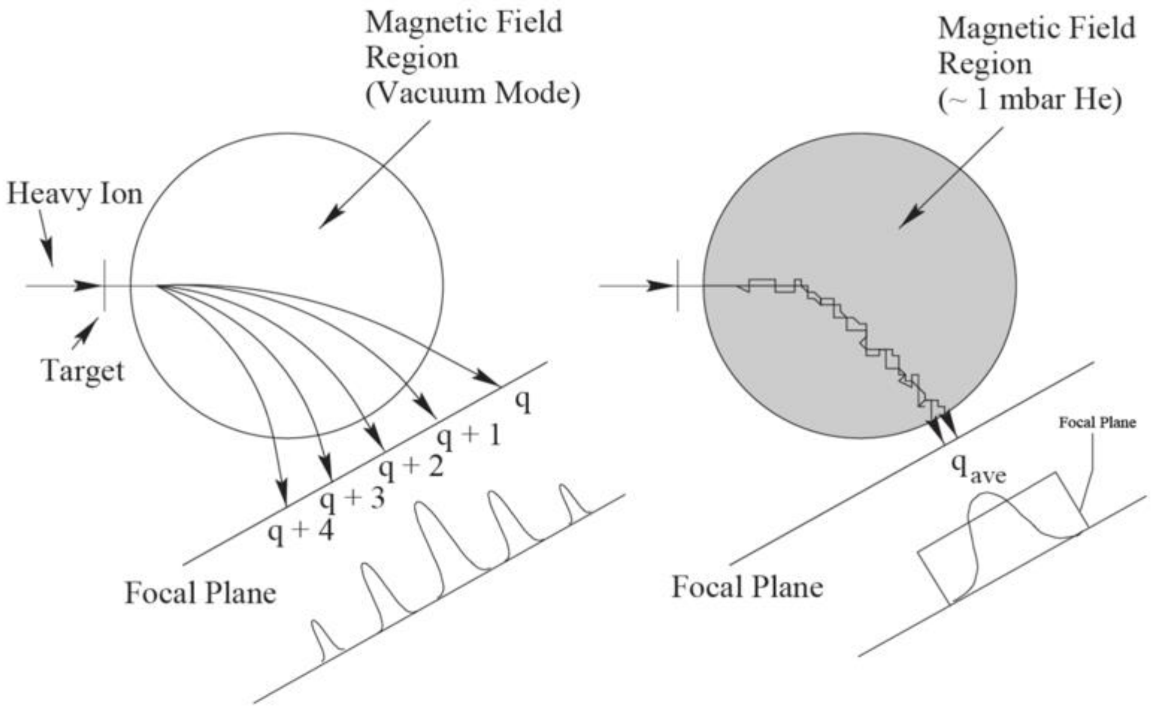
MNT : $^{136}Xe + ^{198}Pt$
~ 8 MeV / u
59 % above barrier



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

Fragmentation : ^{208}P
+ ^{9}Be
1 GeV/u

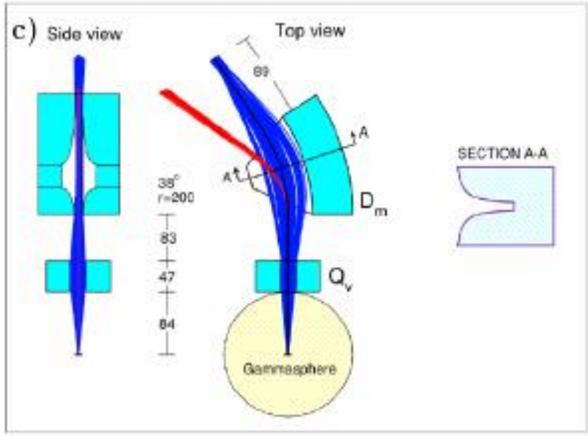
AGFA GFS

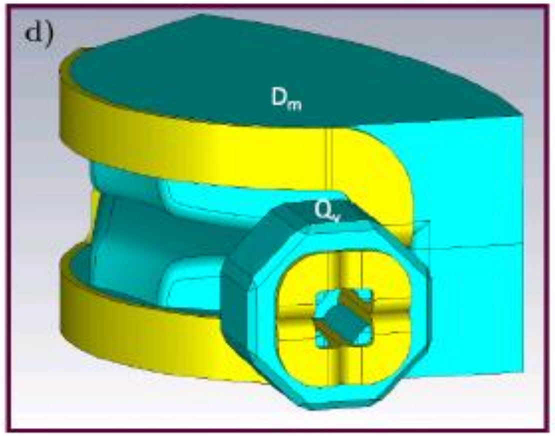


Greenlees, P; PhD thesis (University of Liverpool, 1999).

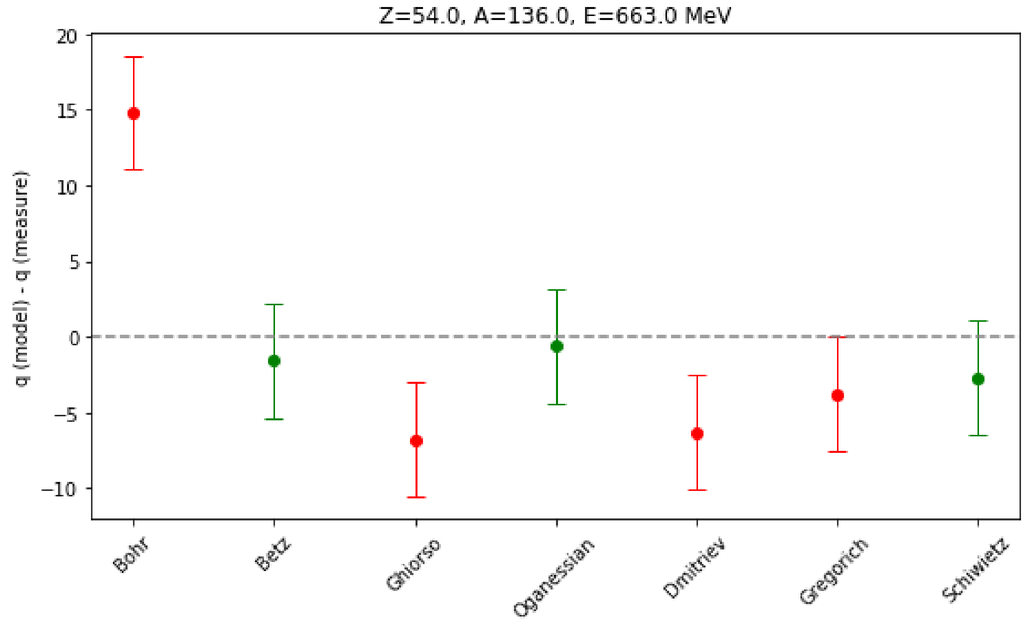
a)

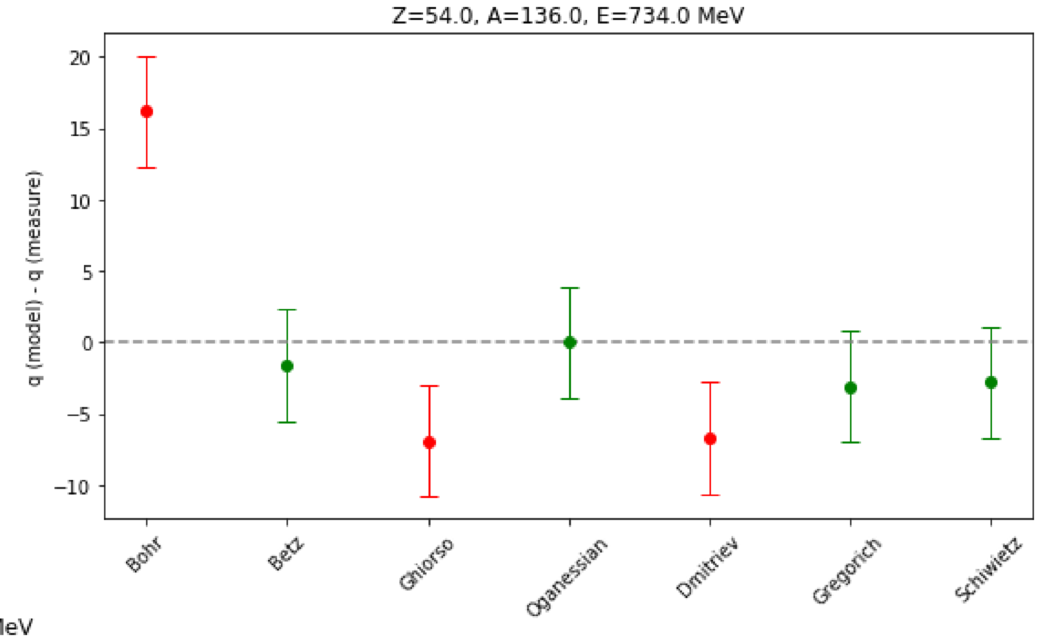
Parameter	Value	
Configuration	$Q_v D_m$	
Maximum bending power, $B\rho$	2.5 Tesla-m	
Maximum field at Q_v pole tip	1.24 Tesla	
Maximum field at D_m pole tip	1.7 Tesla	
Bend angle	38 degrees	
Target to Q_v distance	40 cm	84 cm
Solid angle, Ω	44 msr	22 msr
Target to focal plane distance	3.7 m	4.3 m

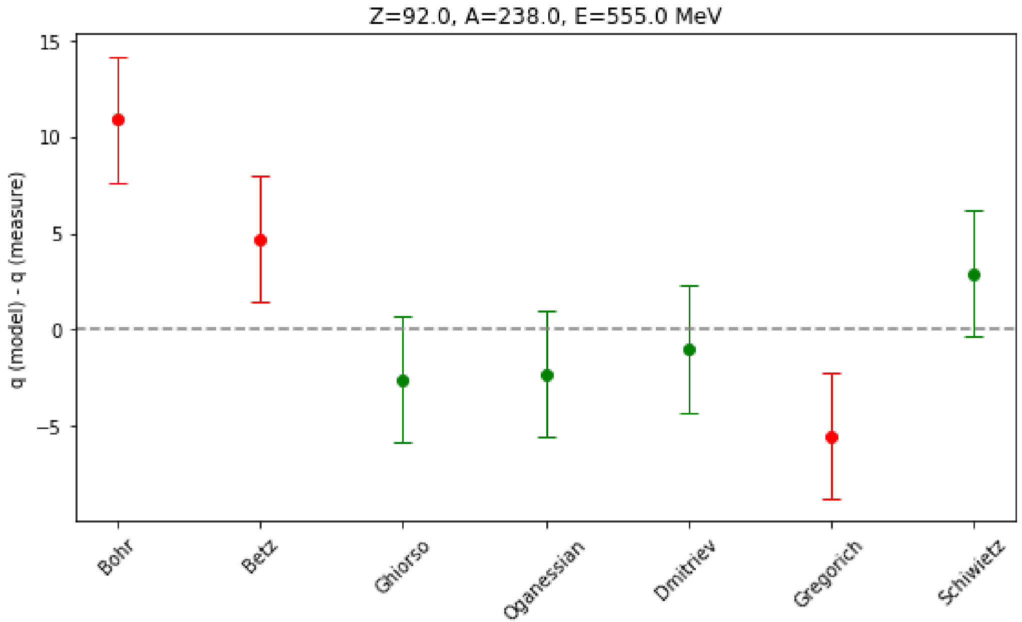




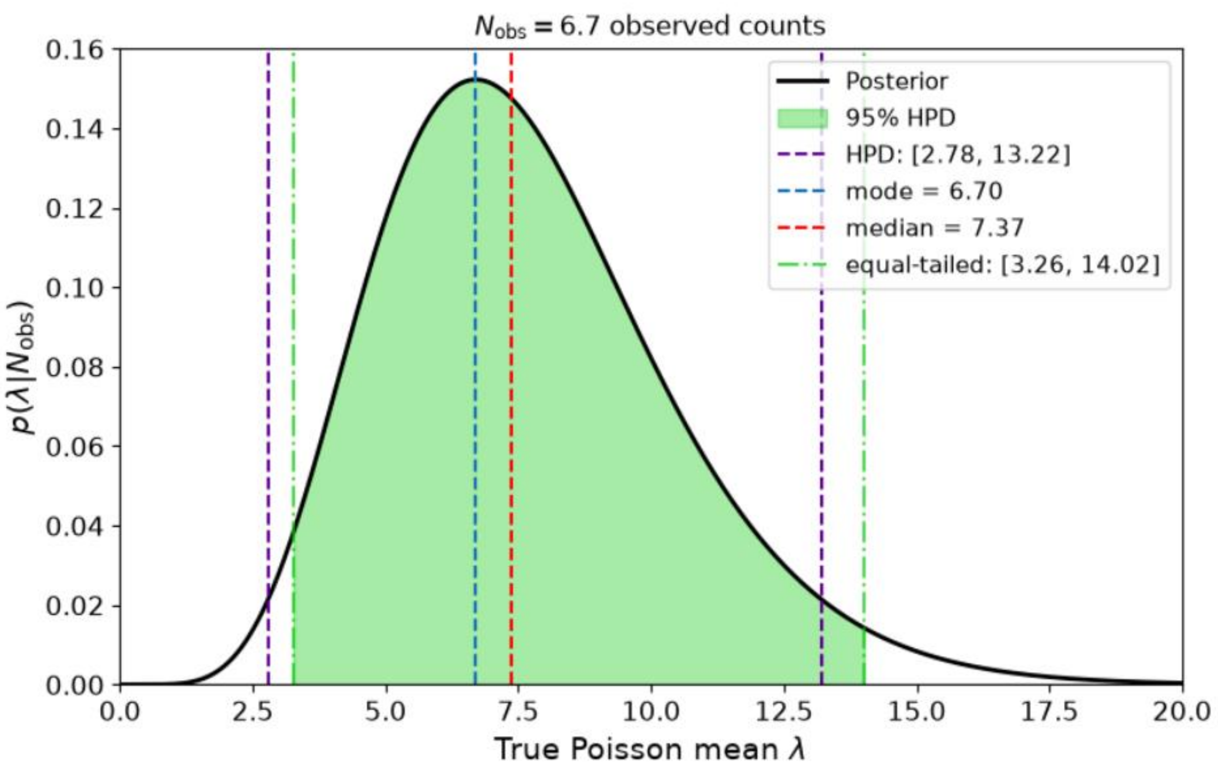
Magnetic rigidity : models

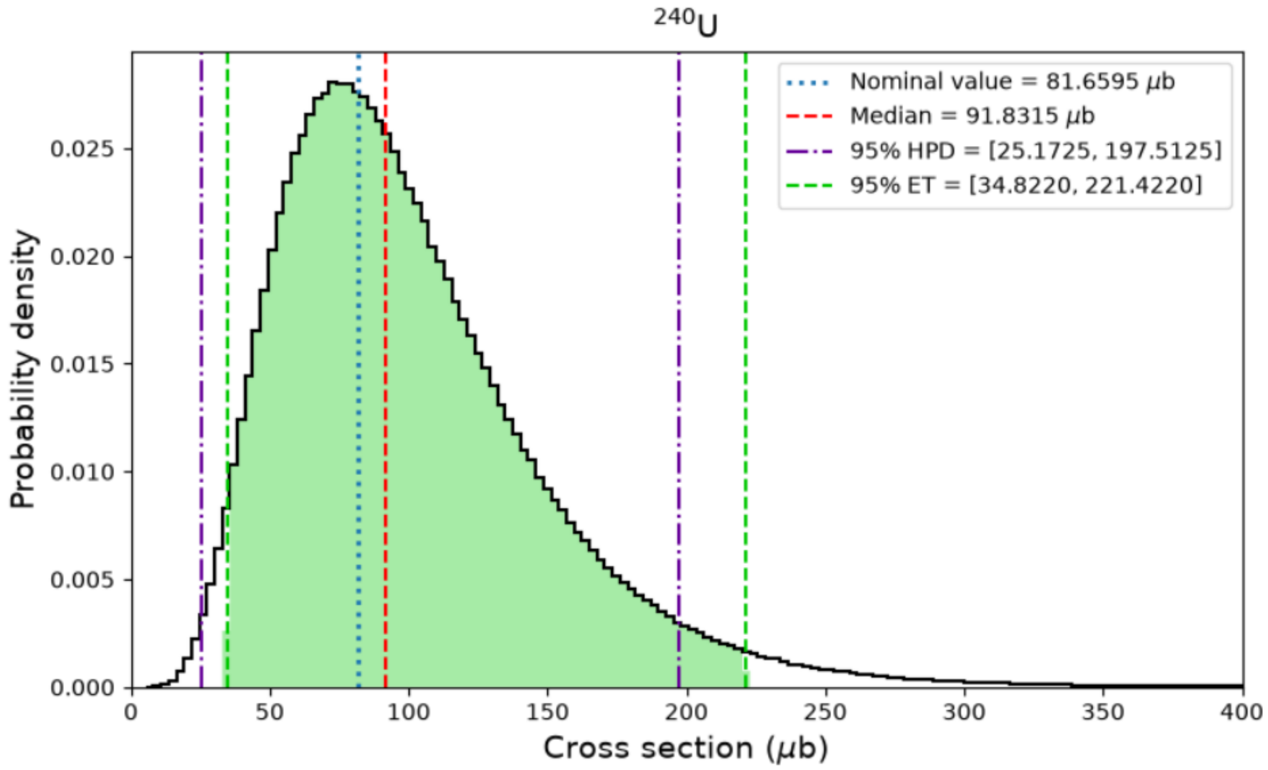




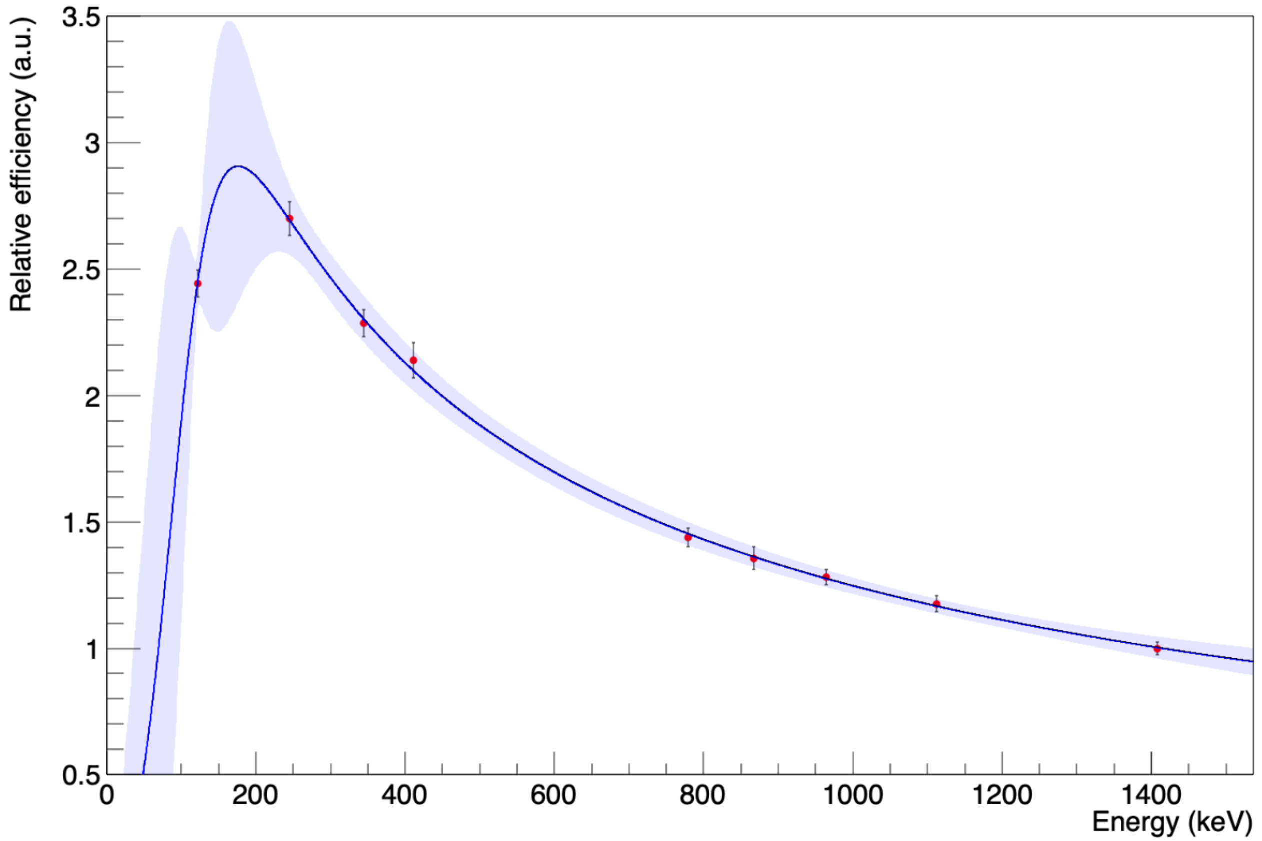


Poisson statistics





Gammasphere : efficiency

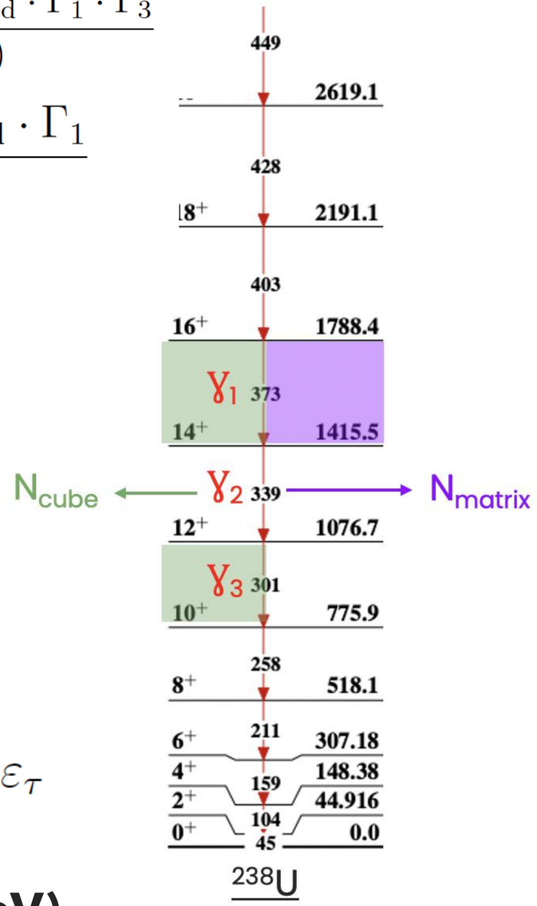


$$N_{\gamma\gamma\gamma,2} = \frac{\varepsilon_{\mathrm{GS1}} \cdot \varepsilon_{\mathrm{GS2}} \cdot \varepsilon_{\mathrm{GS3}} \cdot \varepsilon_{\mathrm{AGFA}} \cdot N_{\mathrm{produced}} \cdot \Gamma_1 \cdot \Gamma_3}{(1+\alpha_1)(1+\alpha_2)(1+\alpha_3)}$$

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

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

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



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

9.25 % (1408 KeV)

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

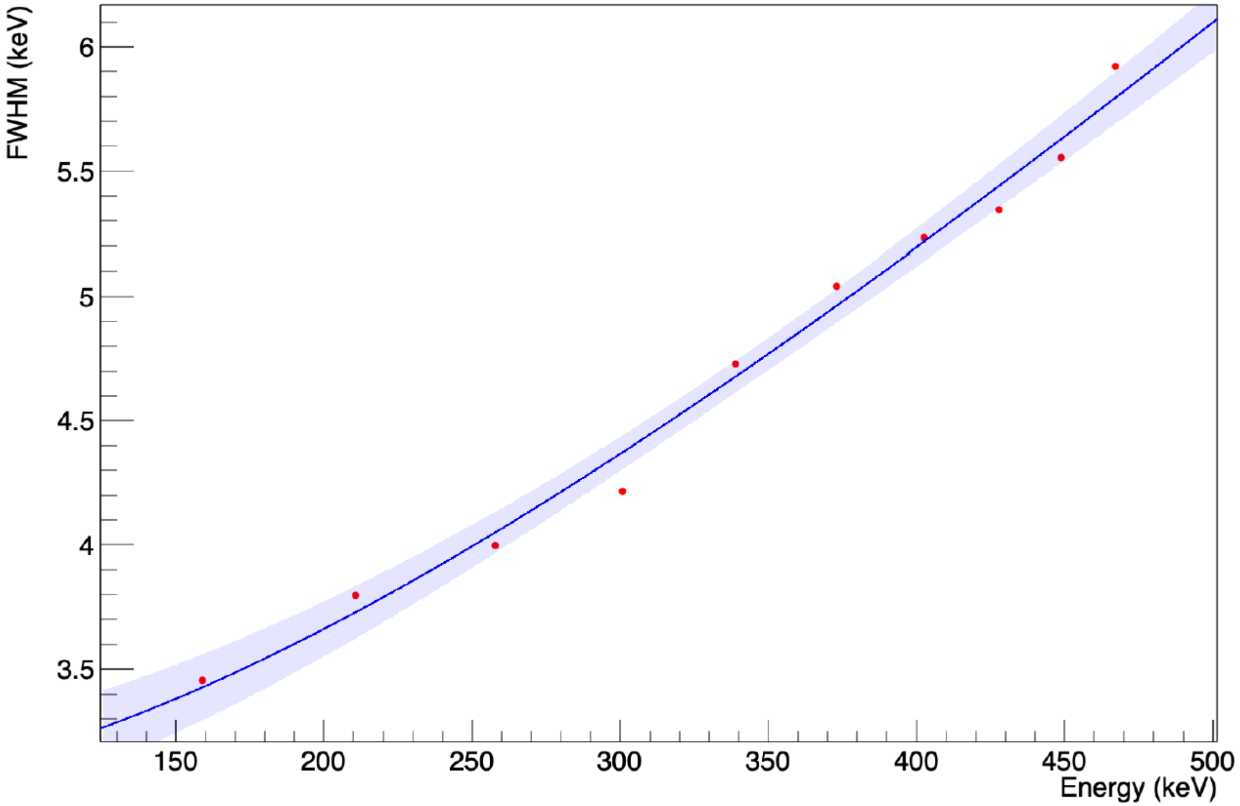
Interaction parameter between the two energy regions

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

Scaling factor K

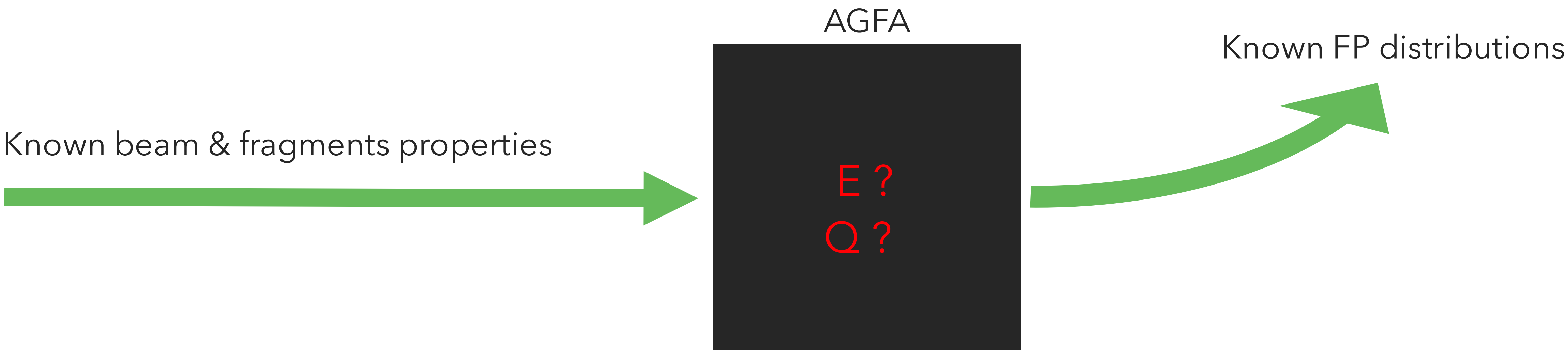
High-energy component: $y = \ln\left(\frac{E}{E_2}\right)$ with $E_2 = 1$ MeV

Gating efficiency



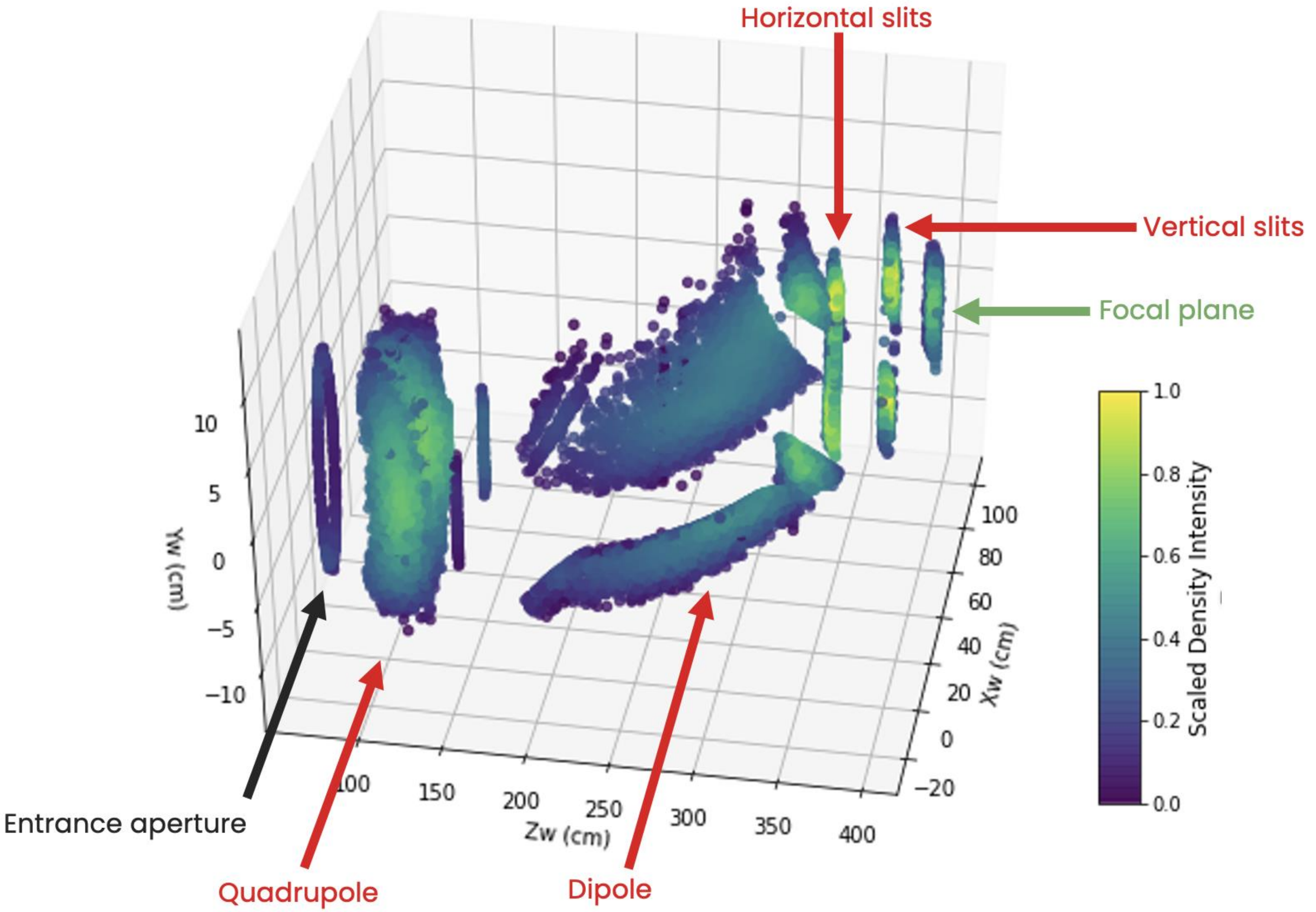
$$\Gamma = \frac{\int_{E_1}^{E_2} A \exp\left(-\frac{(E-E_0)^2}{2\sigma^2}\right) dE}{\int_0^{+\infty} A \exp\left(-\frac{(E-E_0)^2}{2\sigma^2}\right) dE} = \frac{1}{2}\left[\mathrm{erf}\left(\frac{E_2 - E_0}{\sqrt{2}\sigma}\right) - \mathrm{erf}\left(\frac{E_1 - E_0}{\sqrt{2}\sigma}\right)\right]$$

AGFA : transmission

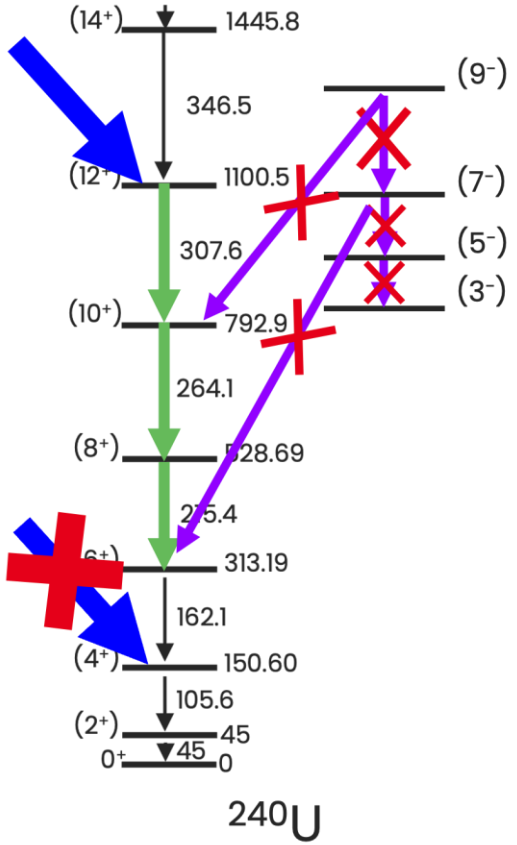


Adiabatic assumption → $(E_{start}, Q_{start}) = (E_f, Q_f)$ → Set parameters to retrieve the final distribution

Assumptions



1) Transmission evaluated with simulations



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

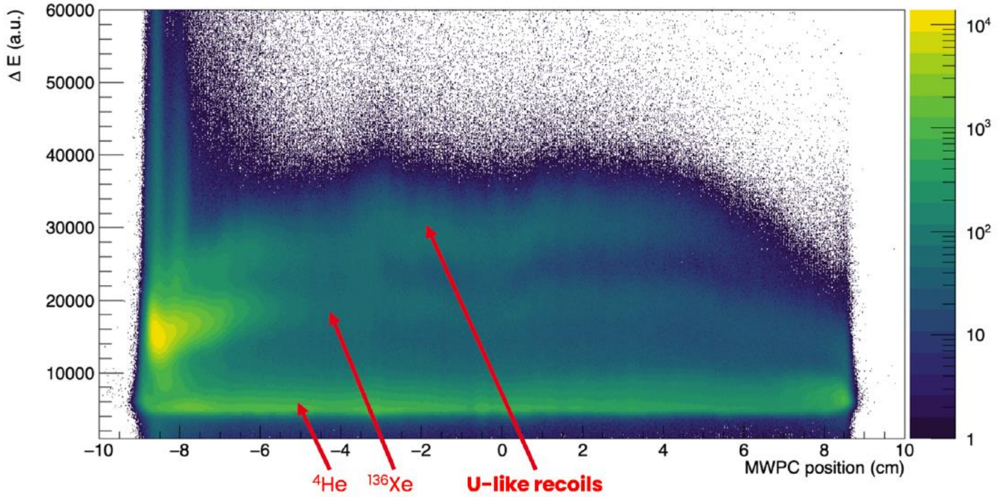
2) All products are at least excited up to the highest considered state in the triplet

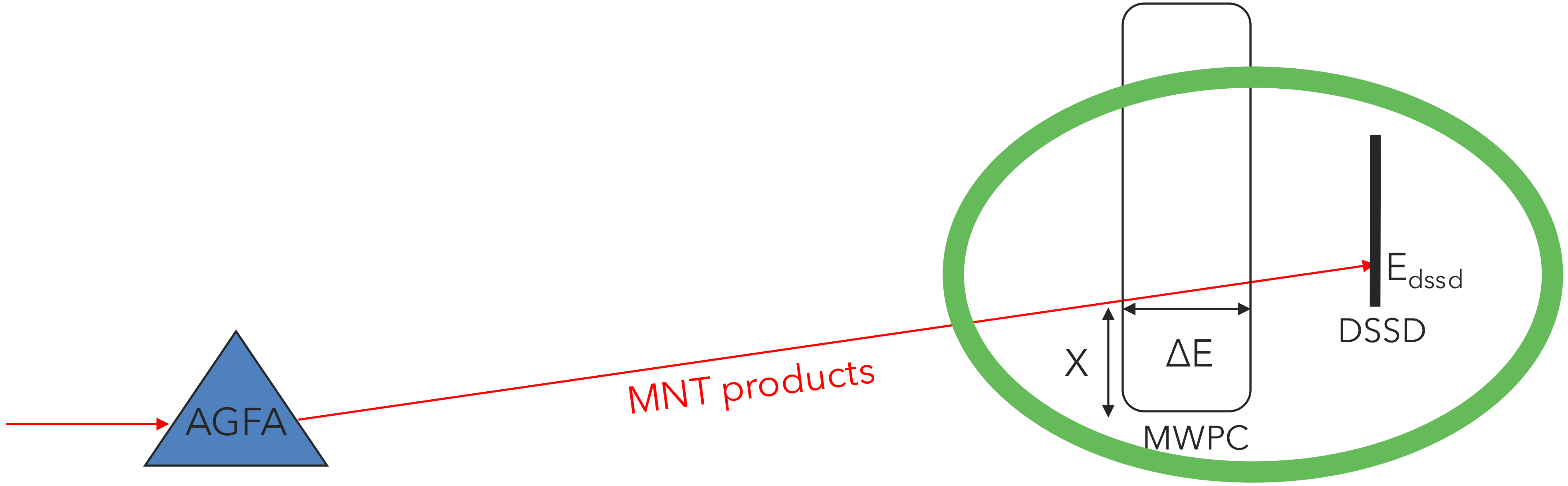
U-like nuclei selection

<u>5 observables for this study:</u>

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

Nuclei selection



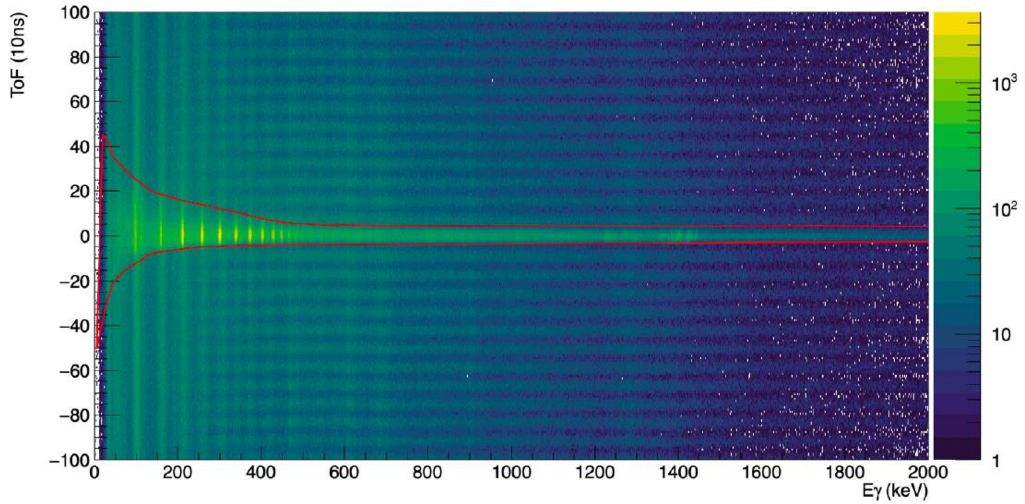


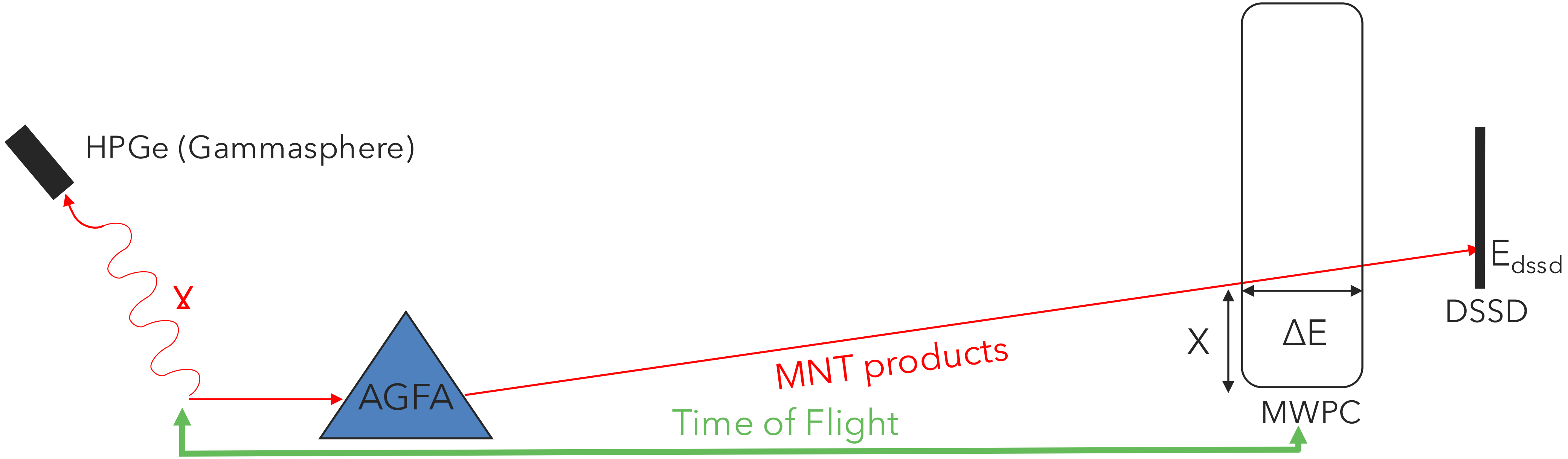
U-like nuclei selection

<u>5 observables for this study:</u>

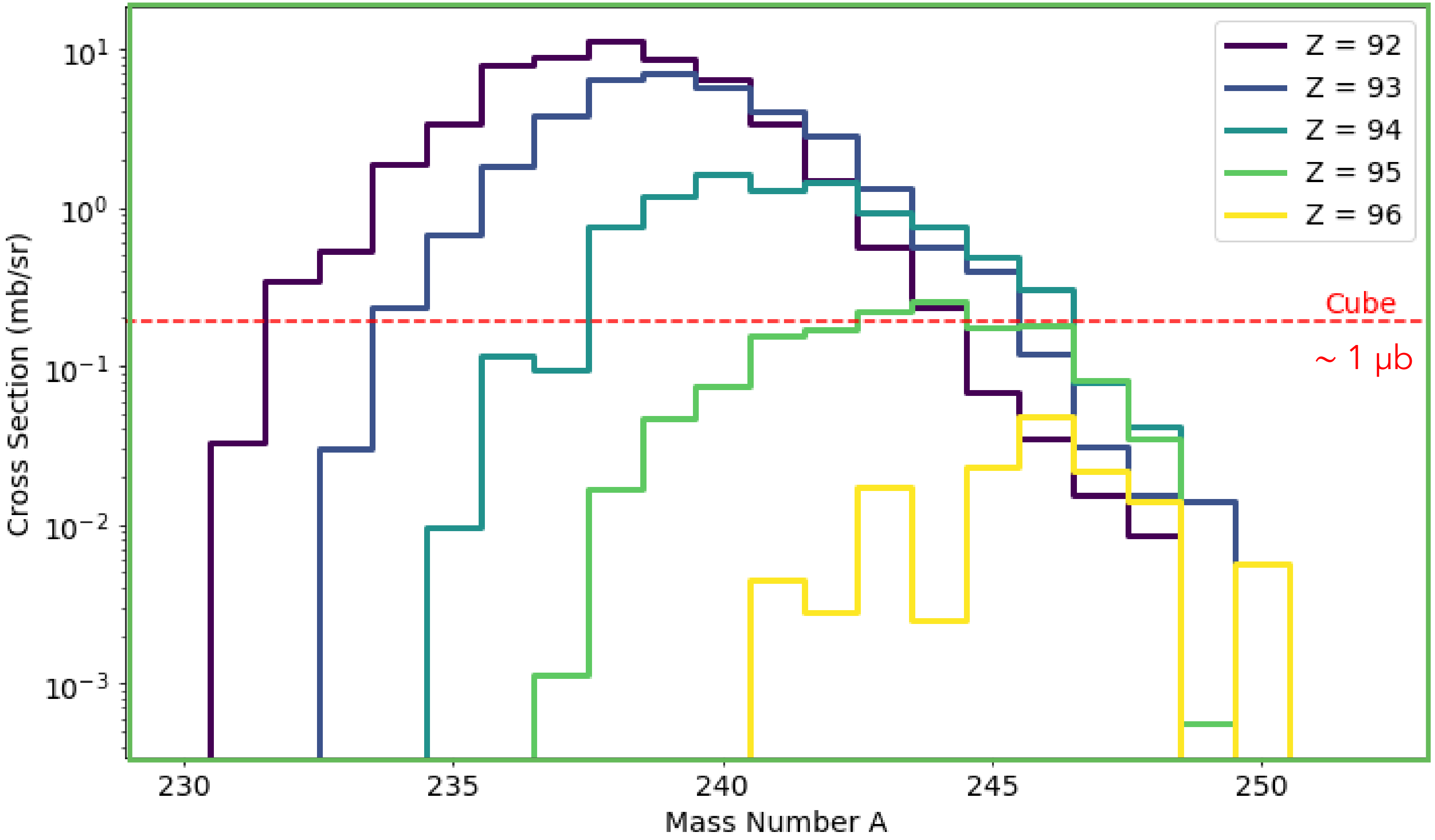
- Energy loss in the PPAC
- Horizontal Position of nuclei in the PPAC (X)
- Implantation energy in the DSSD
- Time of flight (ToF) between nuclei entering the PPAC and the ɣ-rays they emitted in Gammasphere

ɣ-rays selection





Cross-sections : Uranium isotopes at 5.15 MeV/u



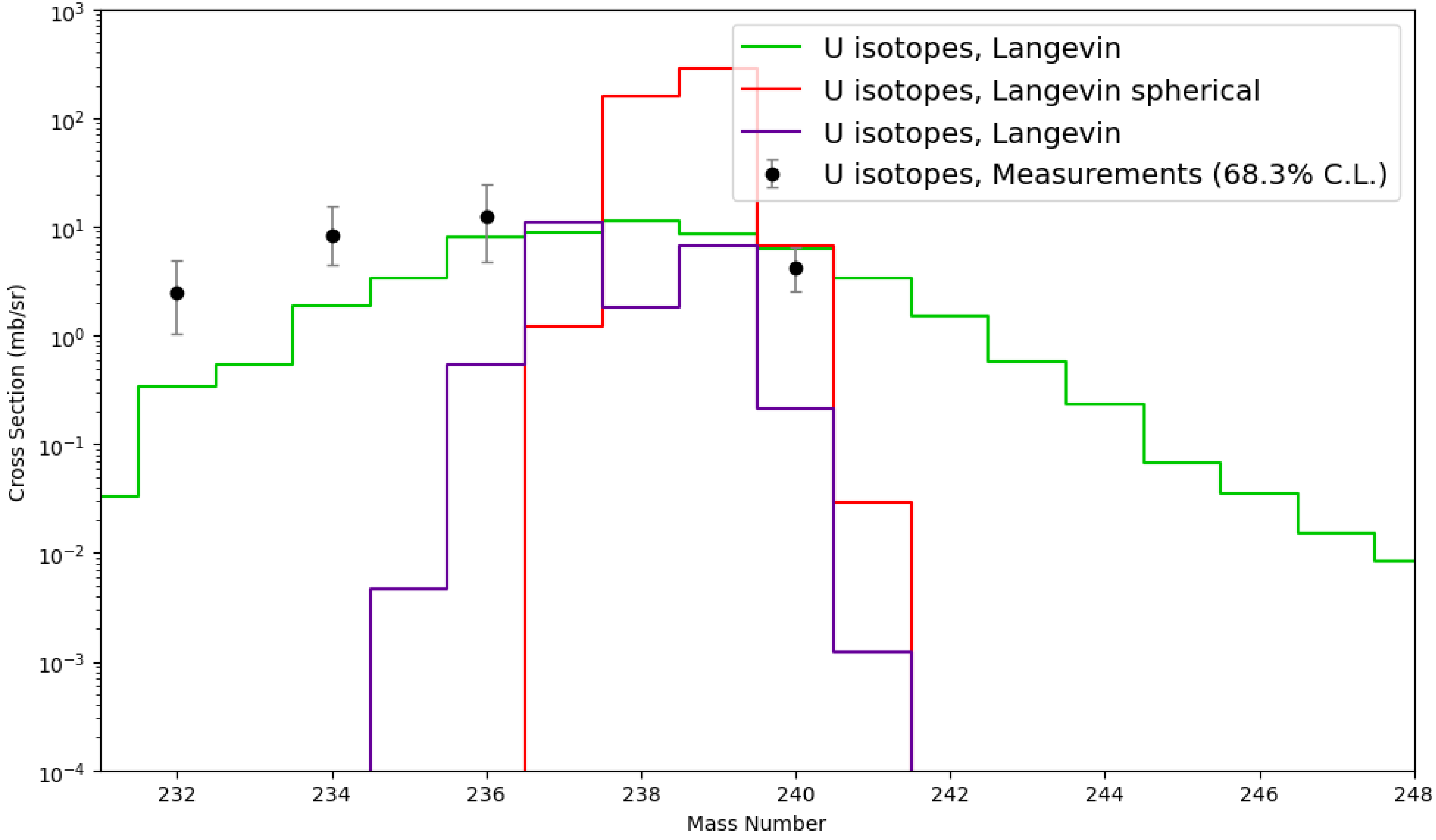
Langevin equations model predictions

Optimal sensitivity limit with cube

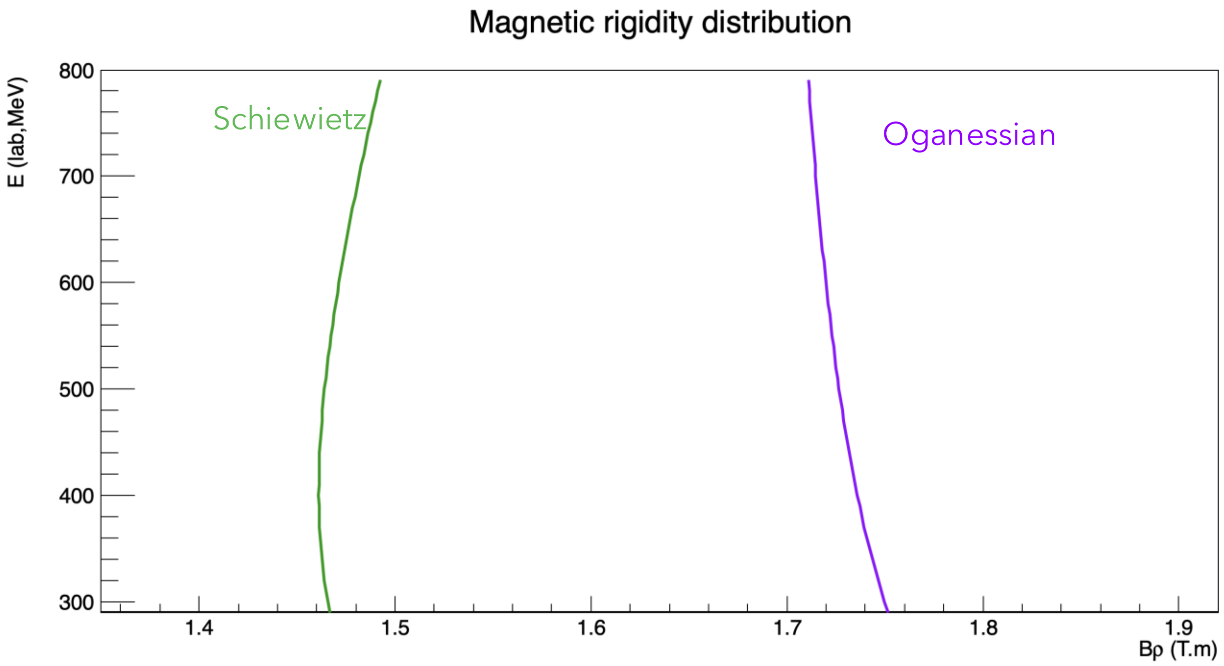
Exploratory experiment with heavy partners, near-barrier & forward angle :

massive transfers out of reach here

Cross-section : « 1σ » error-bars

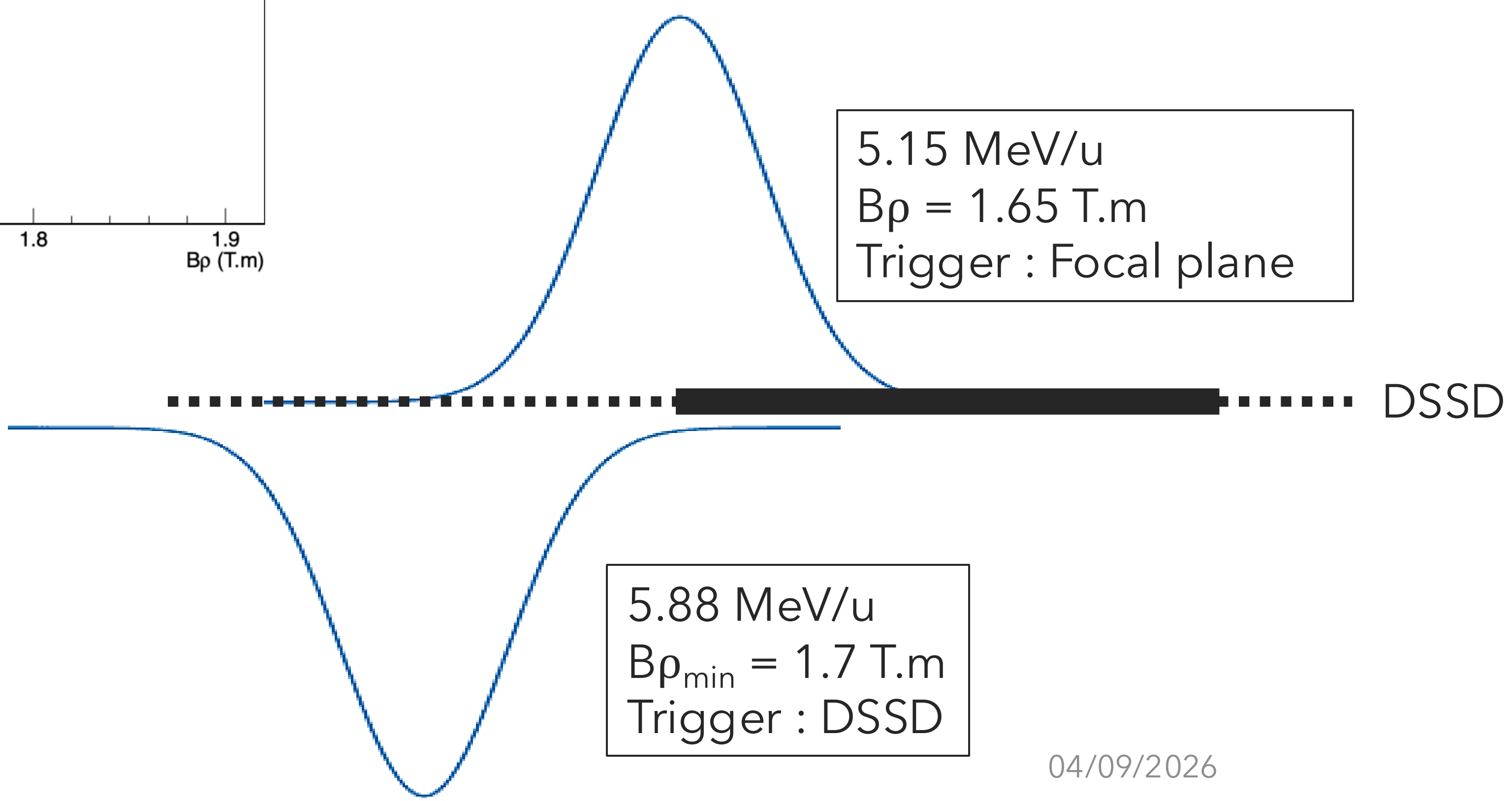


No MNT at 5.88 MeV/u

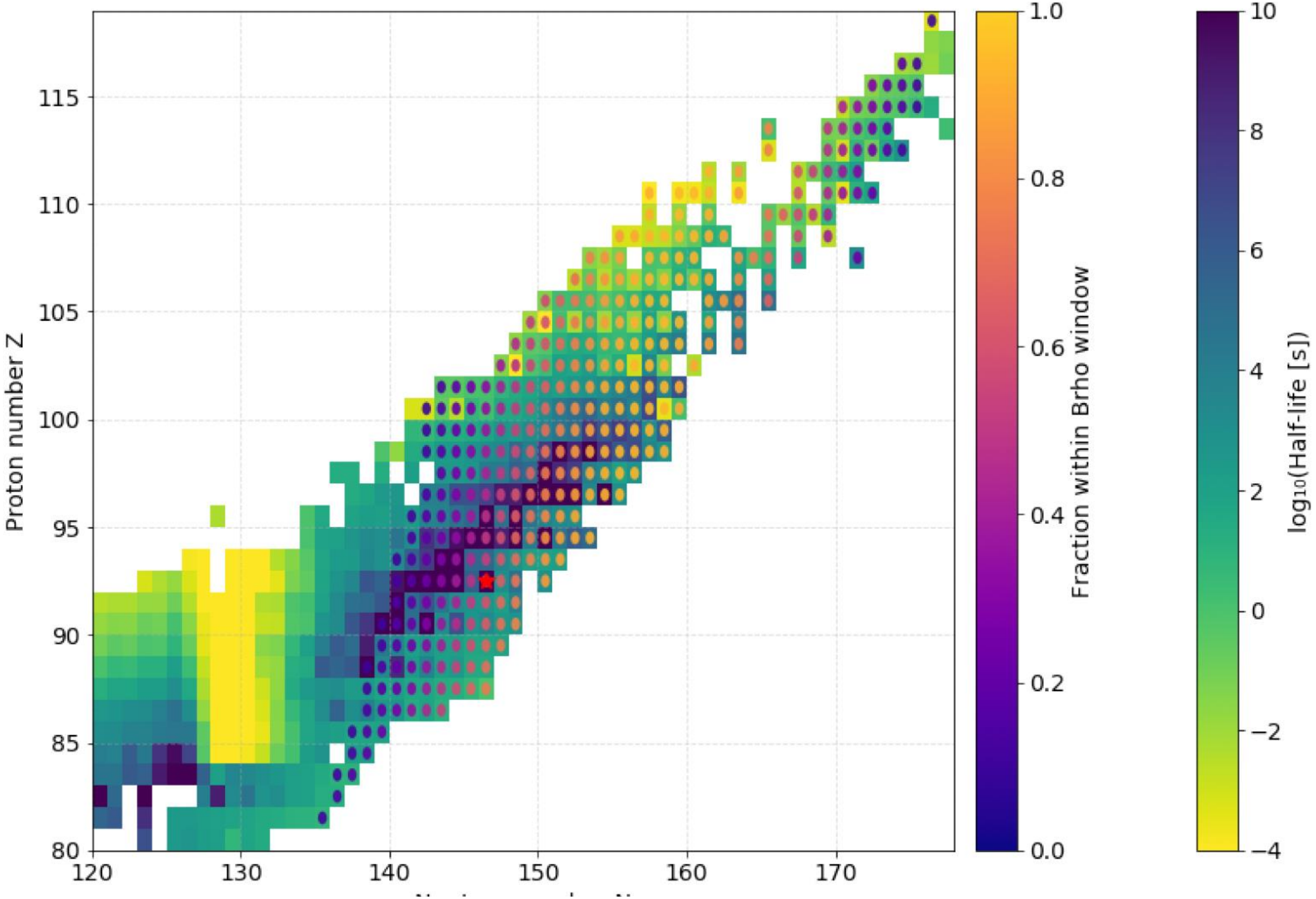


- Bρ scan
- No U-like identified (no CoulEx)
- Simulations : -30% CoulEx expected w.r.t 5.15 MeV/u data

M. Zielinska; private communication

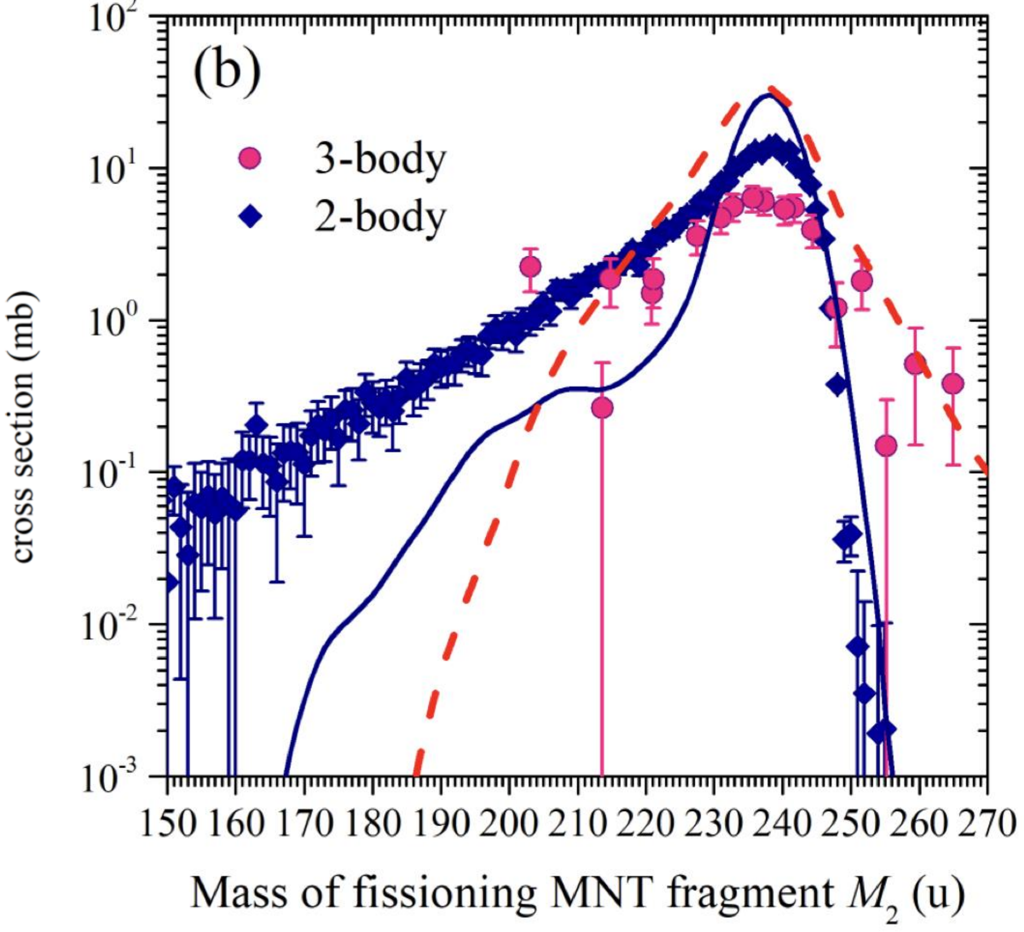


Decay spectroscopy ?



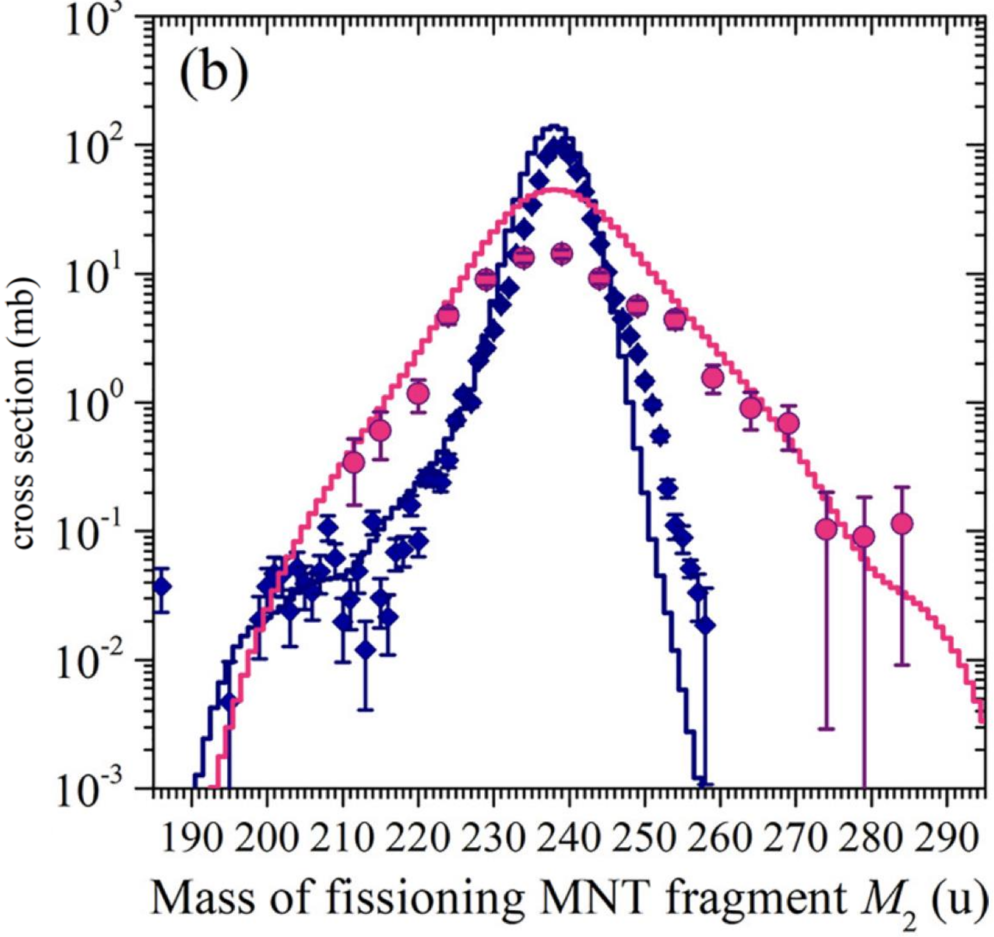
MNT with CORSET

^{136}Xe + ^{238}U : 8.16 MeV/u (51.6 % above barrier)



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

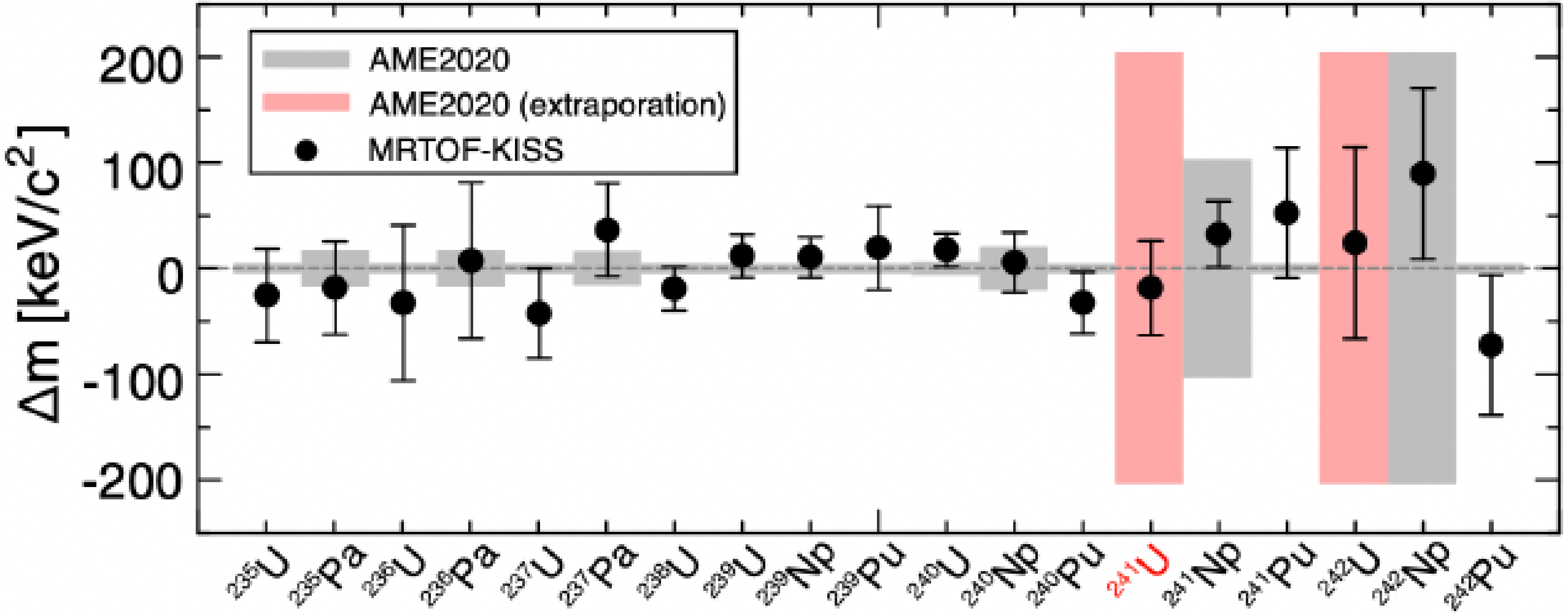
^{209}Bi + ^{238}U : 8.85 MeV/u (45.6 % above barrier)



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

MNT with KISS

$^{238}U + ^{198}Pt$: 10.75 MeV/u



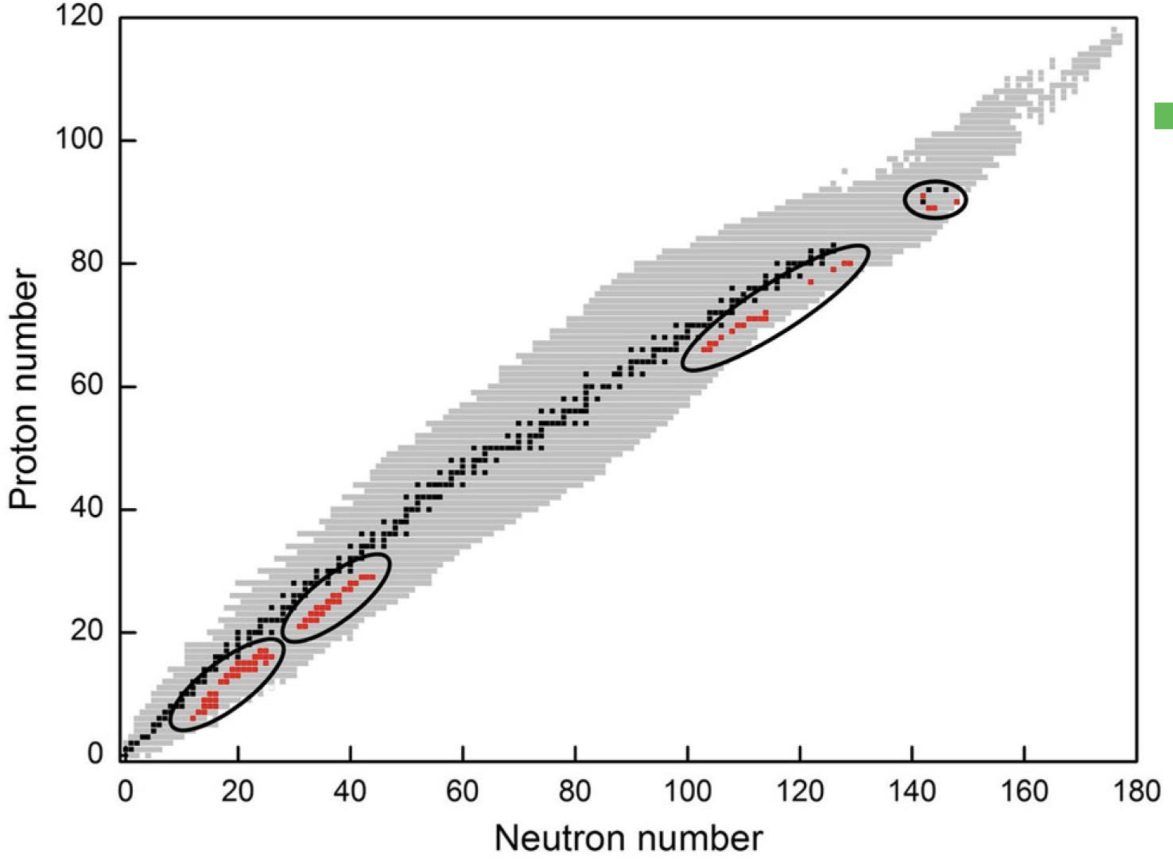
T. Niwase et. al.; PRL 130 (2023)

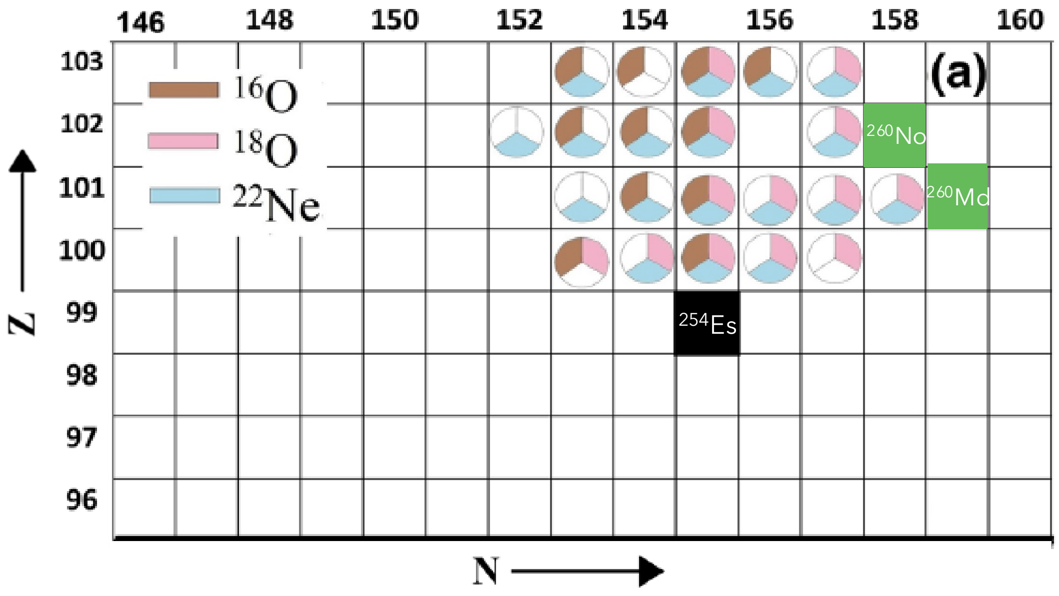
81 % above barrier

Gas-cell (KISS)

Low efficiency setup

MNT : discovering neutron-rich isotopes

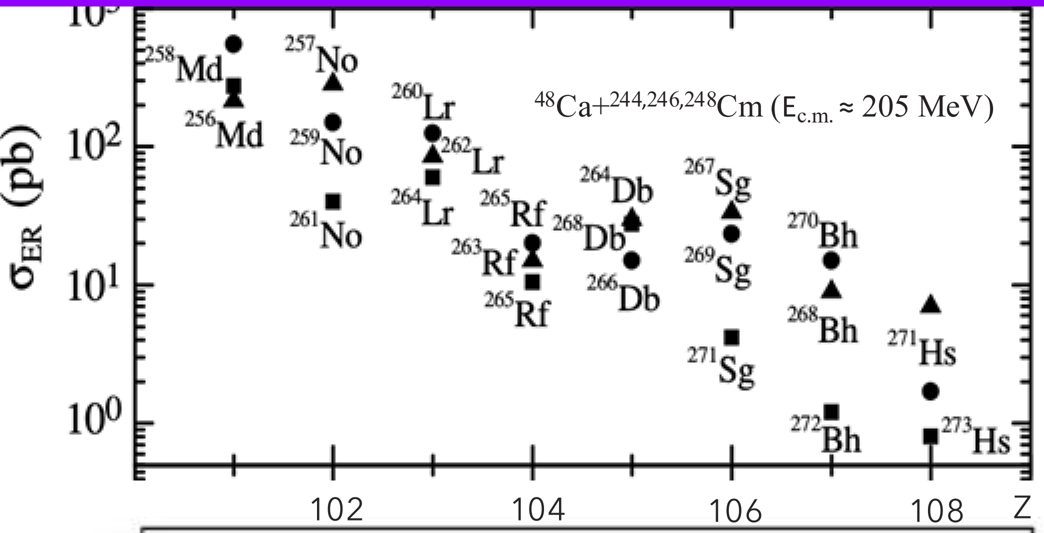




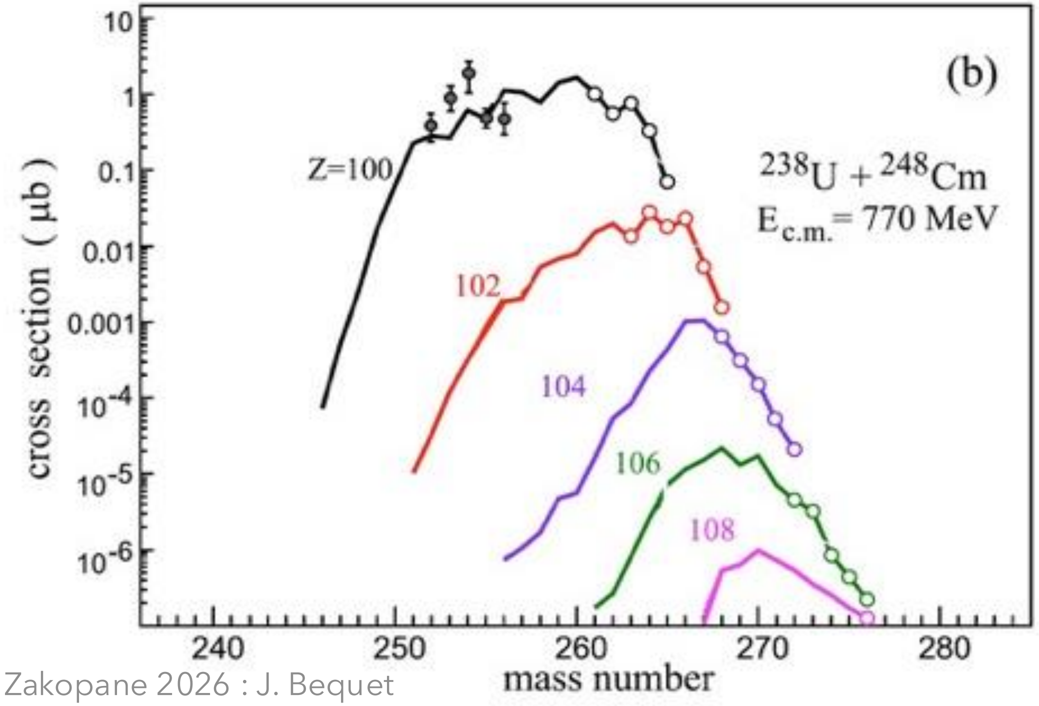
(mostly) neutron-rich discoveries all along the chart

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)



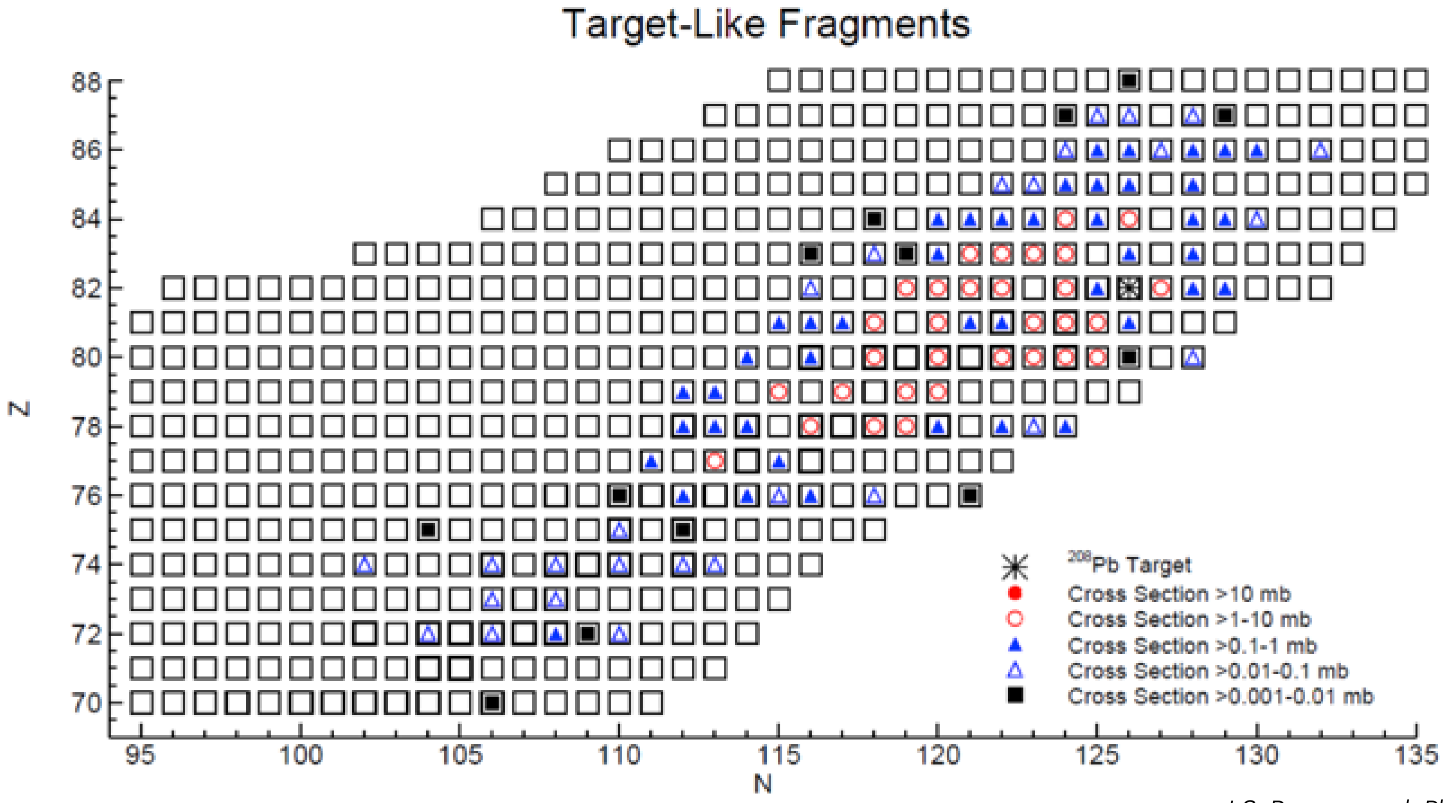
V. Zagrebaev,W. Greiner, NPA 944 (2015)

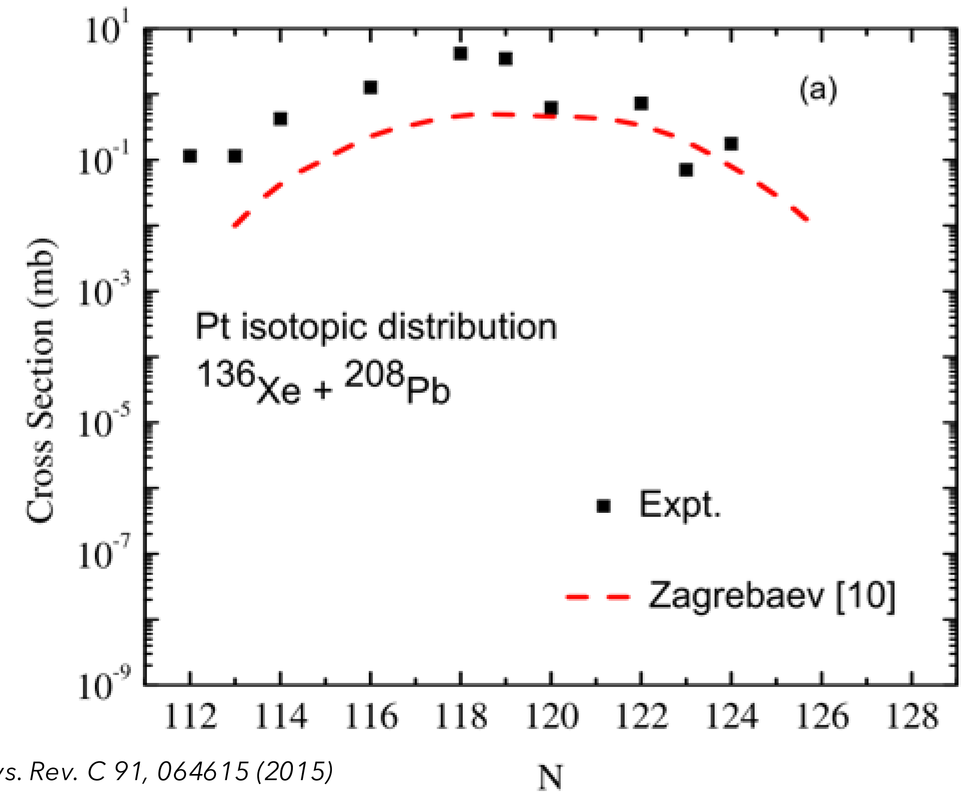
- Adamian et al. describe such reactions as the evolution of a di-nuclear system, using the **diffusion master equation** and diabatic internuclear potential.
- Light beams are favored: shell effect increases the survival probability of primary products.
- Zagrebaev & Greiner, then Karpov & Saiko, developped 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.

Beam & target : validation

$^{136}Xe+^{208}Pb$ 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 !**

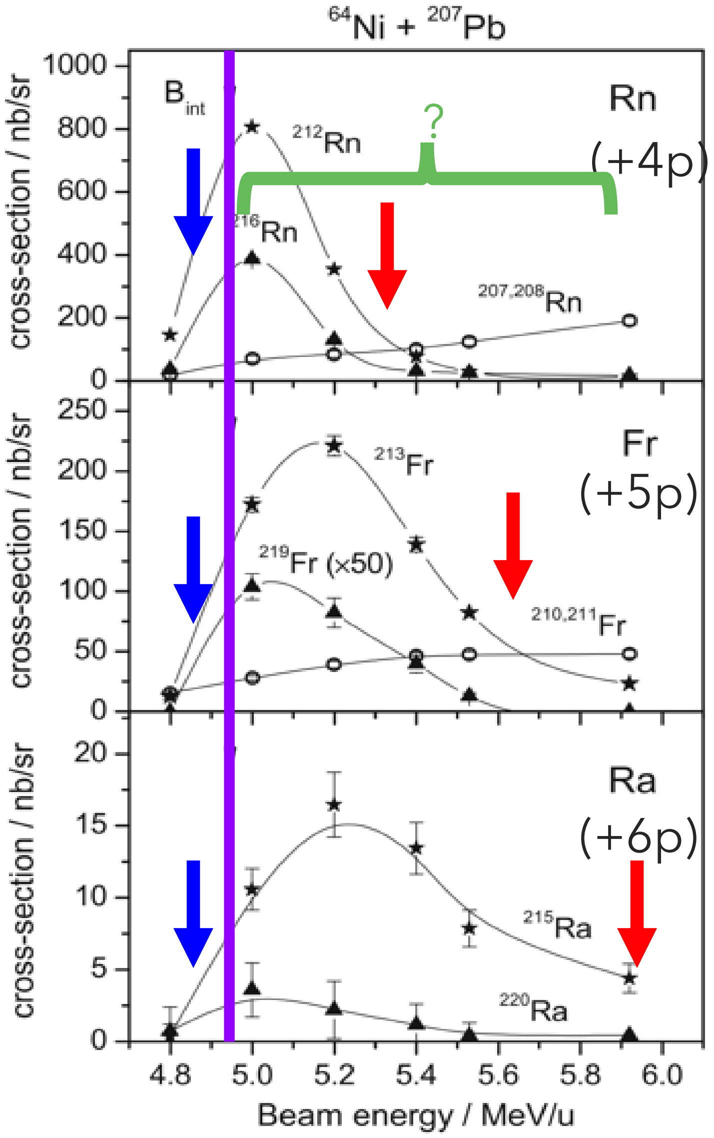
Near barrier reactions

Interaction barrier

No Di-nuclear system

Products lost above a given energy

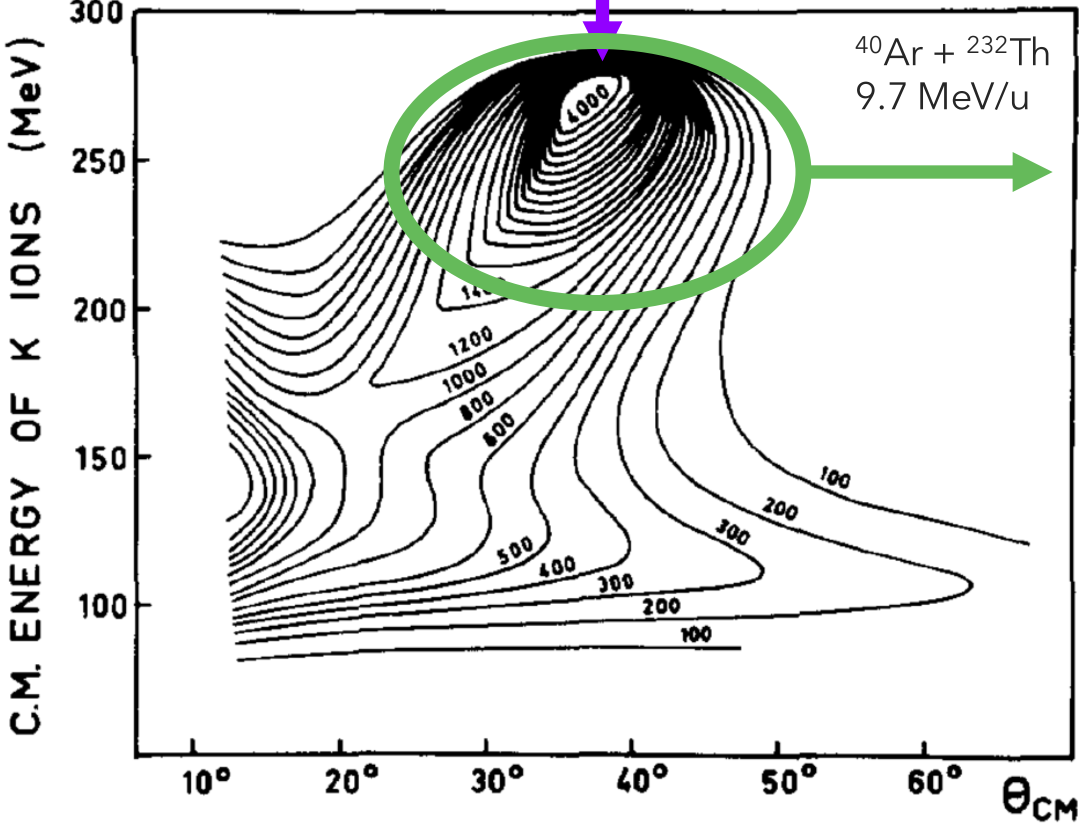
Optimal cross-section to find above the barrier



V. F. Comas, S. Heinz; EPJA i2013-13112-x (2013)

Angular distribution

Maximum of the cross-section

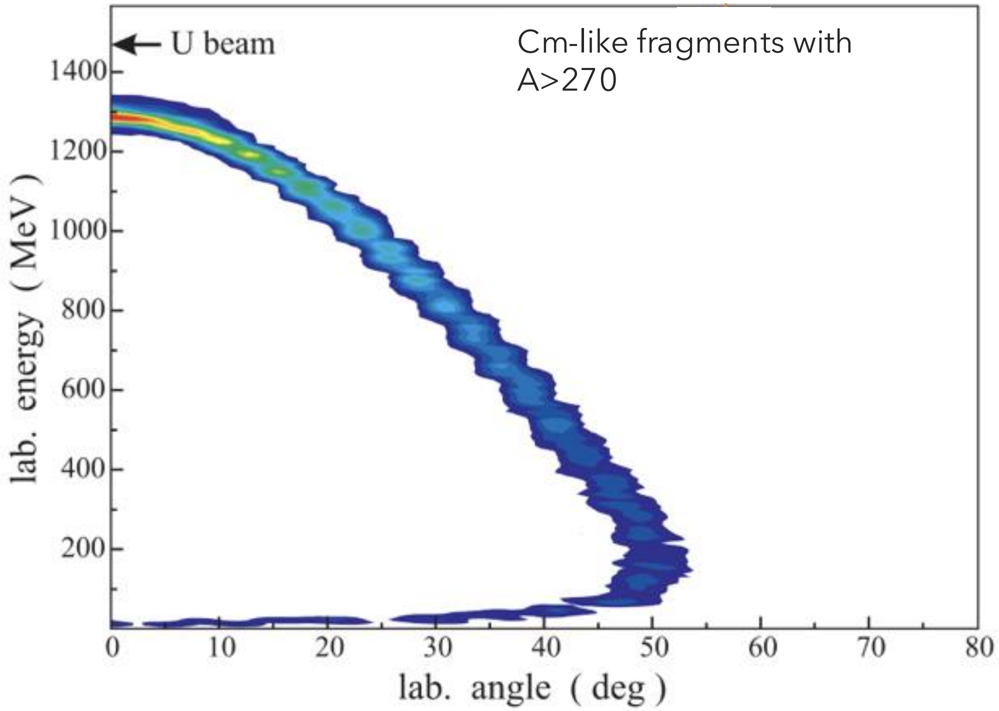


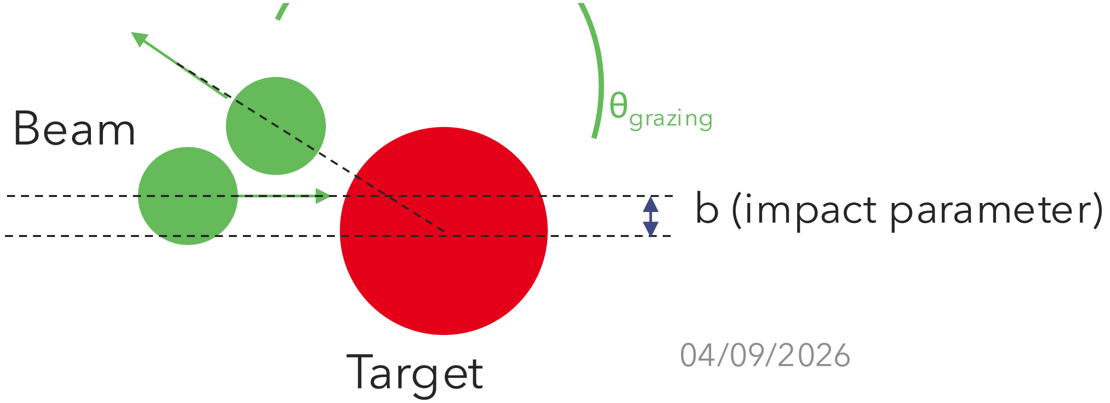
J. Wilczynski; PLB 47 (6), 1973.

Near-barrier → Central collisions

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

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





Models comparison

DIT & GEMINI++ :

- Semi-classical approach of the nucleus
- Simple mean field potential
- Nuclei exchange independant nucleons in a potential well with given probabilities
- Statistical de-excitation and evaporation with GEMINI++
- Purely spherical nuclei
- Statical nuclear properties during the interaction

Langevin equations model :

- Microscopic-Macroscopic approach for nuclear properties
- Adiabatic (+diabatic component) mean field potential
- Evolution of equipotential surfaces through the multi-dimensional Langevin equations
- Evaporation calculated within the model
- Deformations & relative orientations accounted for
- Dynamical deformation of nuclei while approaching

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

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