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Advancements of γ -ray spectroscopy of isotopically identified fission fragments with AGATA and VAMOS++

Jérémie Dudouet

on behalf of the AGATA/VAMOS collaborations

Institut de Physique des deux infinis de Lyon (IP2I)

17th International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics

➔ The presented work is part of the recently published **AGATA Topical Issue in EPJA**:
 ➔ List of articles covering the different AGATA facets (physics, detectors, electronics, softwares...)



EPJ A 2021 Impact factor **3.131**

Hadrons and Nuclei

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The European Physical Journal A
AGATA: Advancements in Science and Technology

Nicolas Alamanos, Maria Jose Garcia Borge, Angela Bracco, Emmanuel Clement, Andres Gadea, Wolfram Korten, Silvia Leoni and John Simpson

Eur. Phys. J. A (2023) 59:134
<https://doi.org/10.1140/epja/s10050-023-01053-0>

THE EUROPEAN
 PHYSICAL JOURNAL A



Regular Article - Experimental Physics

Advancements of γ -ray spectroscopy of isotopically identified fission fragments with AGATA and VAMOS++

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⁵ IRFU, CEA, Universit3 Paris-Saclay, 91191 Gif-sur-Yvette, France

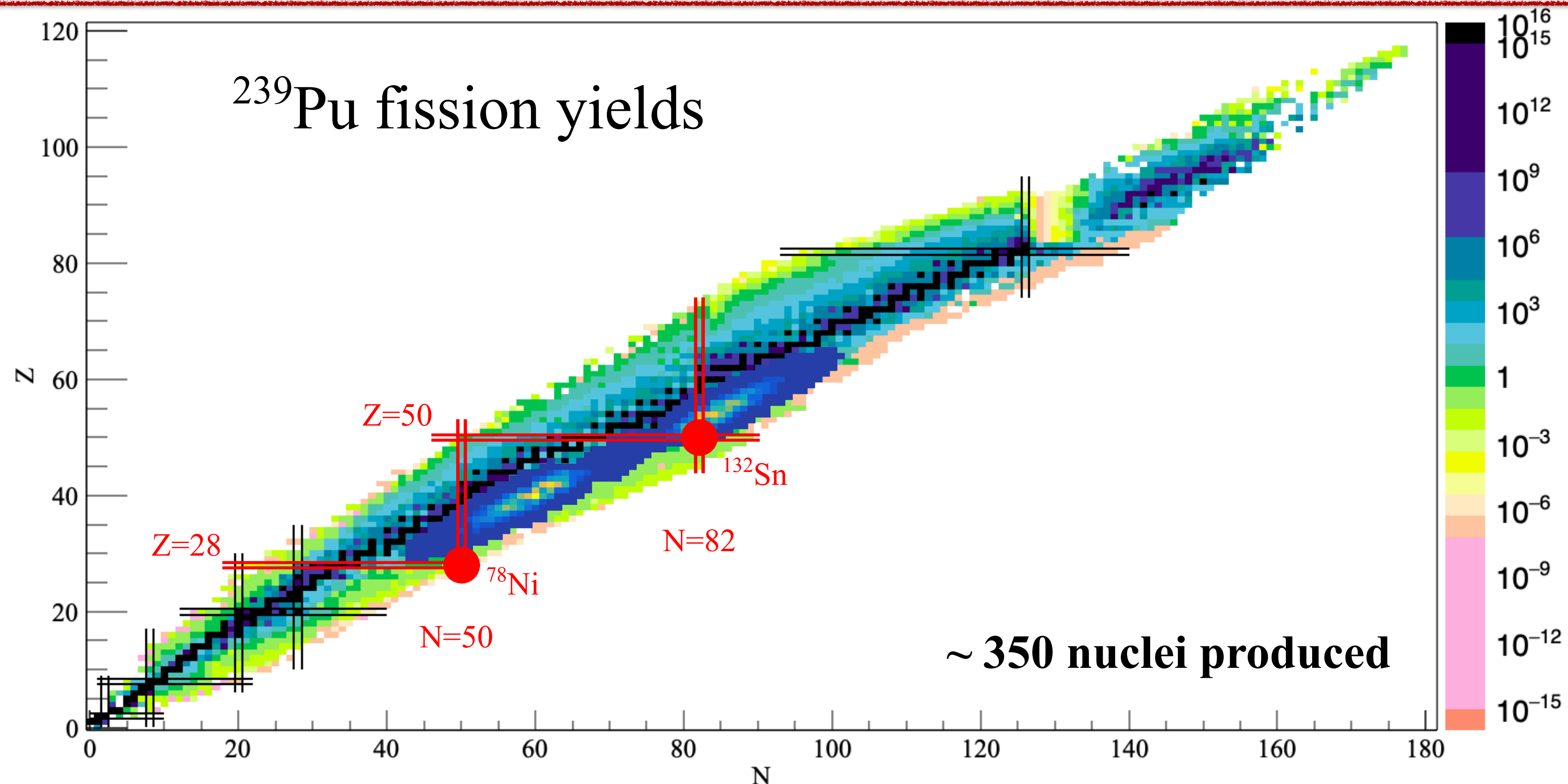
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Communicated by Nicolas Alamanos

The nuclear fission process

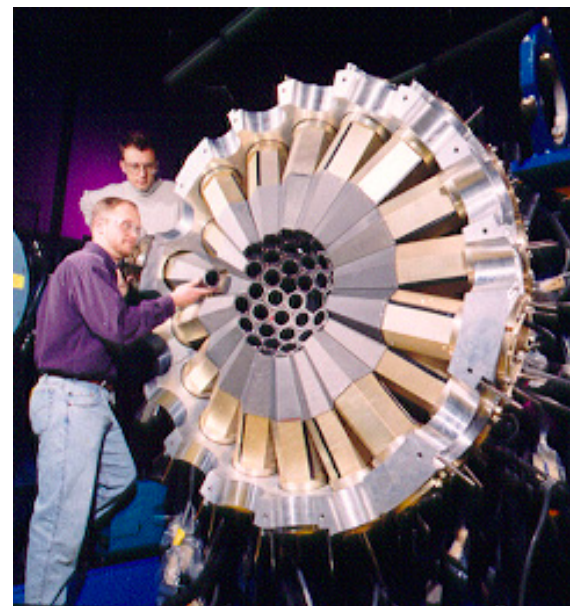
- ➔ Powerful and efficient way to produce neutron rich nuclei
- ➔ Covering a wide range of key nuclei in the nuclear structure understanding



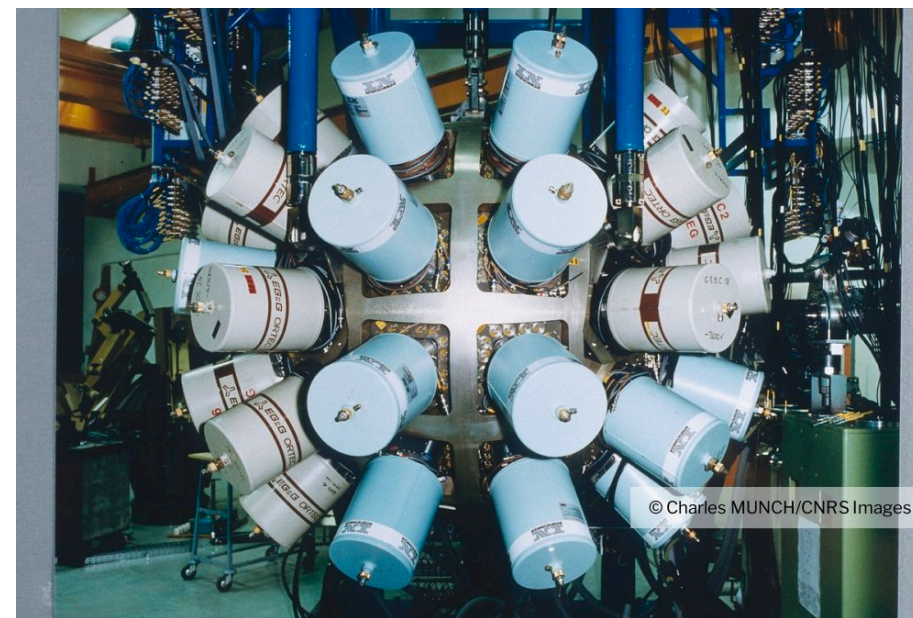
Nuclear fission fragments spectroscopy

→ Two schools: **High fold studies** / **fission fragments identification**

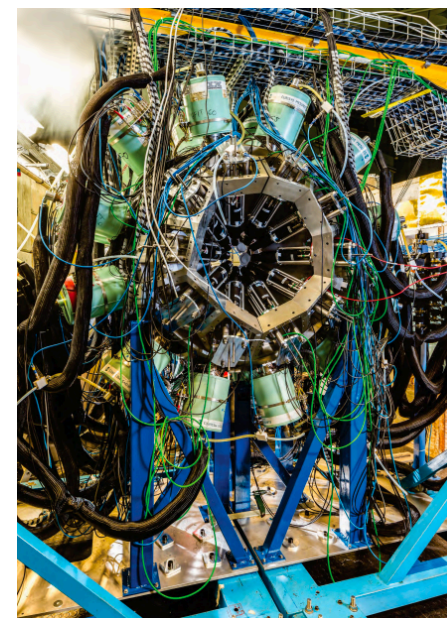
GAMMASPHERE



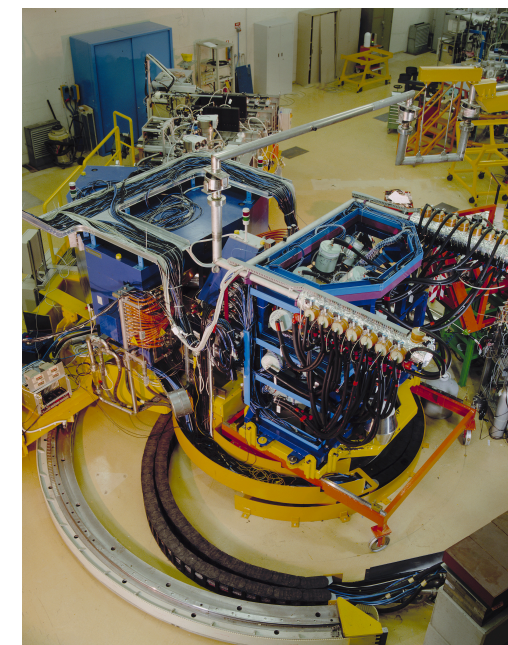
EUROGAM II



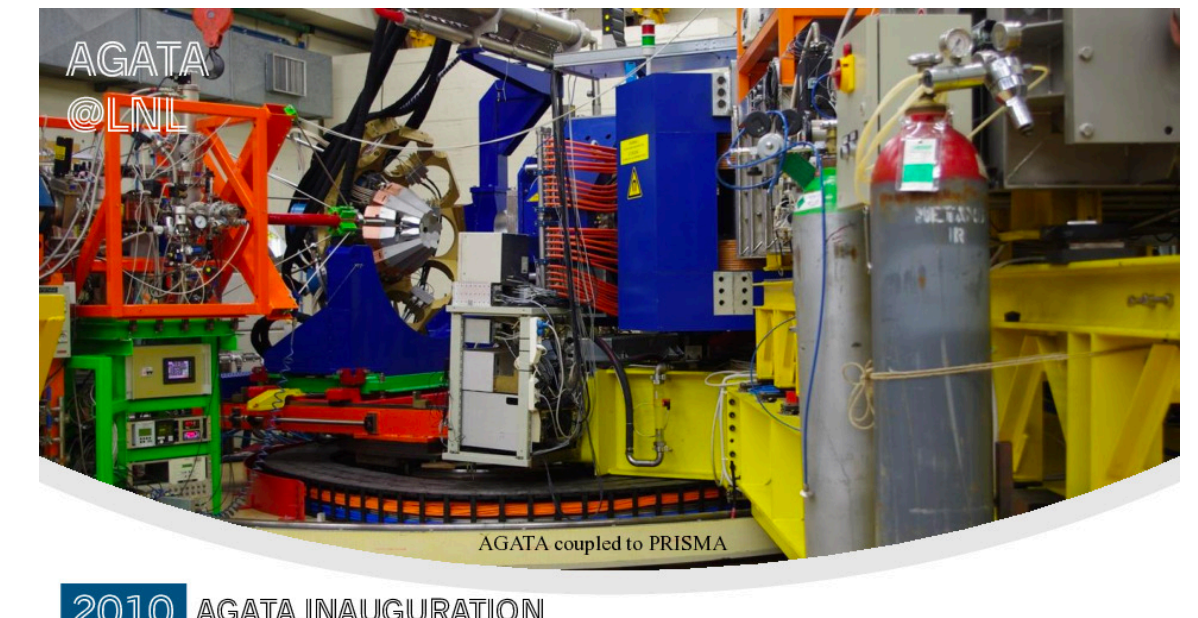
NUBALL



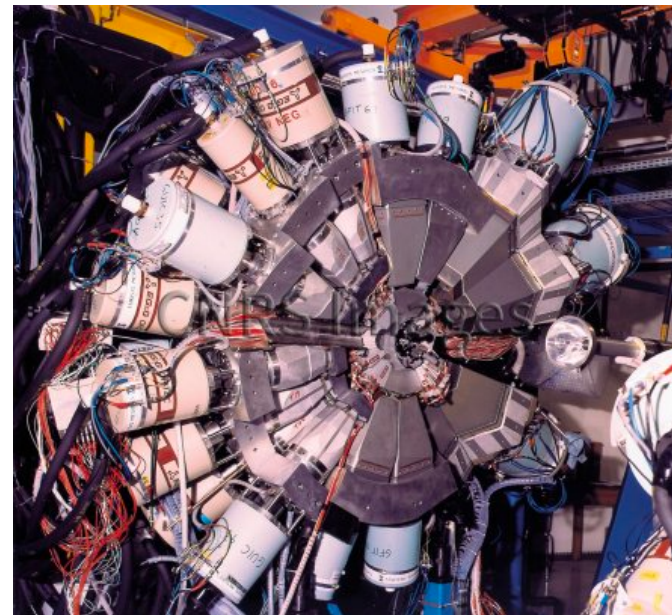
PRISMA/CLARA



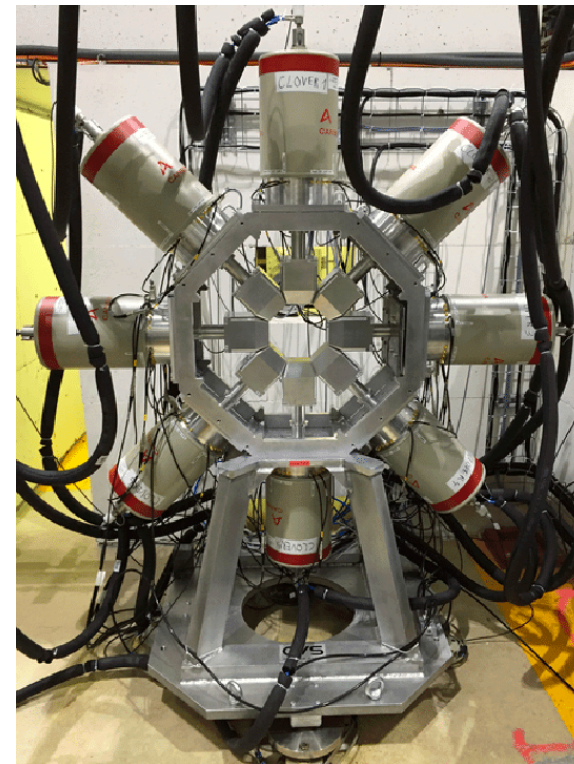
PRISMA/AGATA



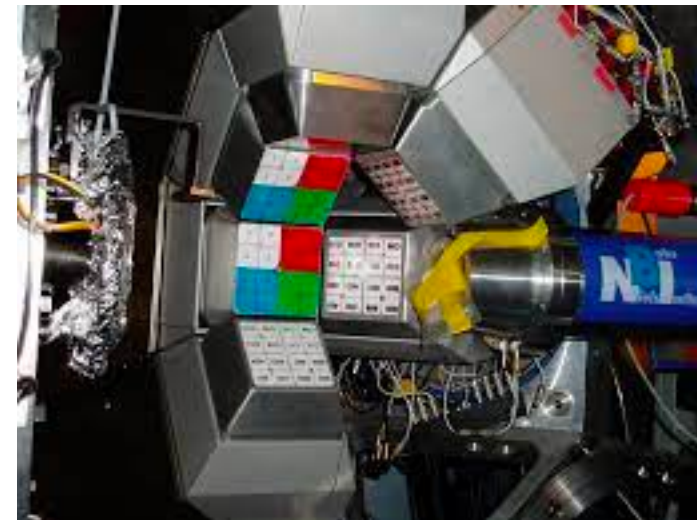
EUROBALL IV



FIPPS



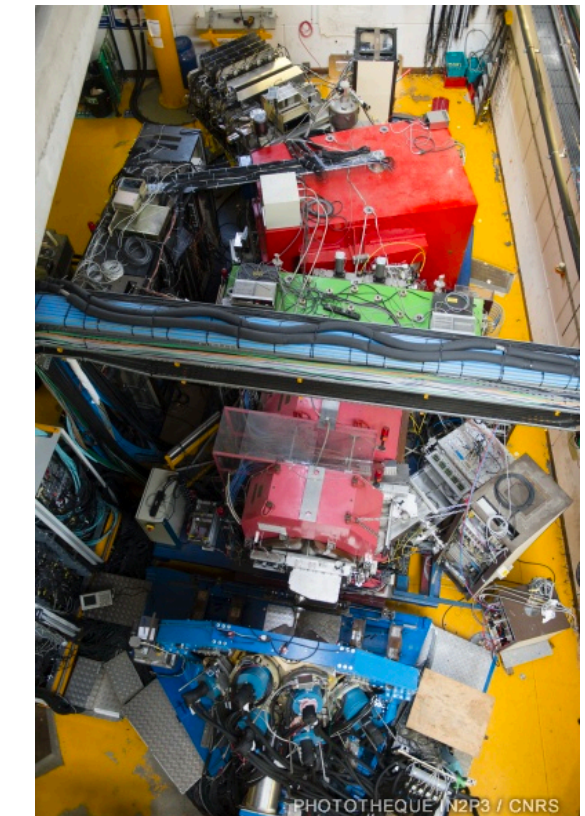
EXOGAM



VAMOS/EXOGAM

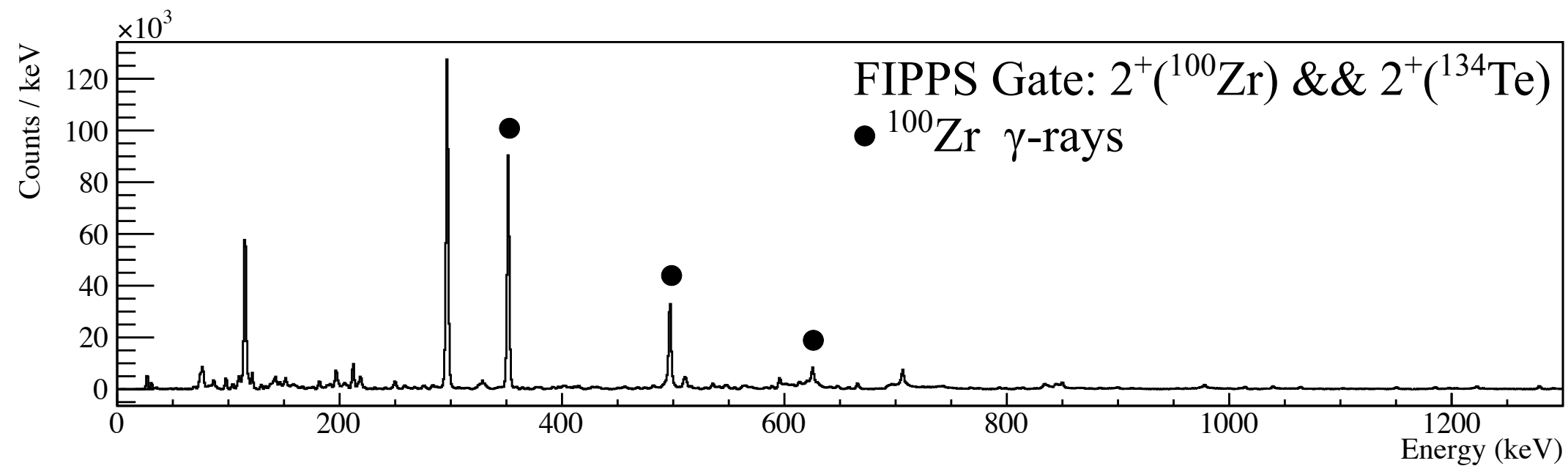
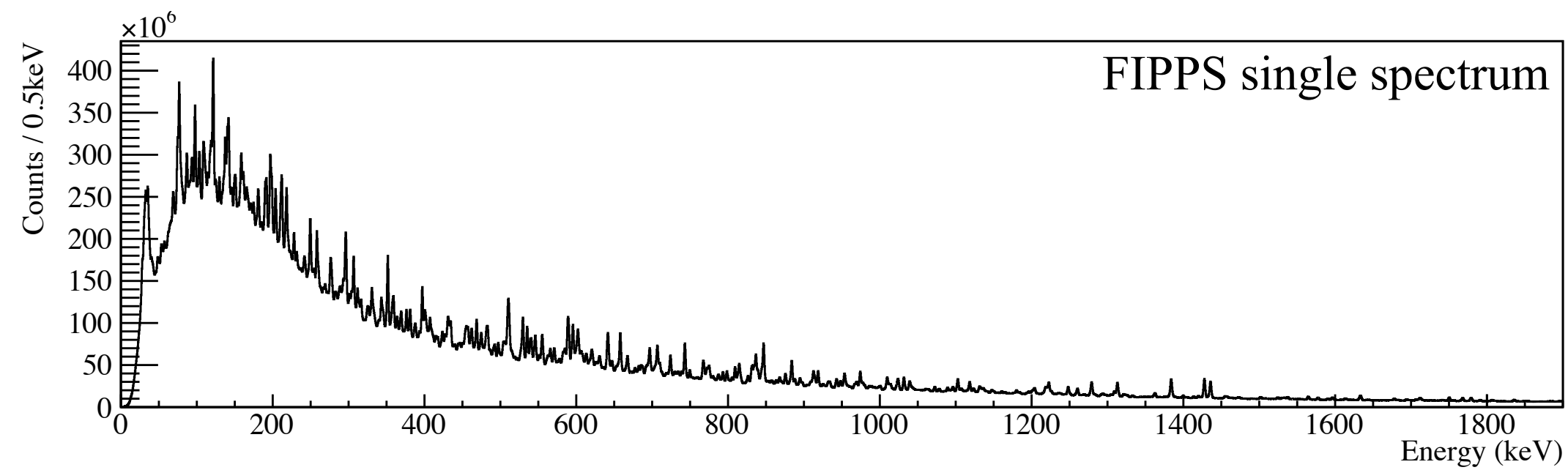


VAMOS++/AGATA

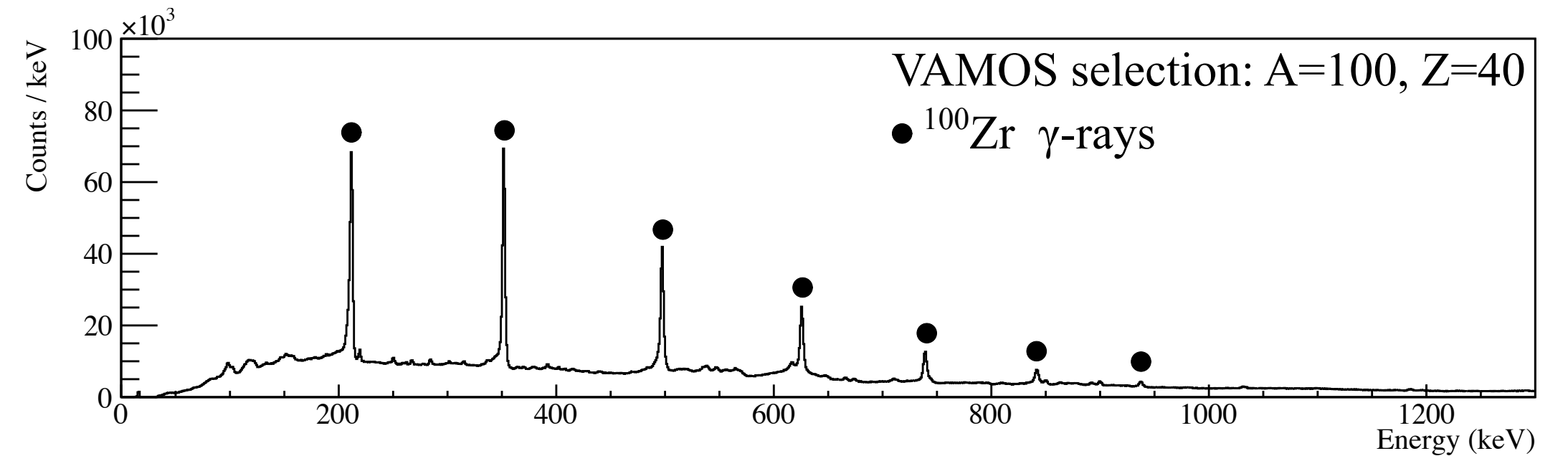
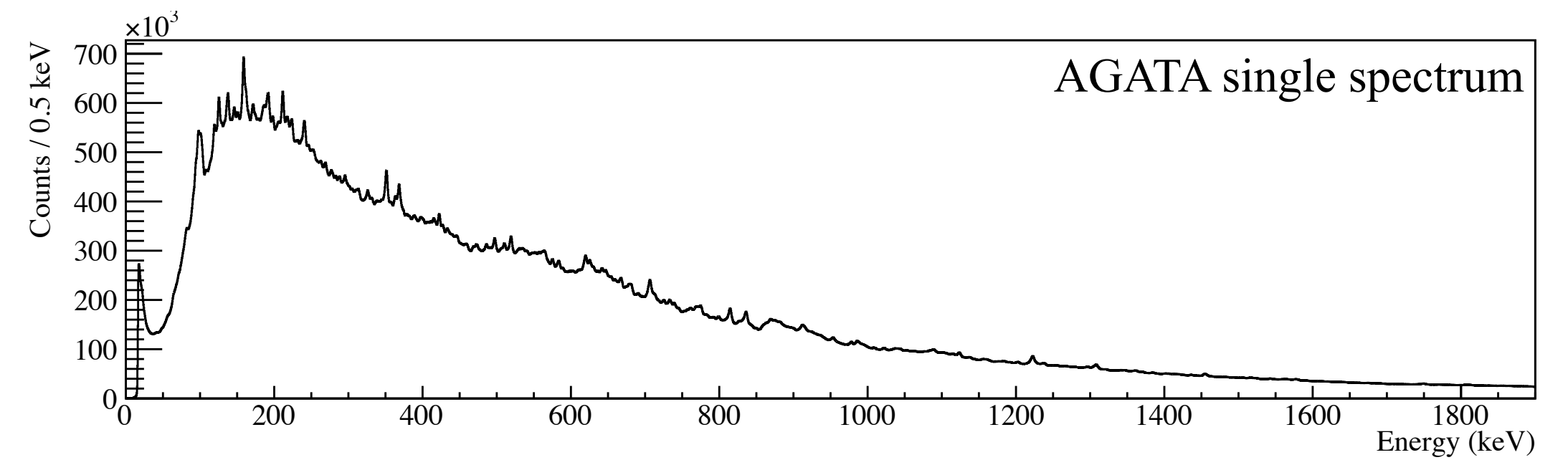


Nuclear fission fragments spectroscopy

➔ Two schools: **High fold studies / fission fragments identification**



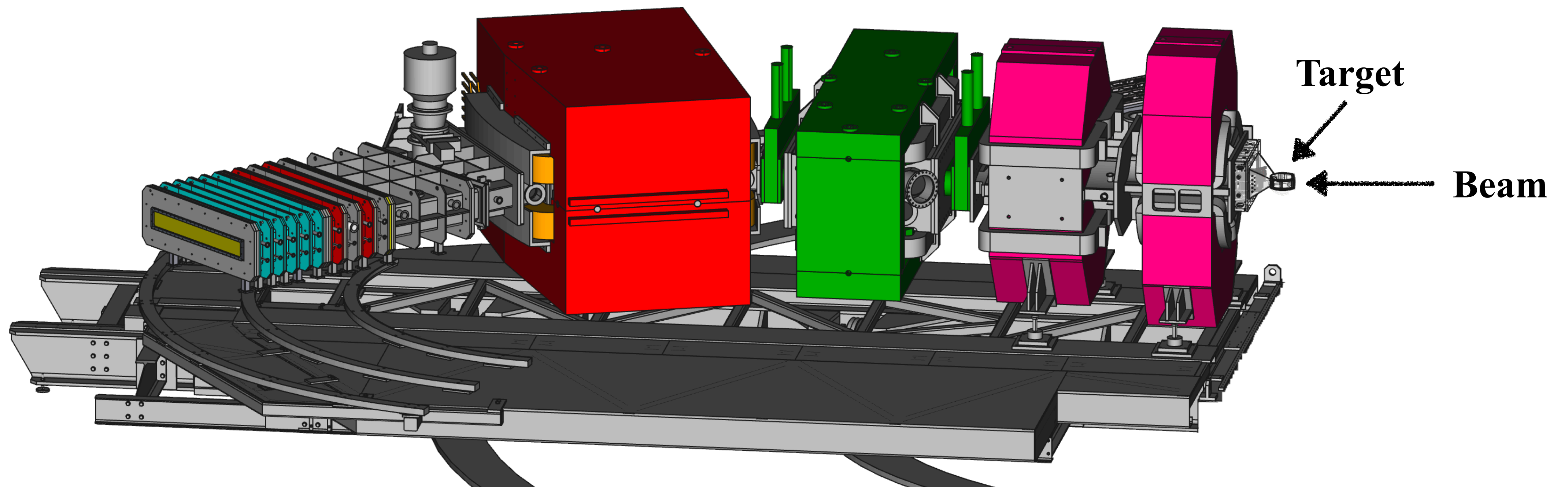
- Lot of statistics available with high folds (fold ≥ 3)
- Require a minimal knowledge of the nucleus
- Complicated analysis to avoid bad γ -ray attribution



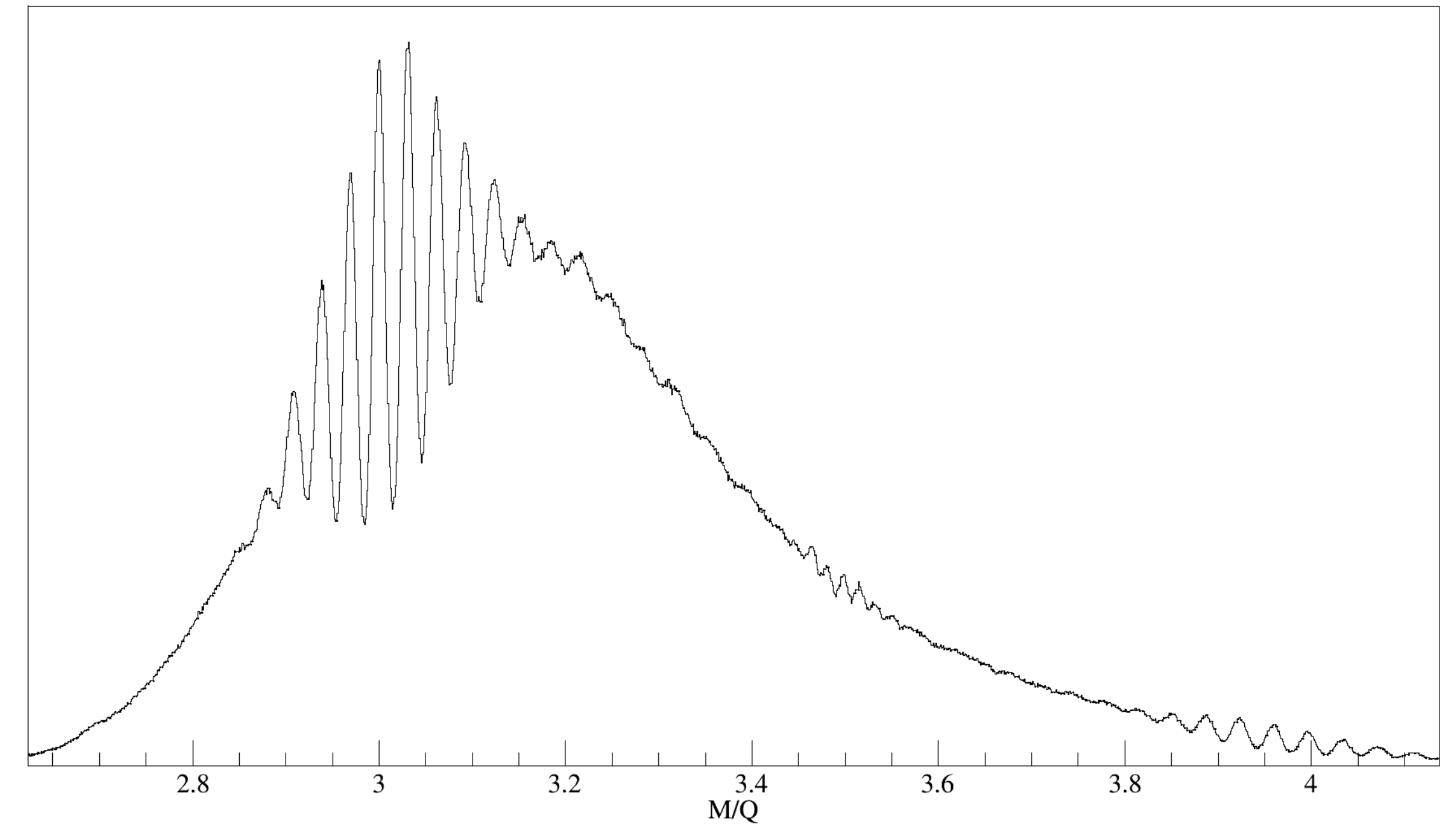
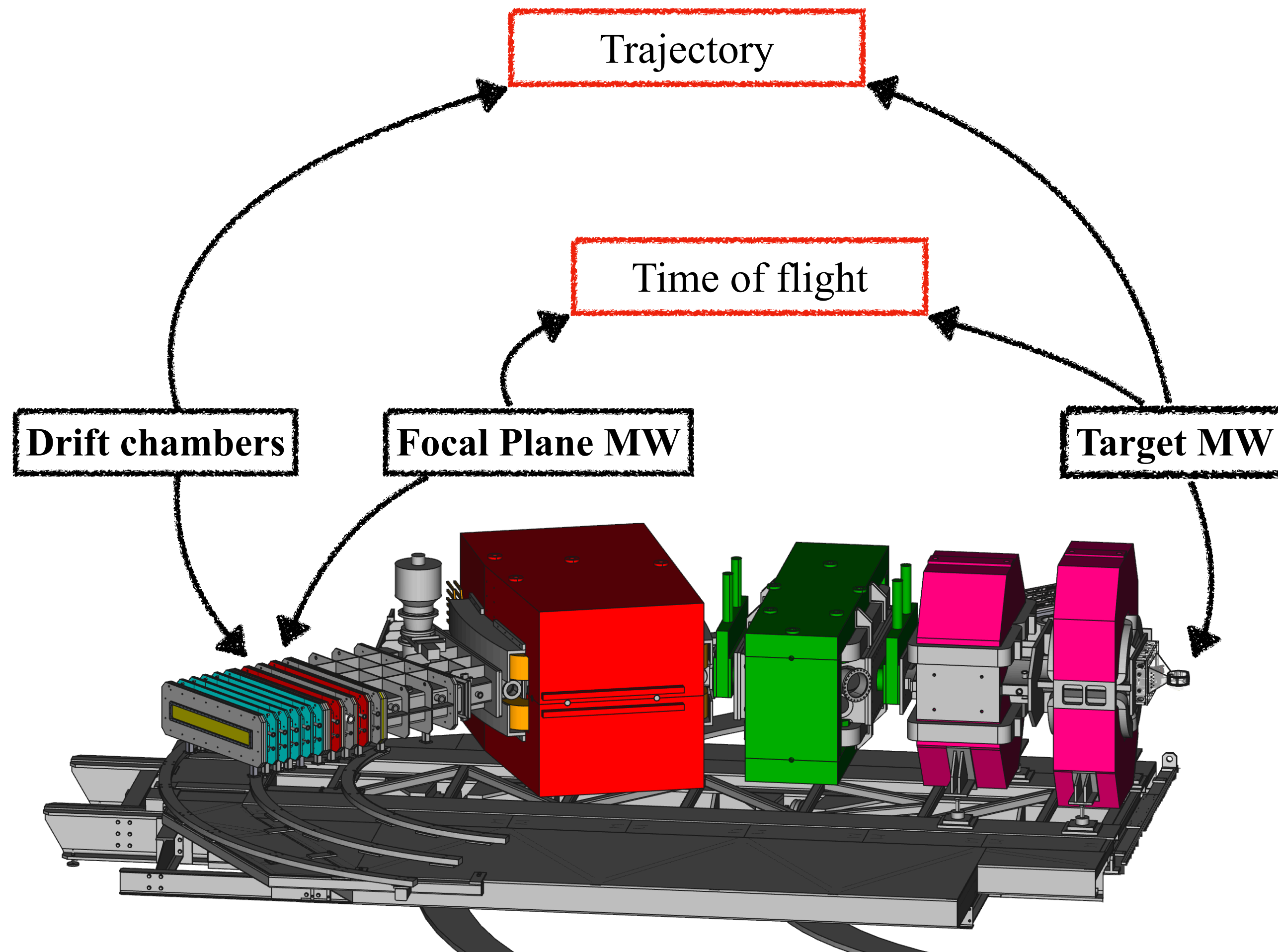
- Experimental setup much more complicated
- No statistics for fold ≥ 2 (γ - γ analysis only)
- Can be used on unknown nuclei
- Much simpler analysis

The VAMOS++ spectrometer

- ➔ Beam: ^{238}U @ 6.2 MeV/u, $I \sim 30 \text{ enA}$
- ➔ Target: ^9Be $\sim 10 \mu\text{m}$
- ➔ Detection angle: $19^\circ < \theta < 28^\circ$
- ➔ Recoil velocities: $\beta \sim 0.1$
- ➔ Validation rate: $\sim 1.5 \text{ kHz}$

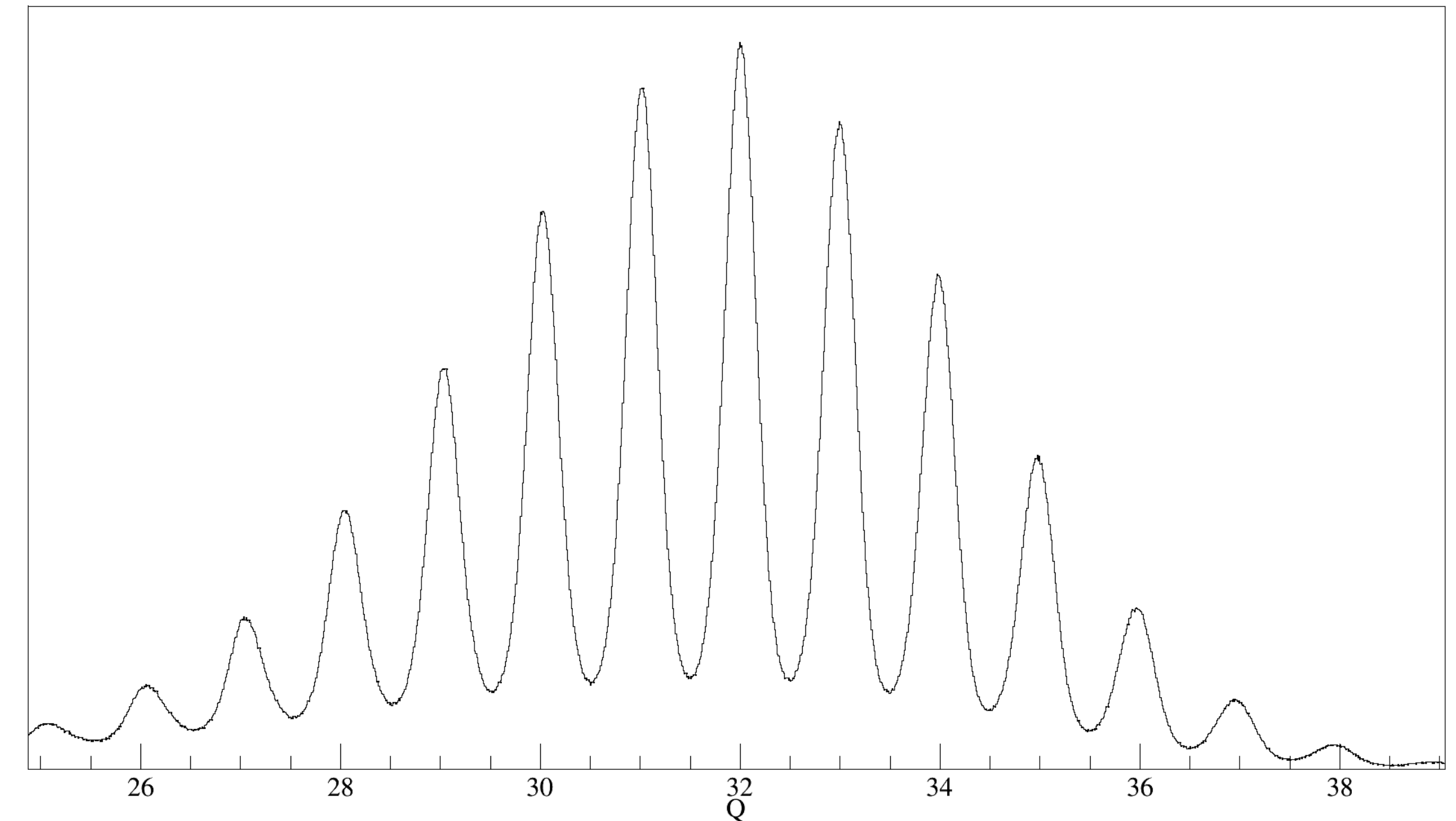
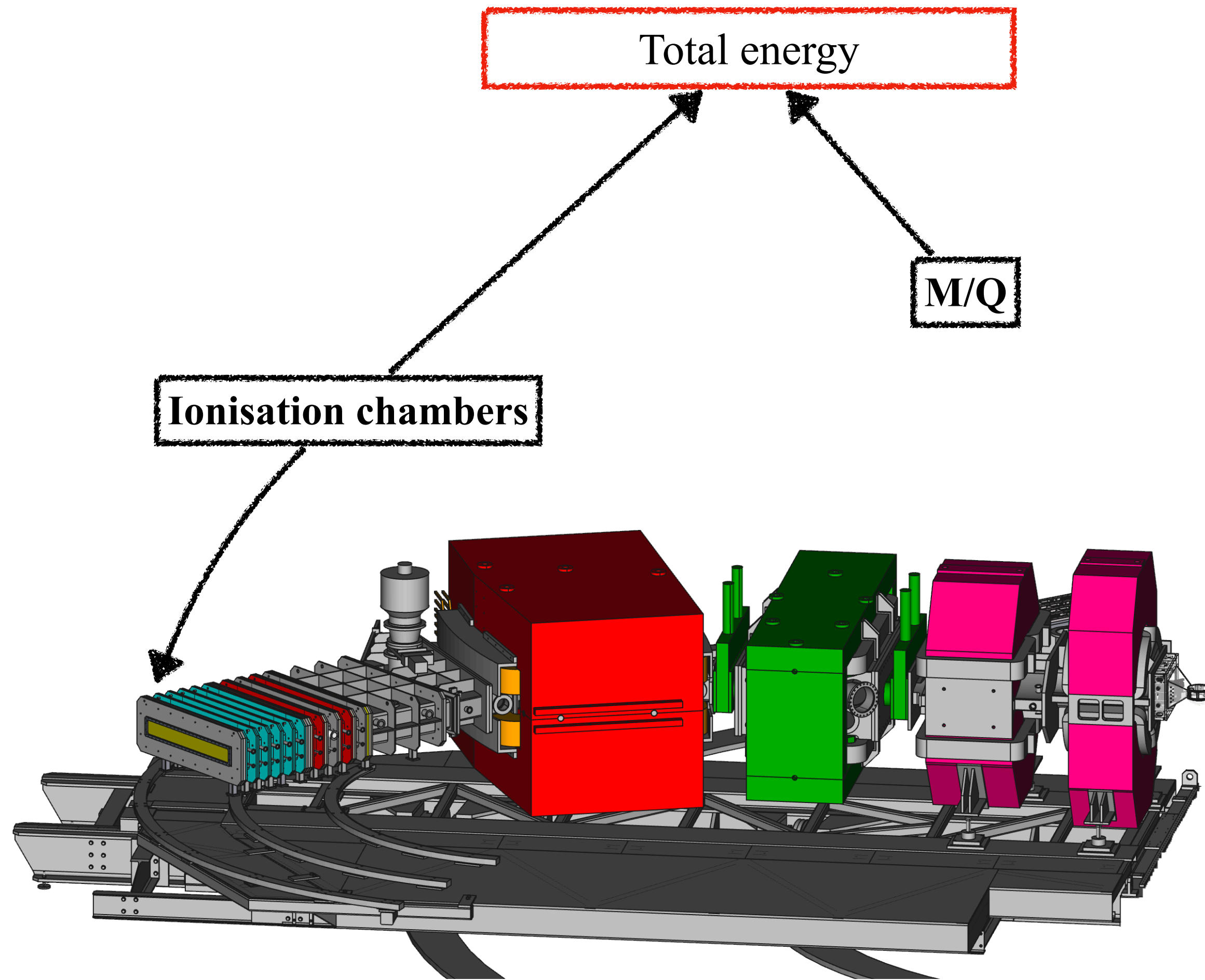


The VAMOS++ spectrometer: Mass identification



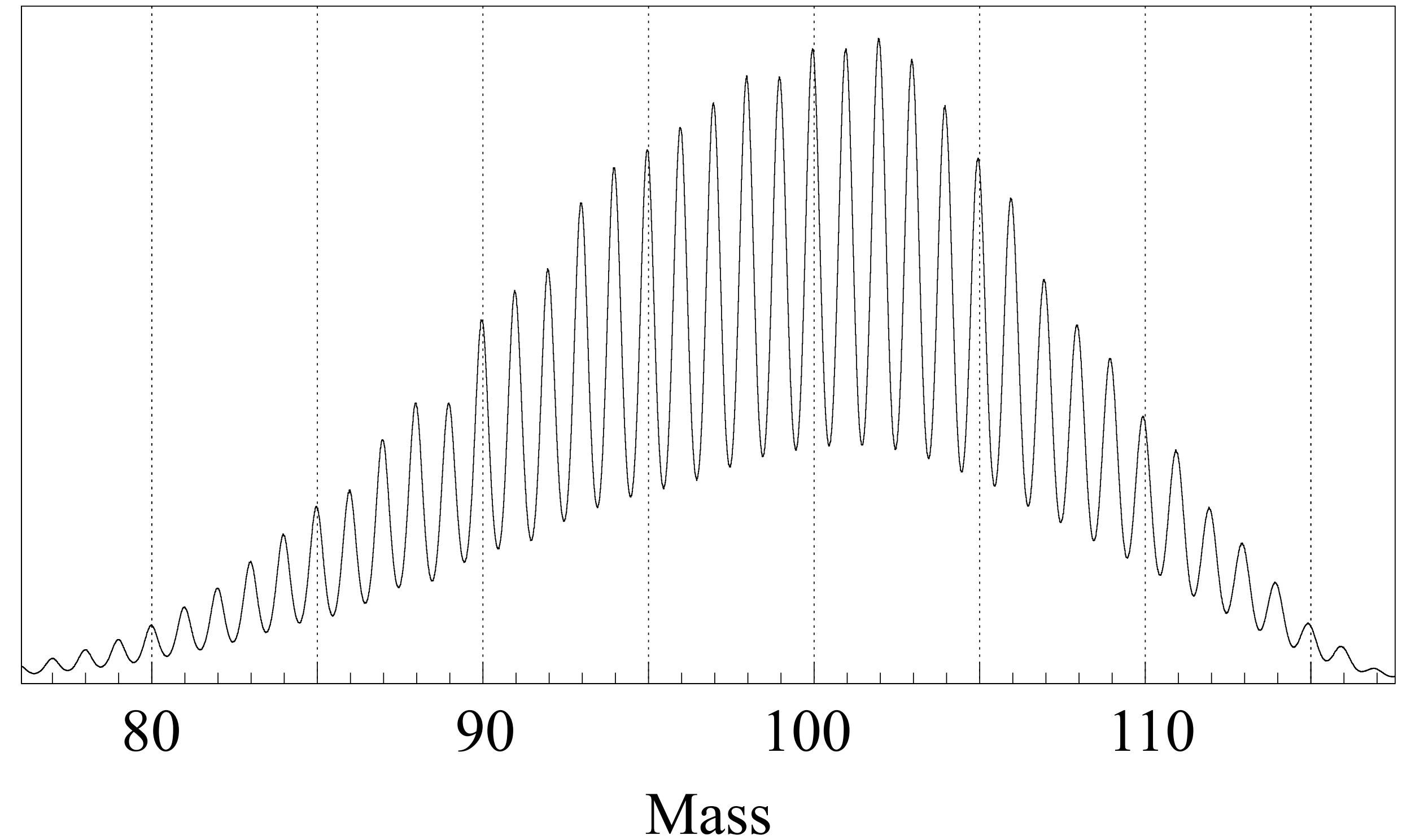
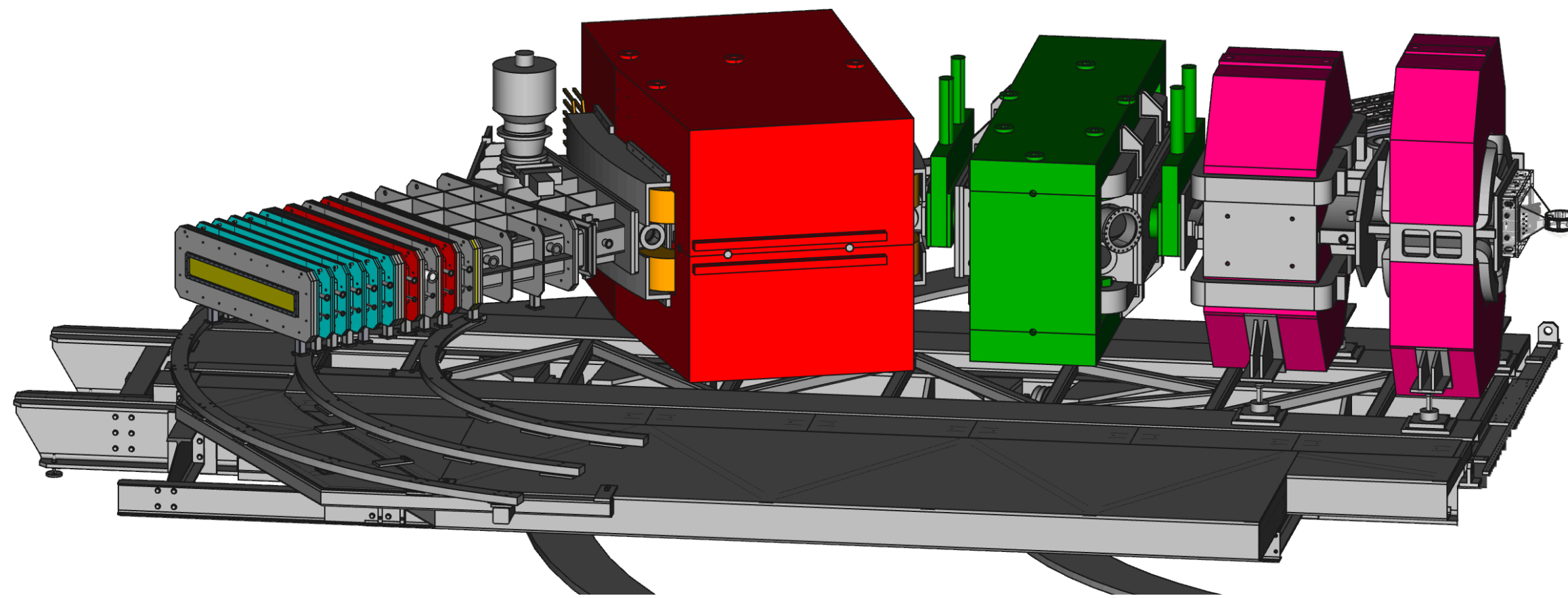
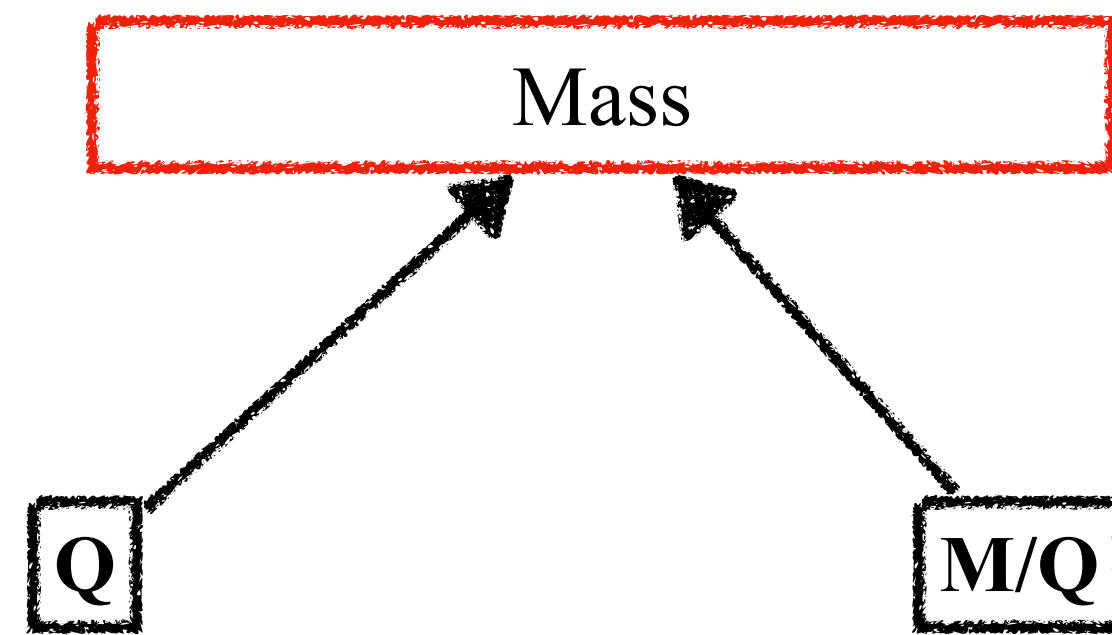
$$\frac{M}{Q} = \frac{B\rho}{3.105 \times \beta}$$

The VAMOS++ spectrometer: Mass identification



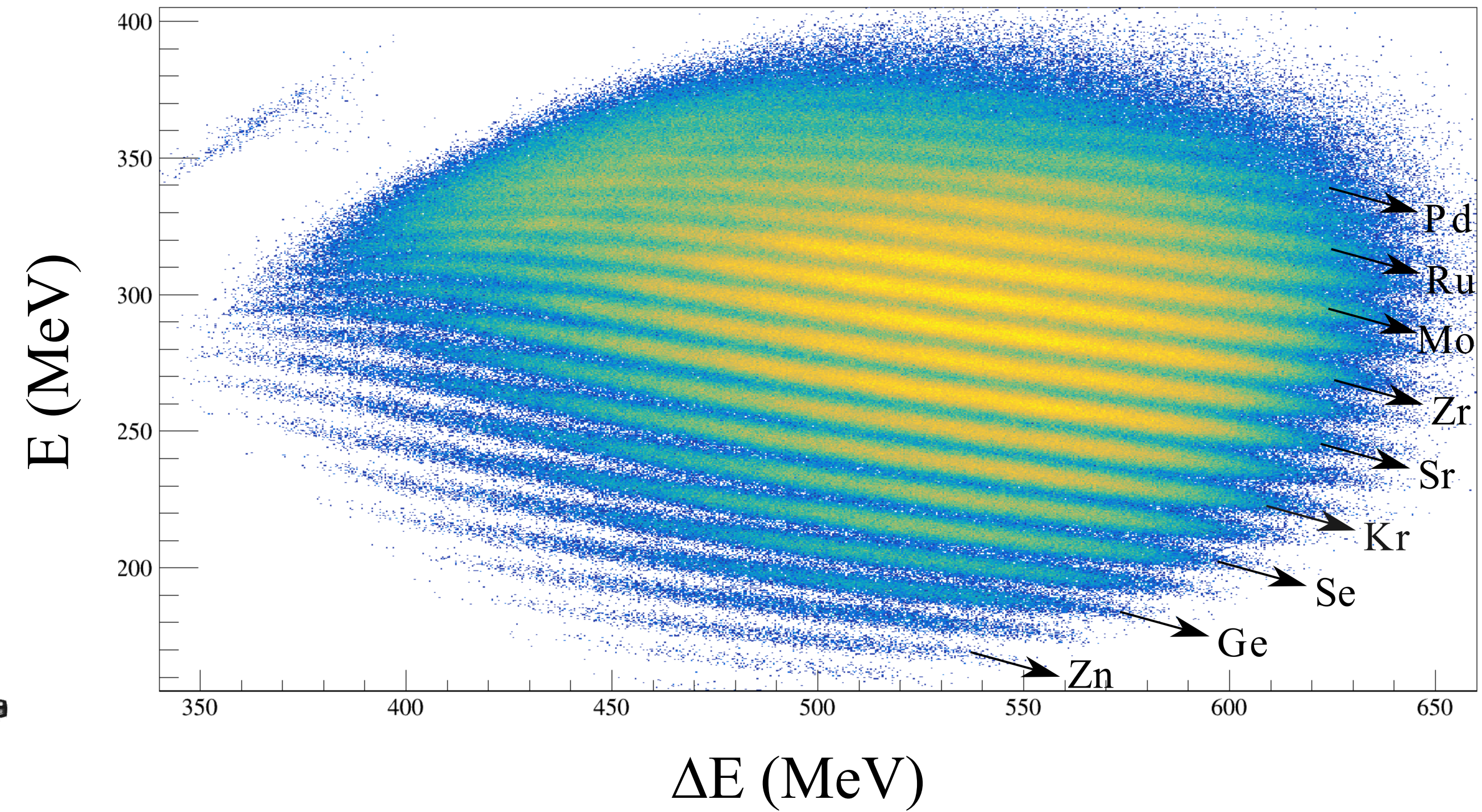
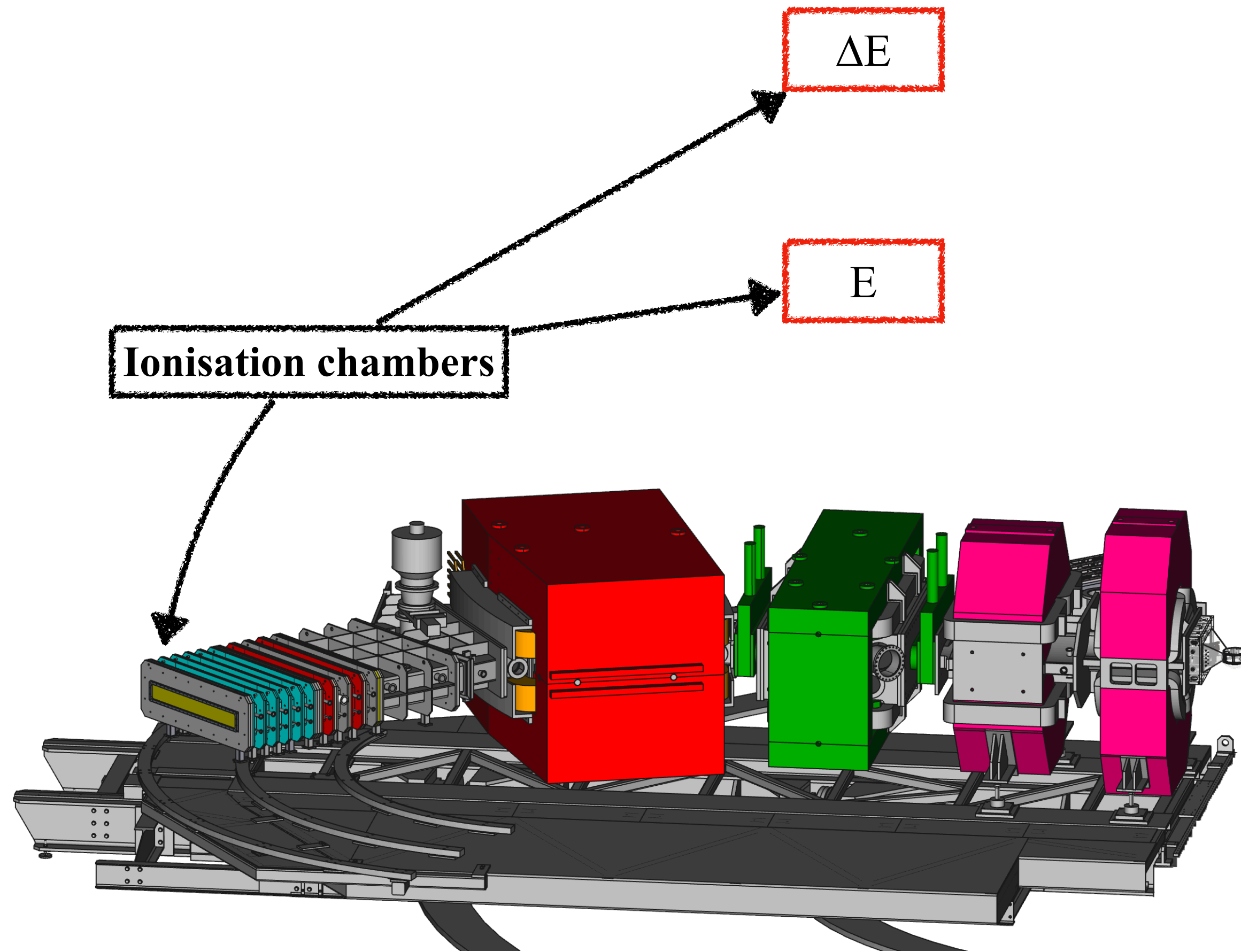
$$Q = \frac{2 \times E_{tot}}{931.5 \times \beta^2} \times \frac{Q}{M}$$

The VAMOS++ spectrometer: Mass identification

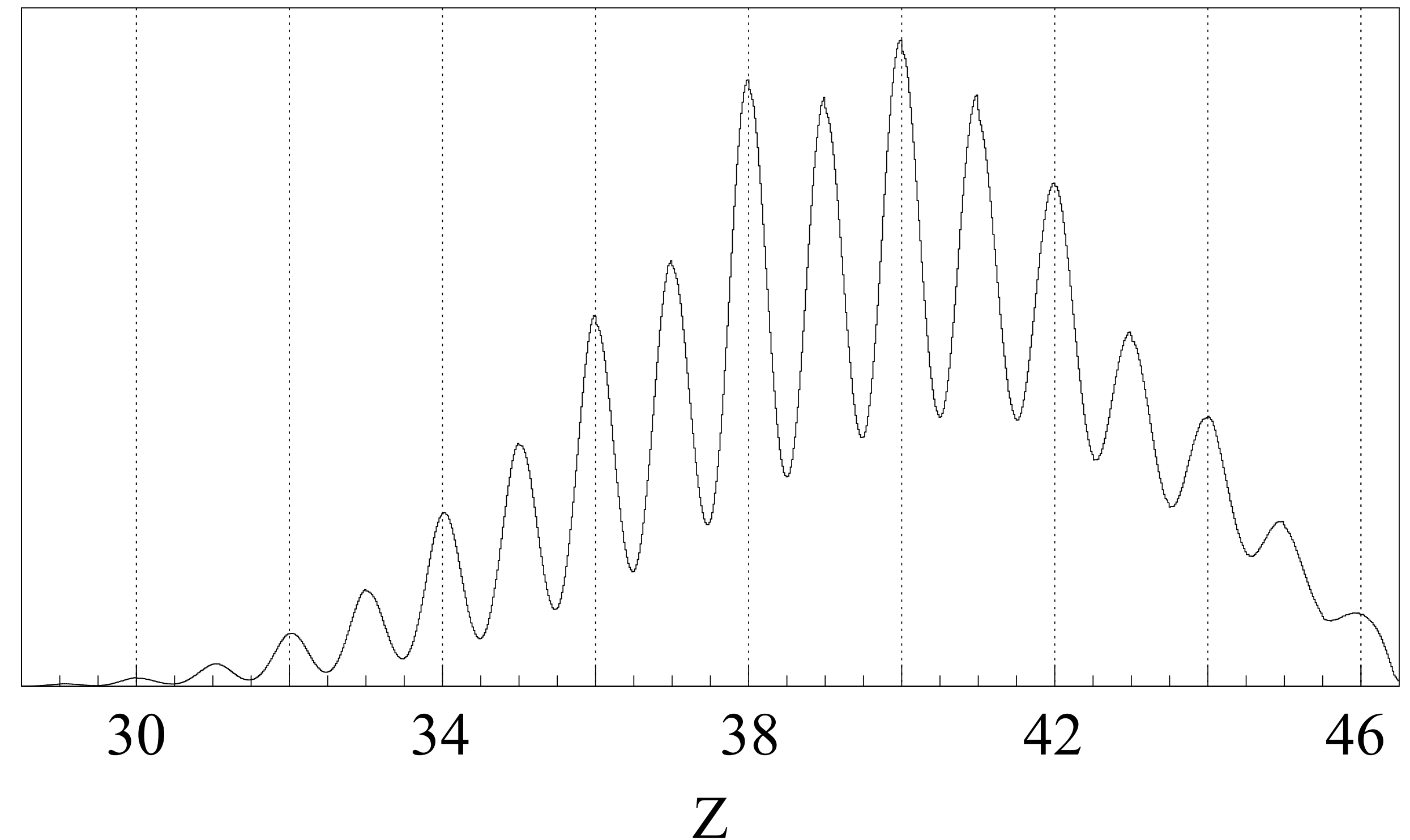
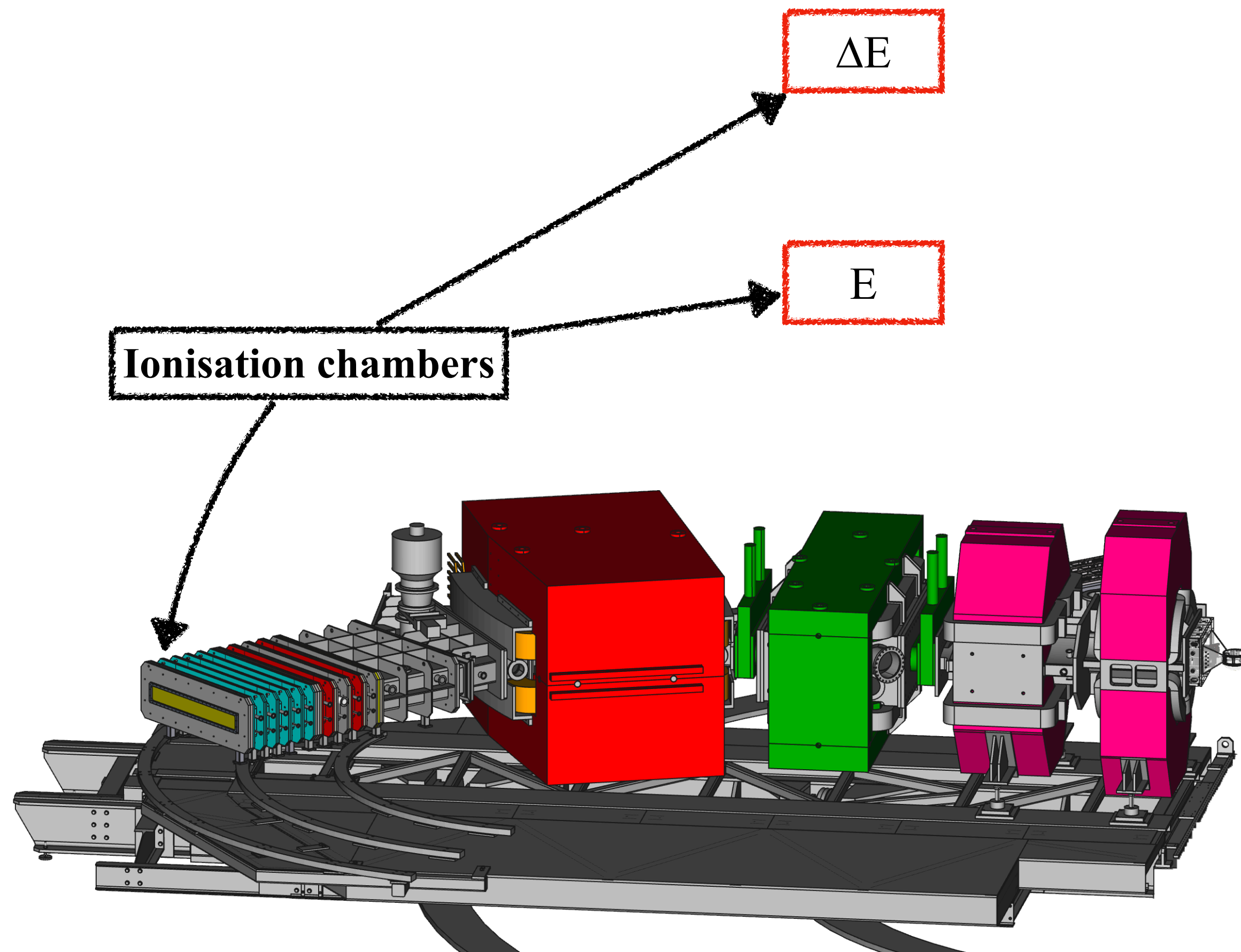


$$\frac{\Delta M}{M} \sim 0.6\%$$

The VAMOS++ spectrometer: Z identification

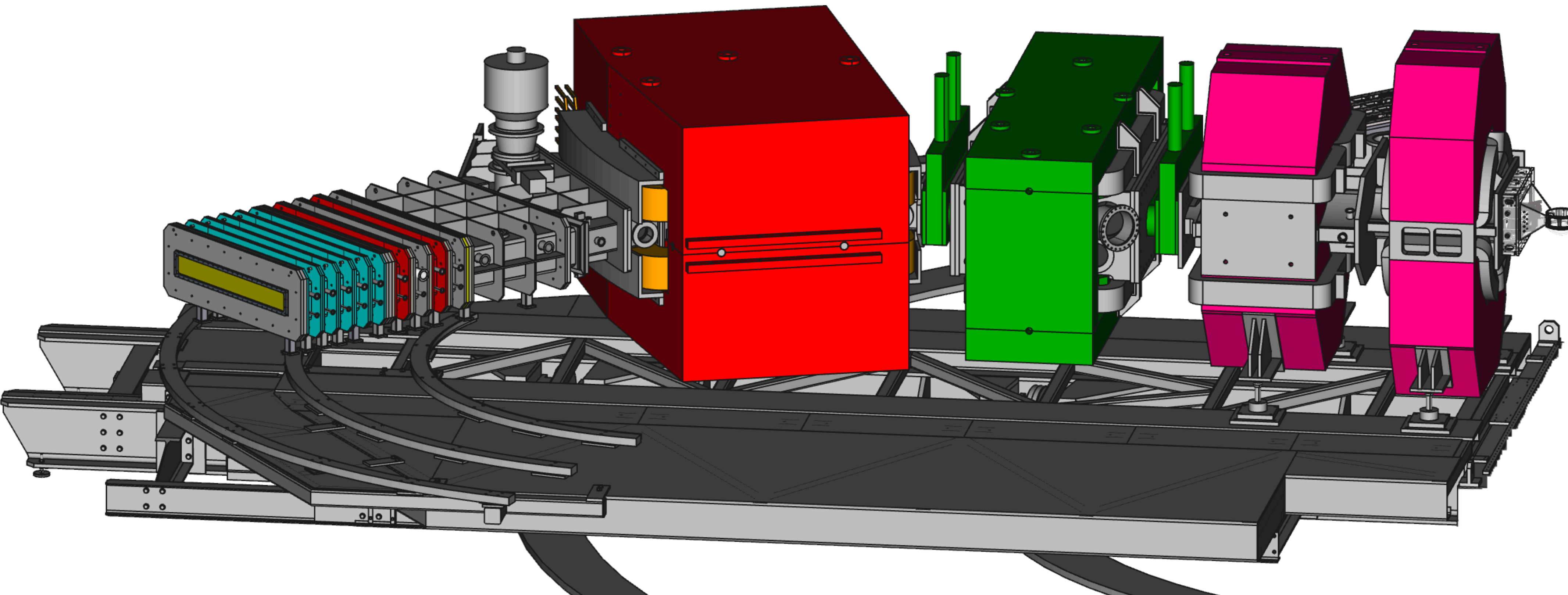


The VAMOS++ spectrometer: Z identification

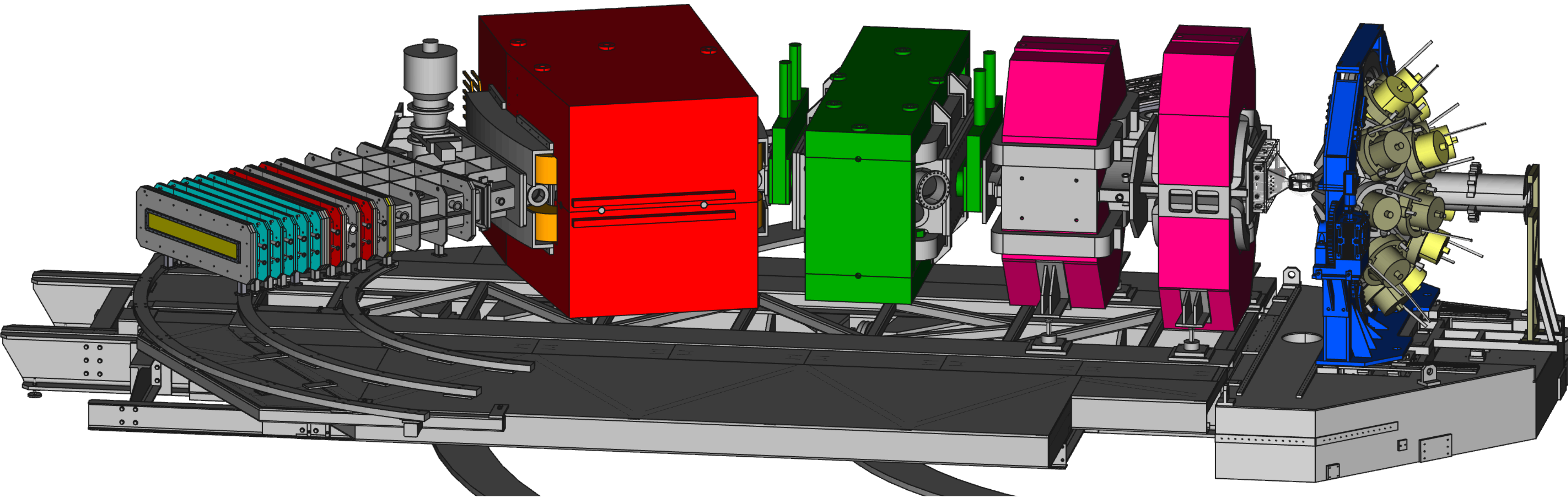


$$\frac{\Delta Z}{Z} \sim 1.5\%$$

The VAMOS++ spectrometer

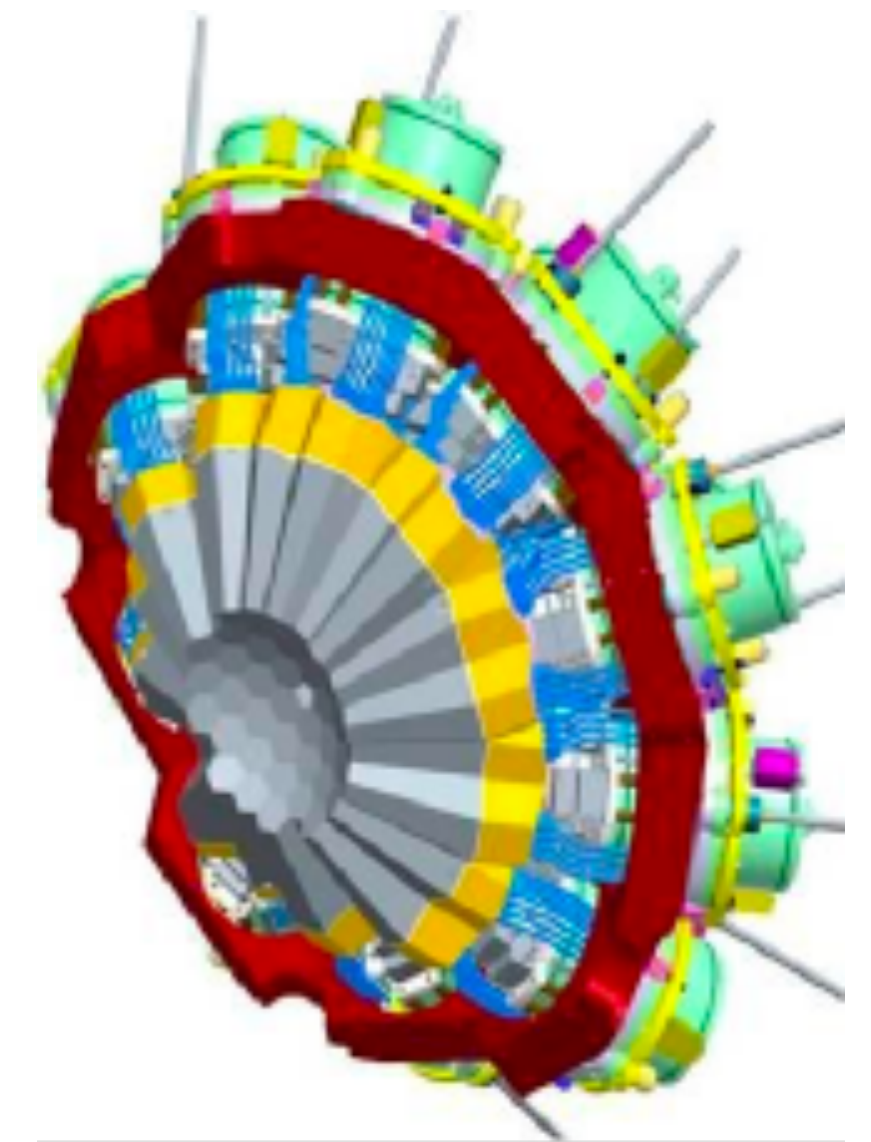
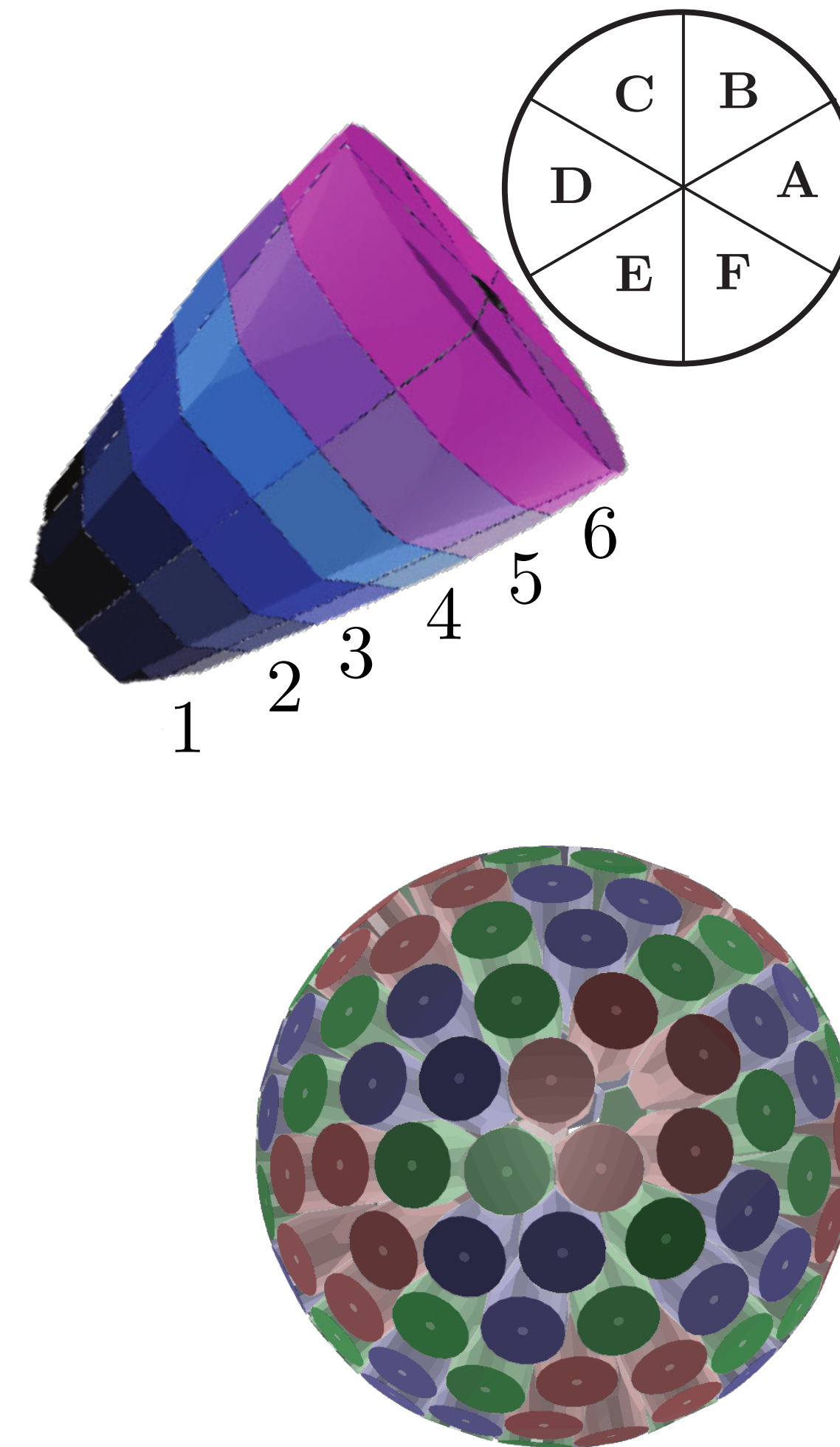


The AGATA Gamma Tracking Array



The AGATA Gamma Tracking Array

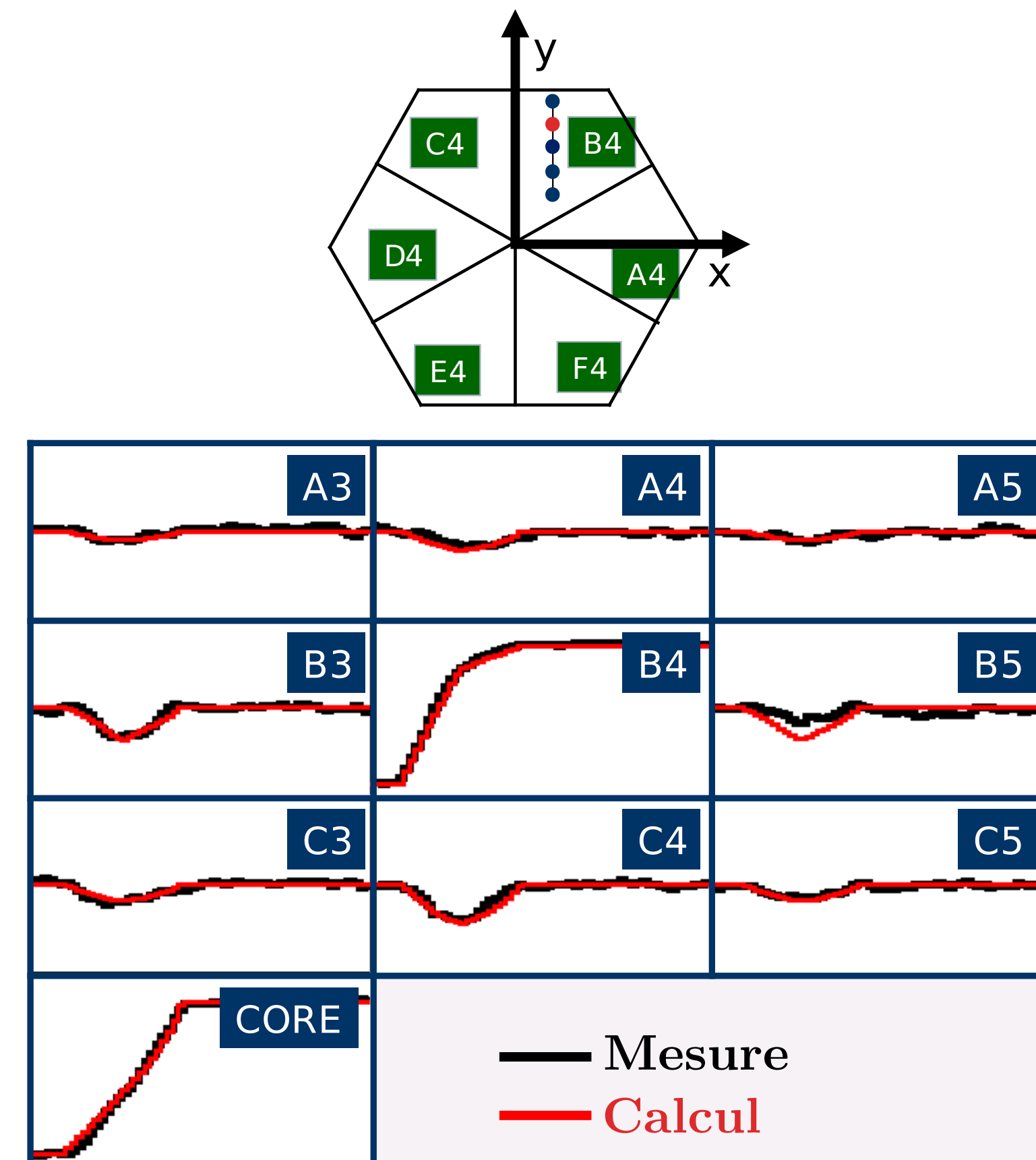
- ➔ Continuous sphere of segmented HPGe crystals
 - ➔ High energy resolution
 - ➔ High efficiency
- ➔ Full digital electronic:
 - ➔ High counting rates capabilities
 - ➔ Position resolution of interaction points ~ 5 mm
- ➔ Tracking of the γ -ray path in the crystals
 - ➔ Increased peak to background ratio
 - ➔ Very precise Doppler Correction



The AGATA Gamma Tracking Array

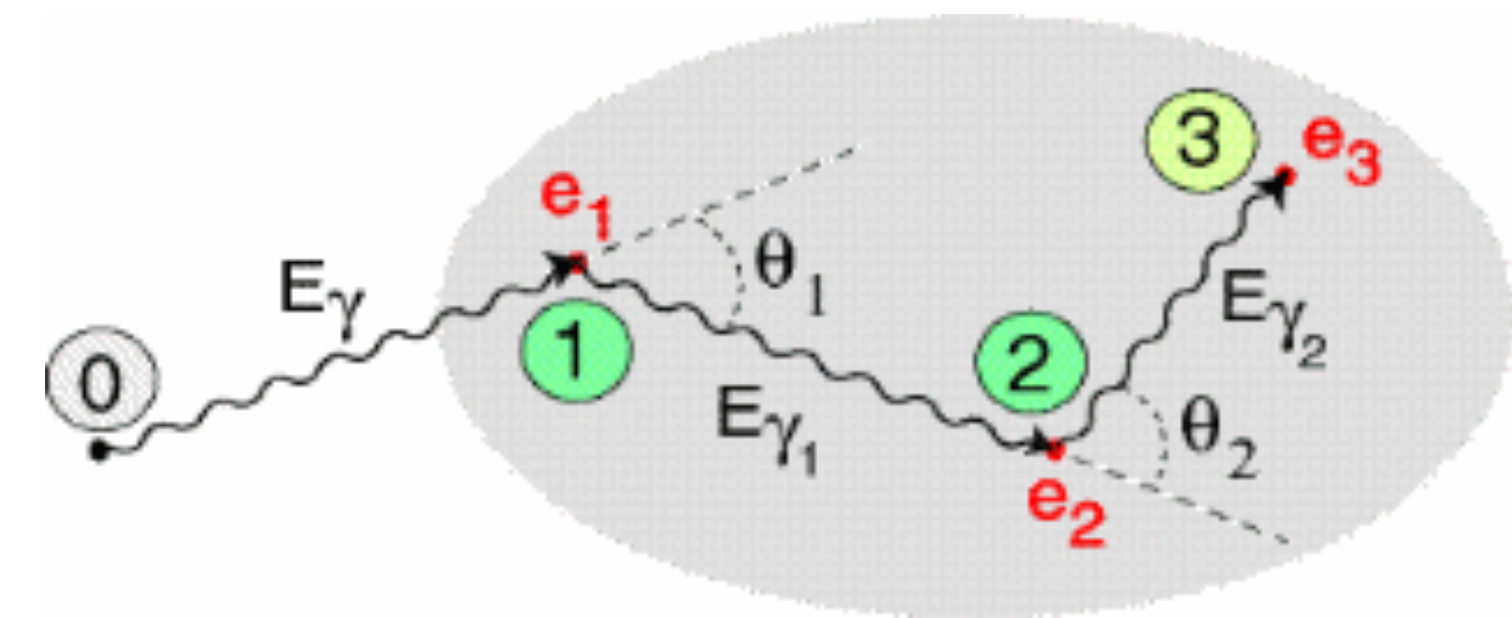
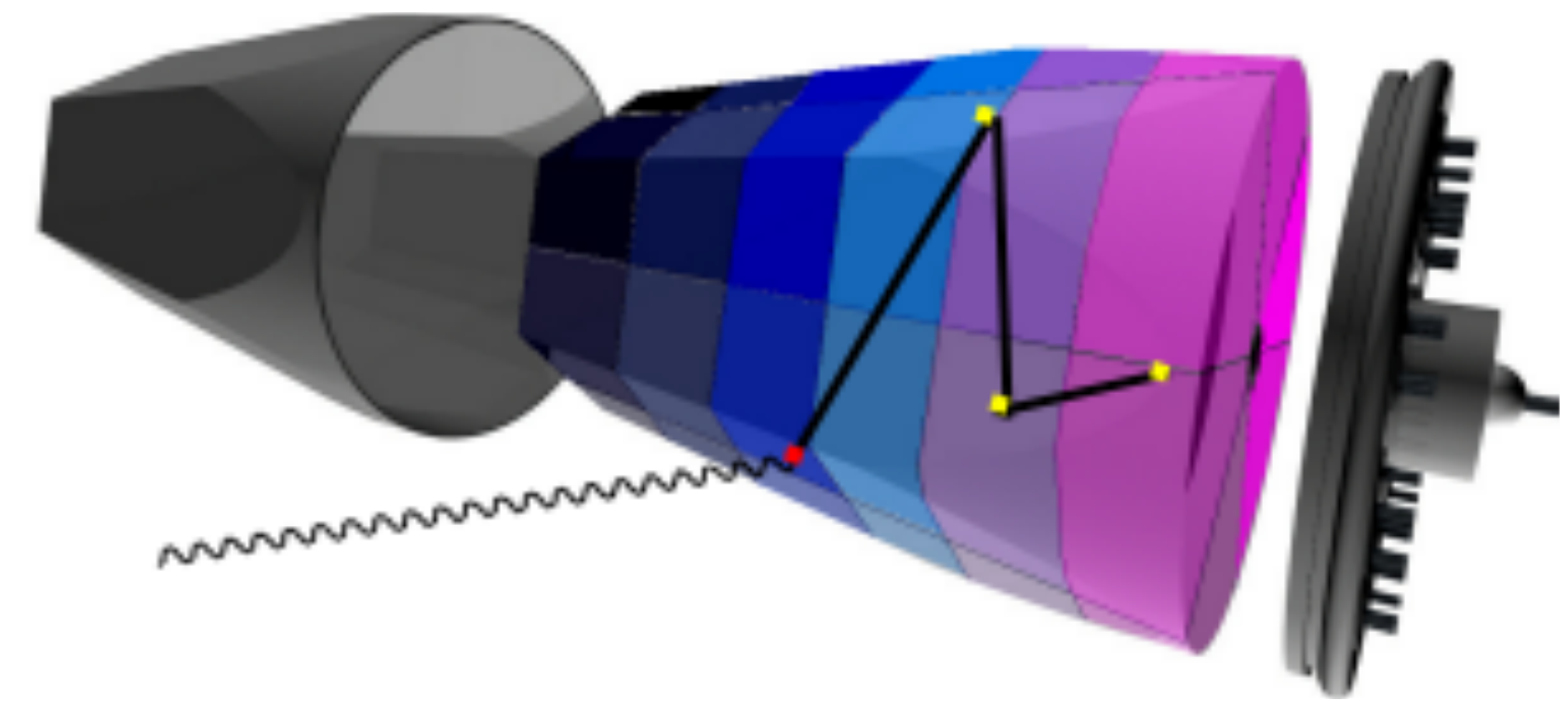
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The Pulse Shape Analysis method (PSA)



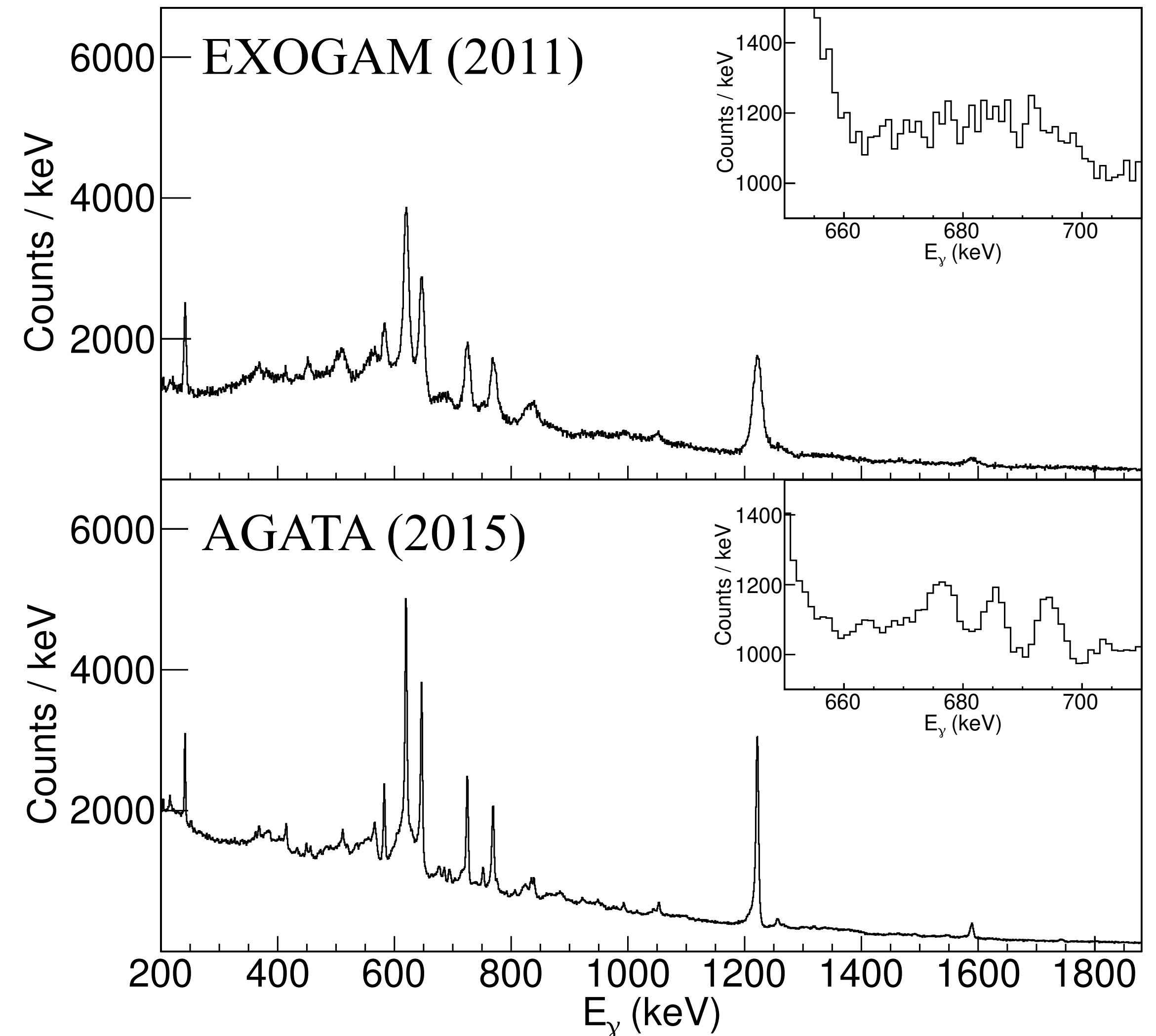
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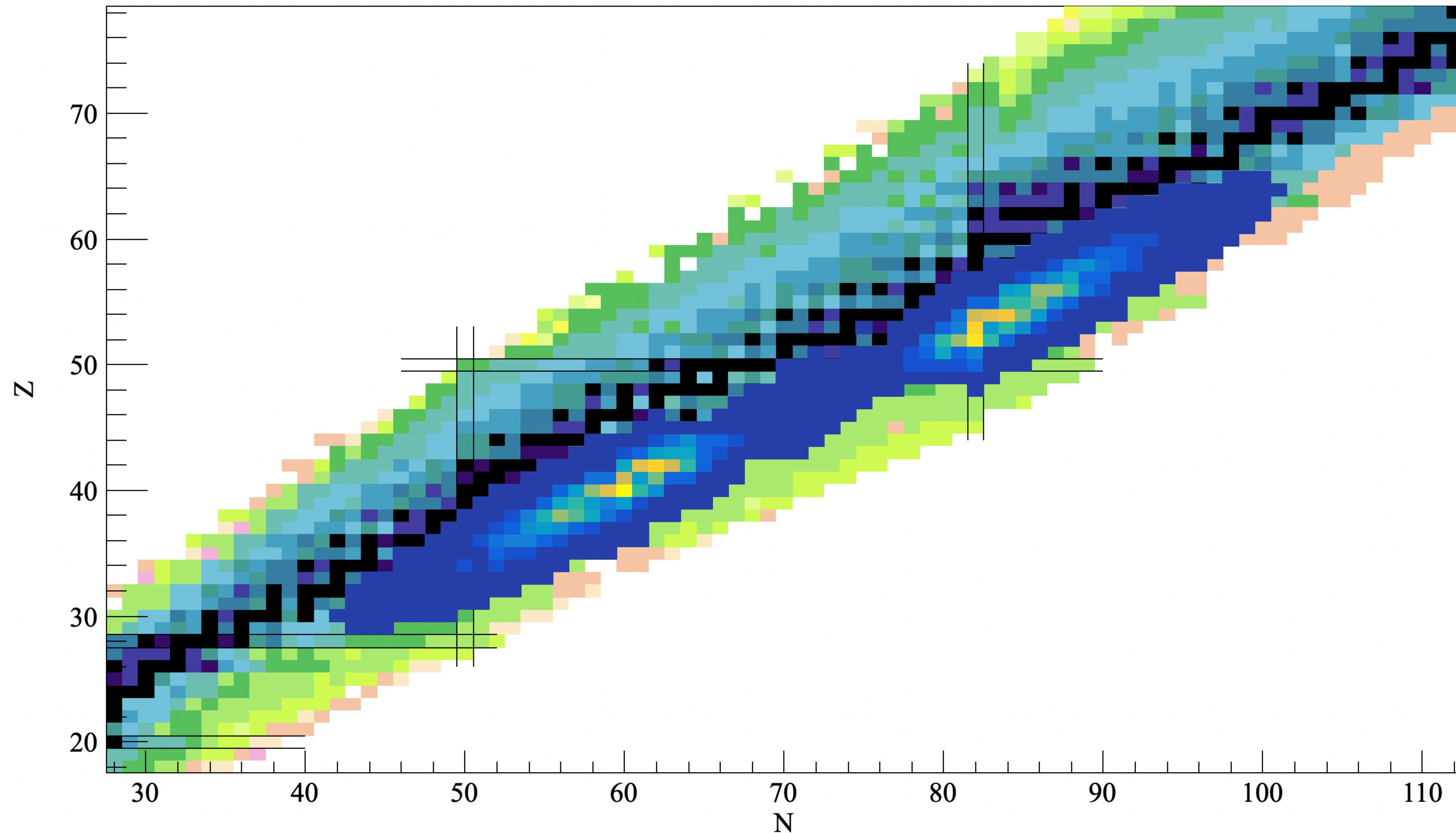
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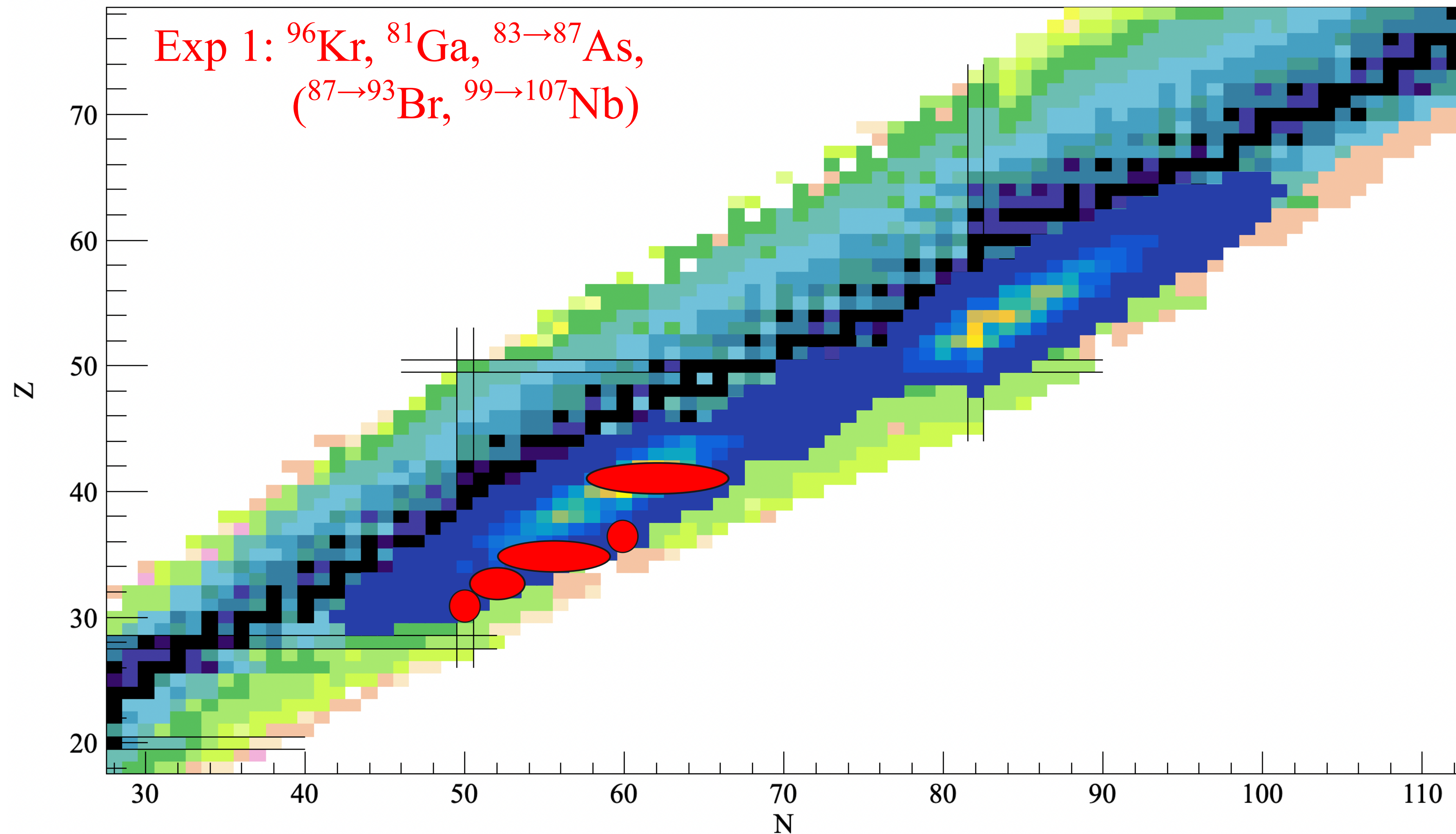
The AGATA / VAMOS++ fission campaigns @ GANIL (2015-2021)

Exp	Duration (days)	VAMOS- γ events	VAMOS			AGATA
			VAMOS angle	Z range	Plunger	Crystals
1	14	6×10^8	28	$\sim [30 ; 45]$		24
2	10	2×10^8	28	$\sim [30 ; 45]$		24
3	14	4×10^8	20	$\sim [35 ; 60]$		32
4	10	4×10^8	19	$\sim [35 ; 60]$		35

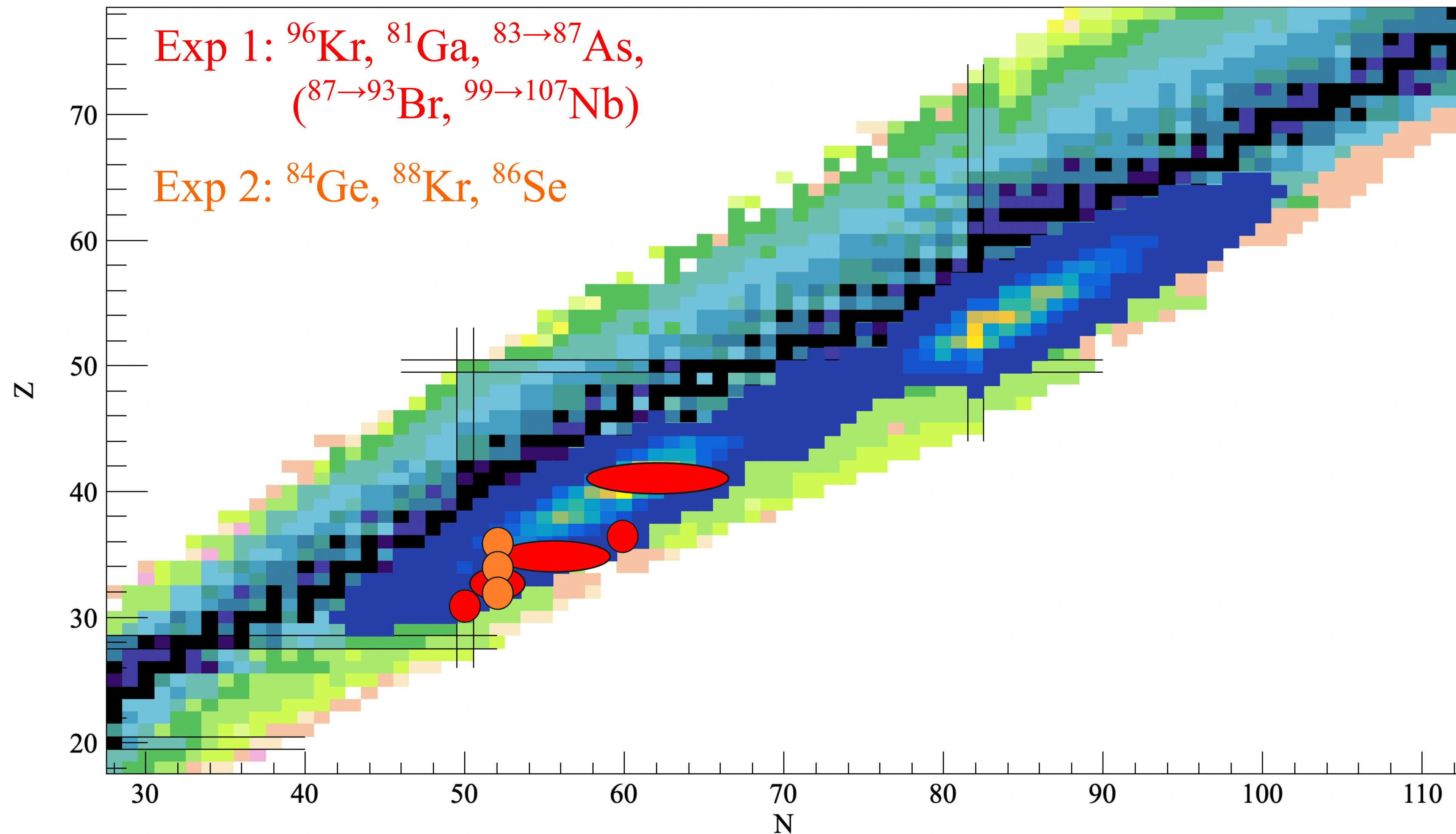
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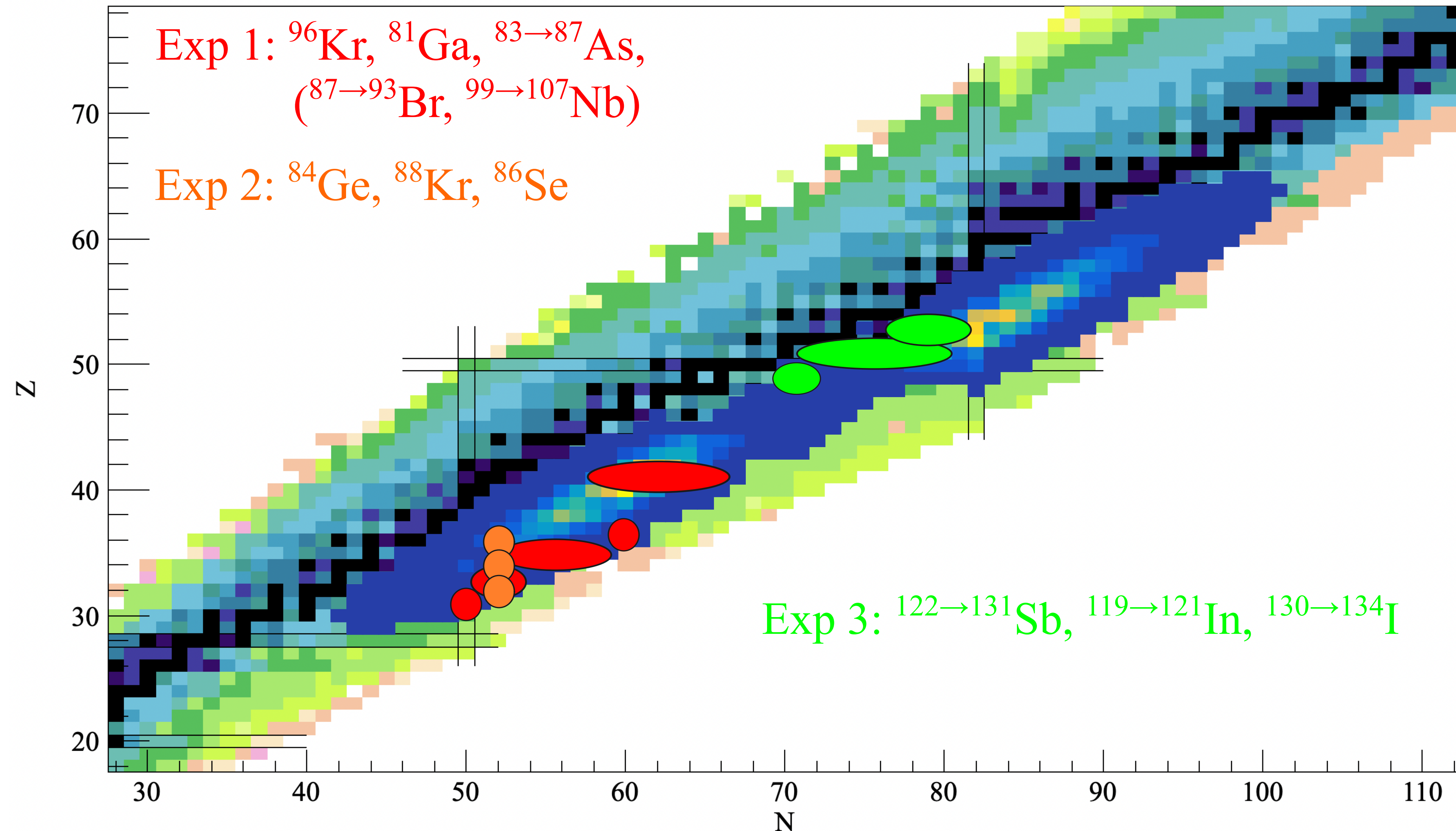
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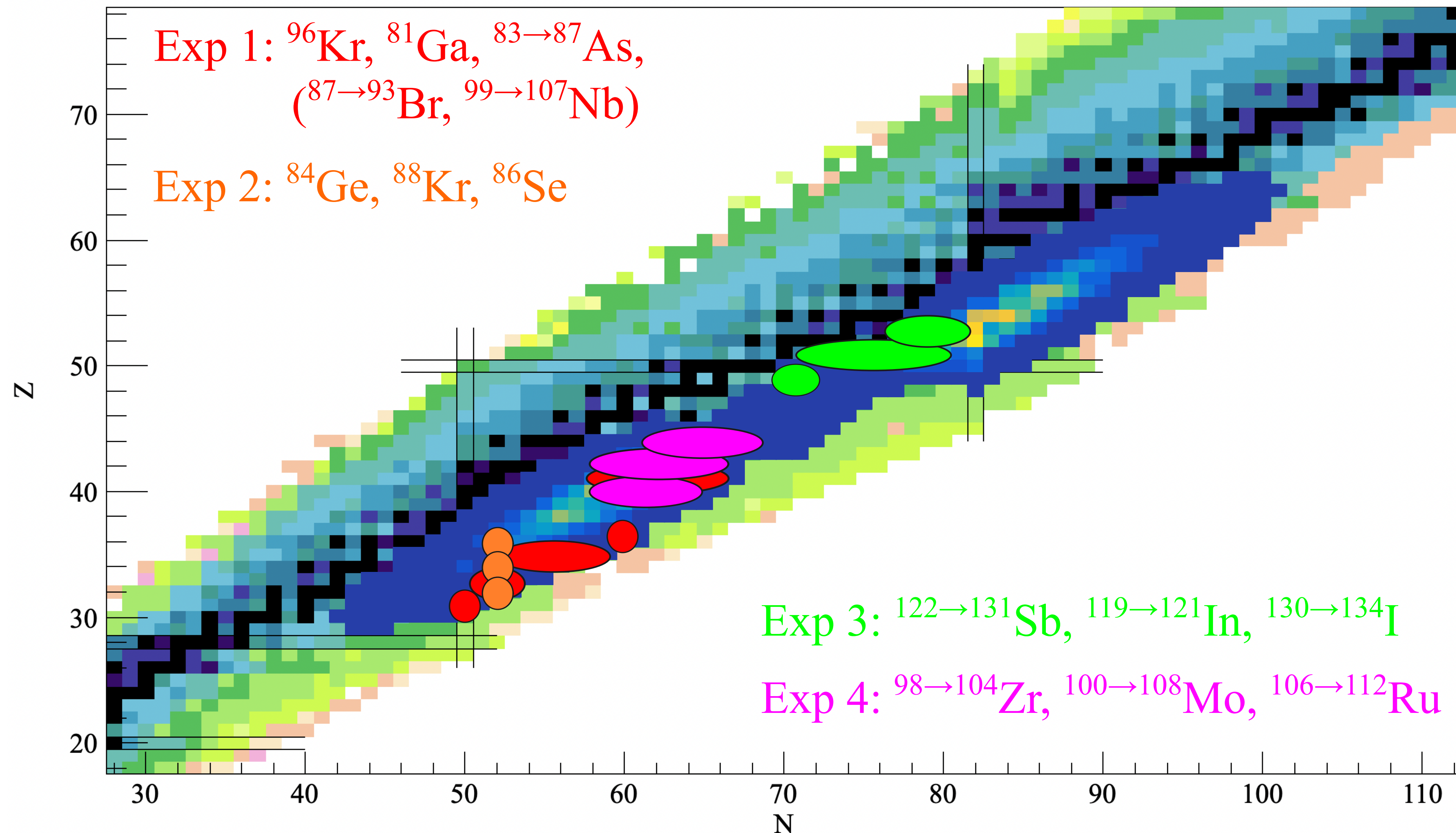
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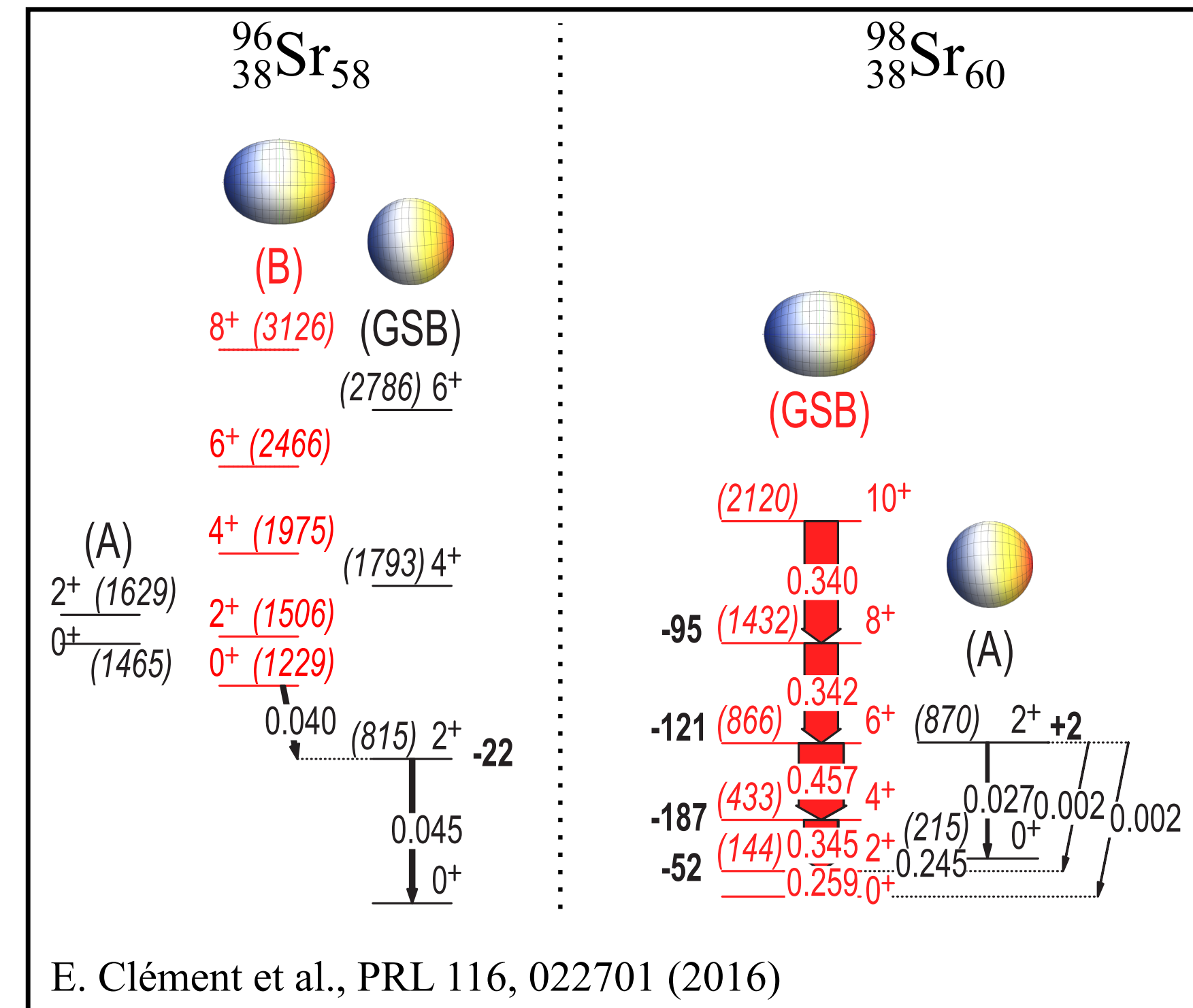
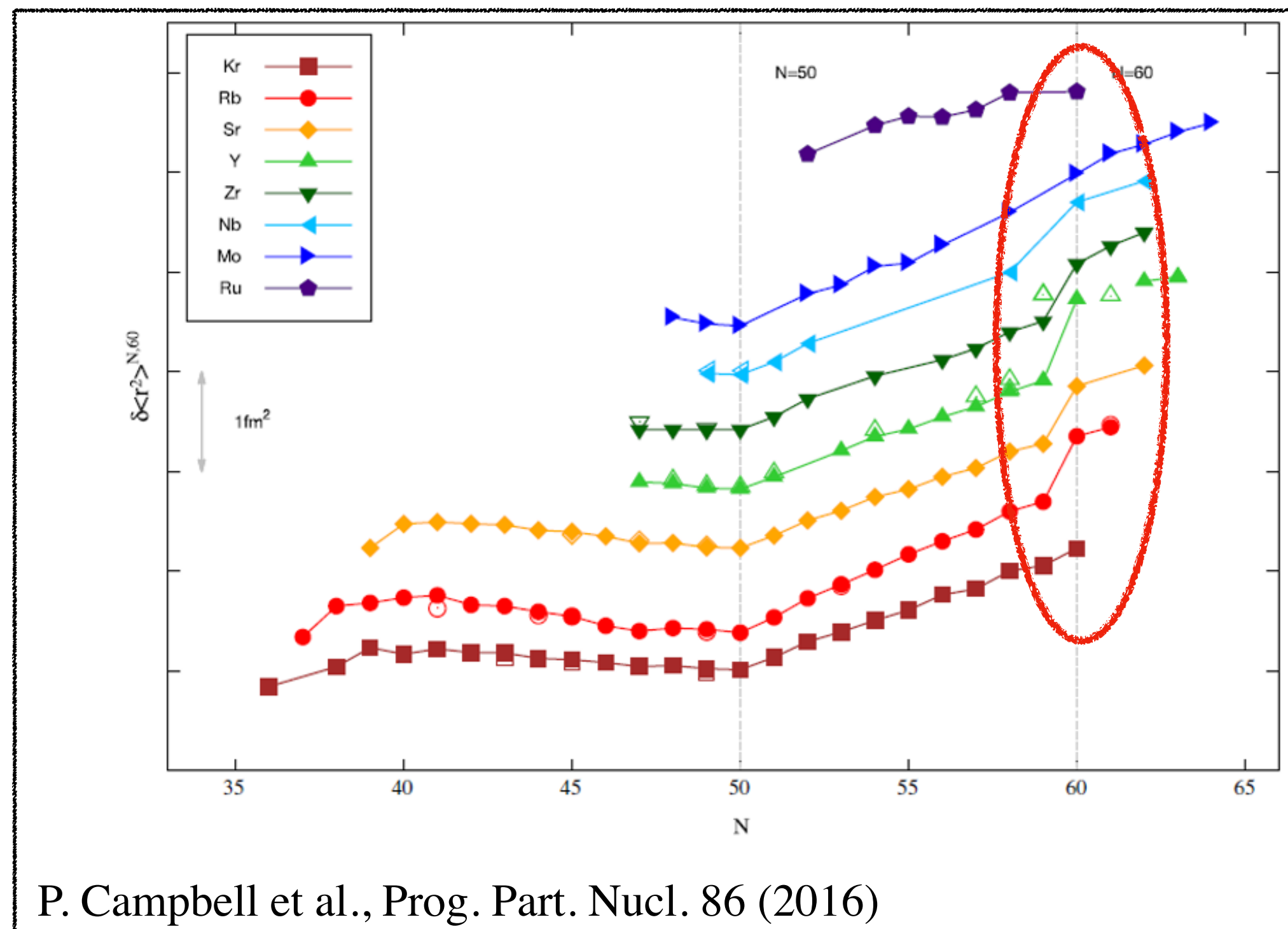


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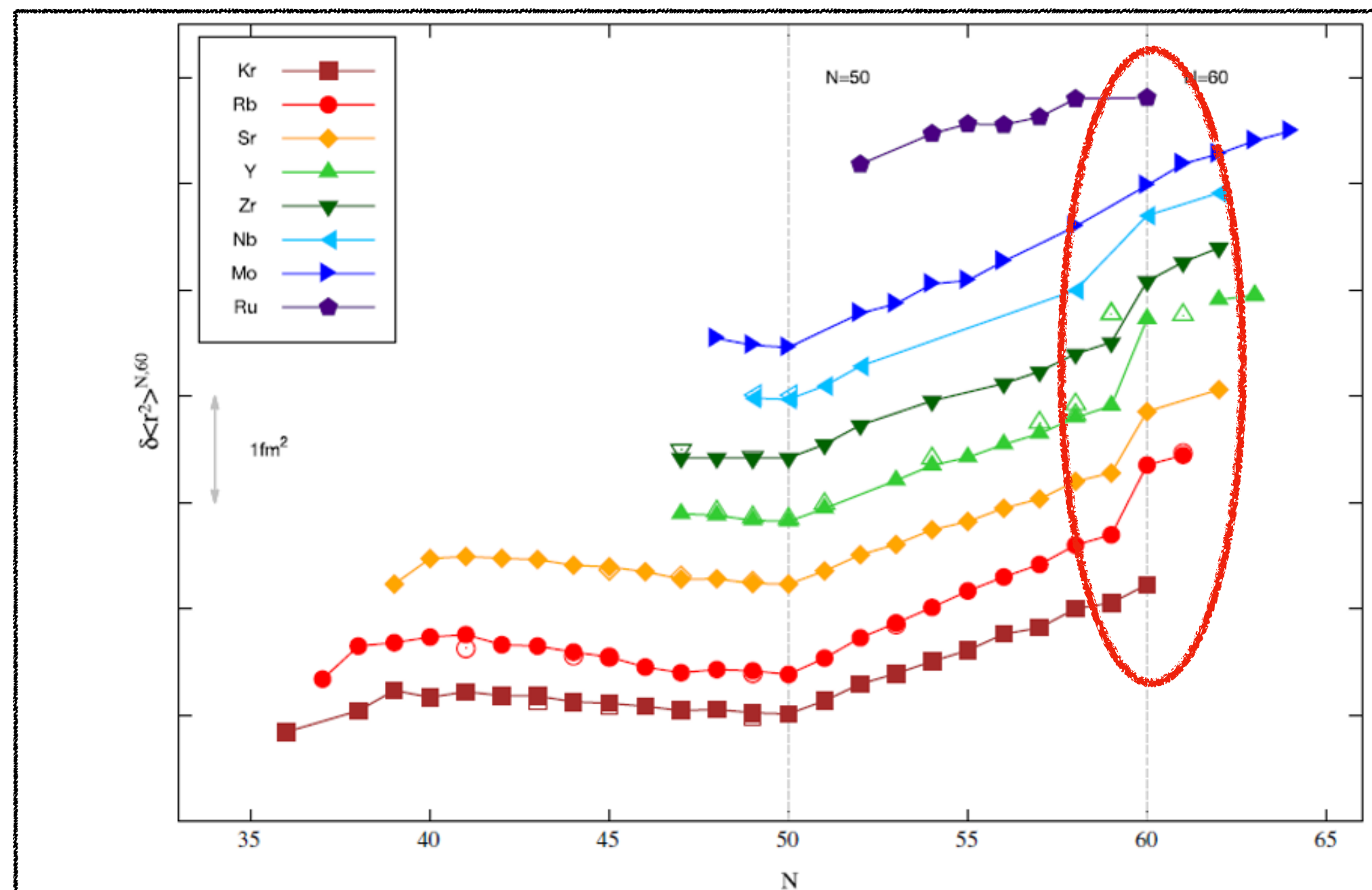
Some physics cases: The ^{96}Kr spectroscopy

- ➔ Spectacular shape transition at $N=60$ due to a shape coexistence phenomenon
- ➔ Well described theoretically by Monte-Carlo Shell Model calculation at $Z=40$
- ➔ but still challenging to describe the limits of this region theoretically

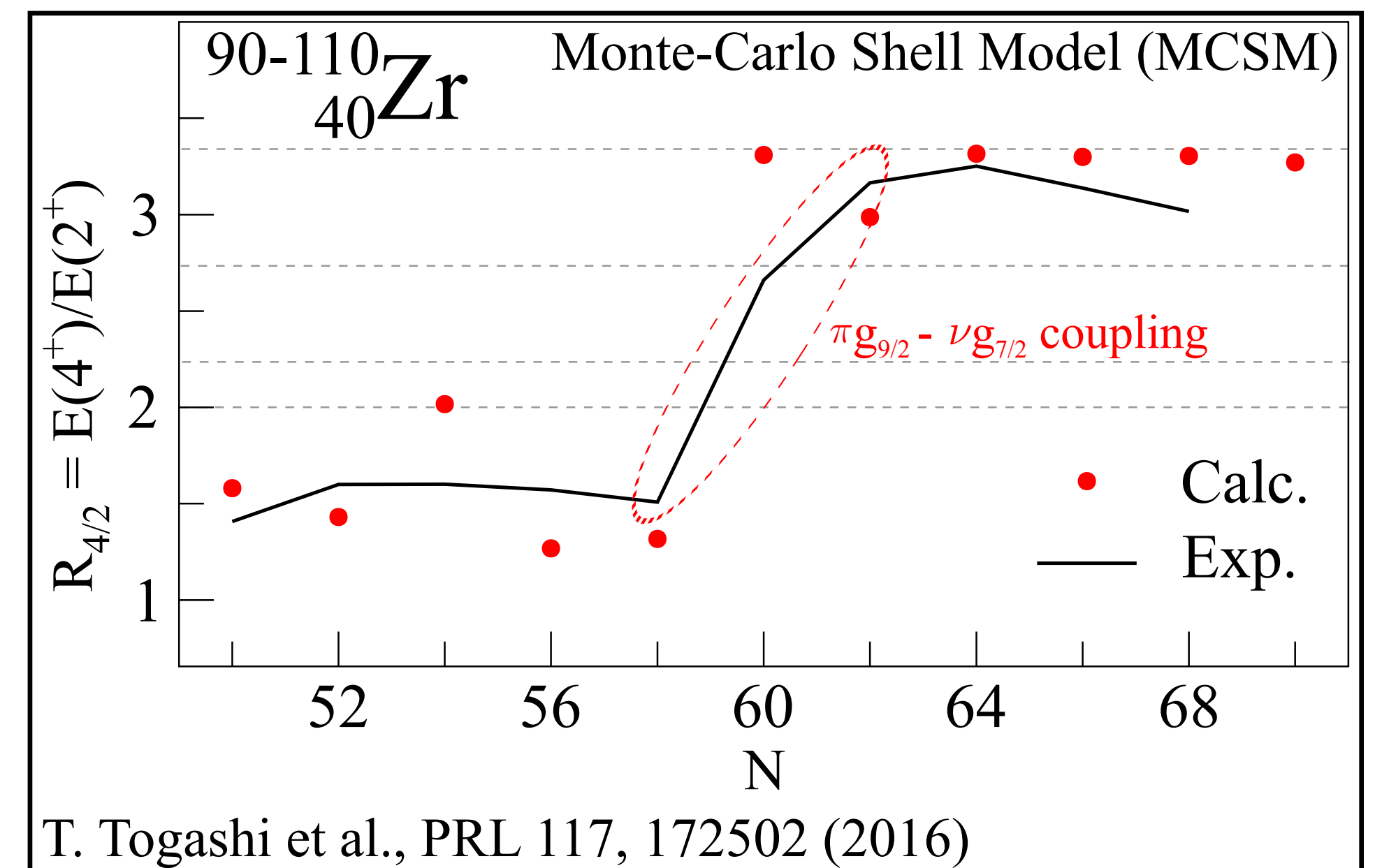


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P. Campbell et al., Prog. Part. Nucl. 86 (2016)



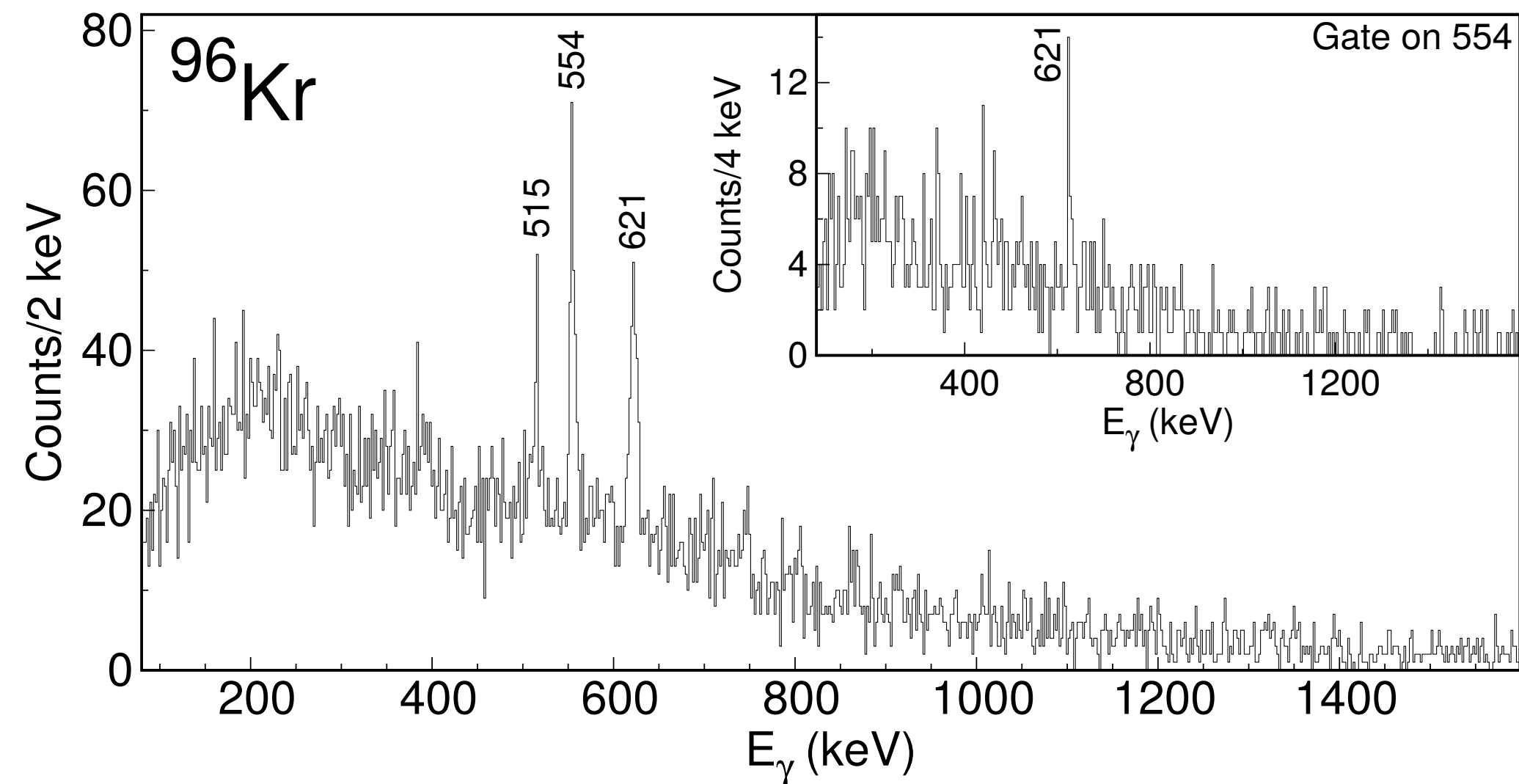
T. Togashi et al., PRL 117, 172502 (2016)

Some physics cases: The ^{96}Kr spectroscopy

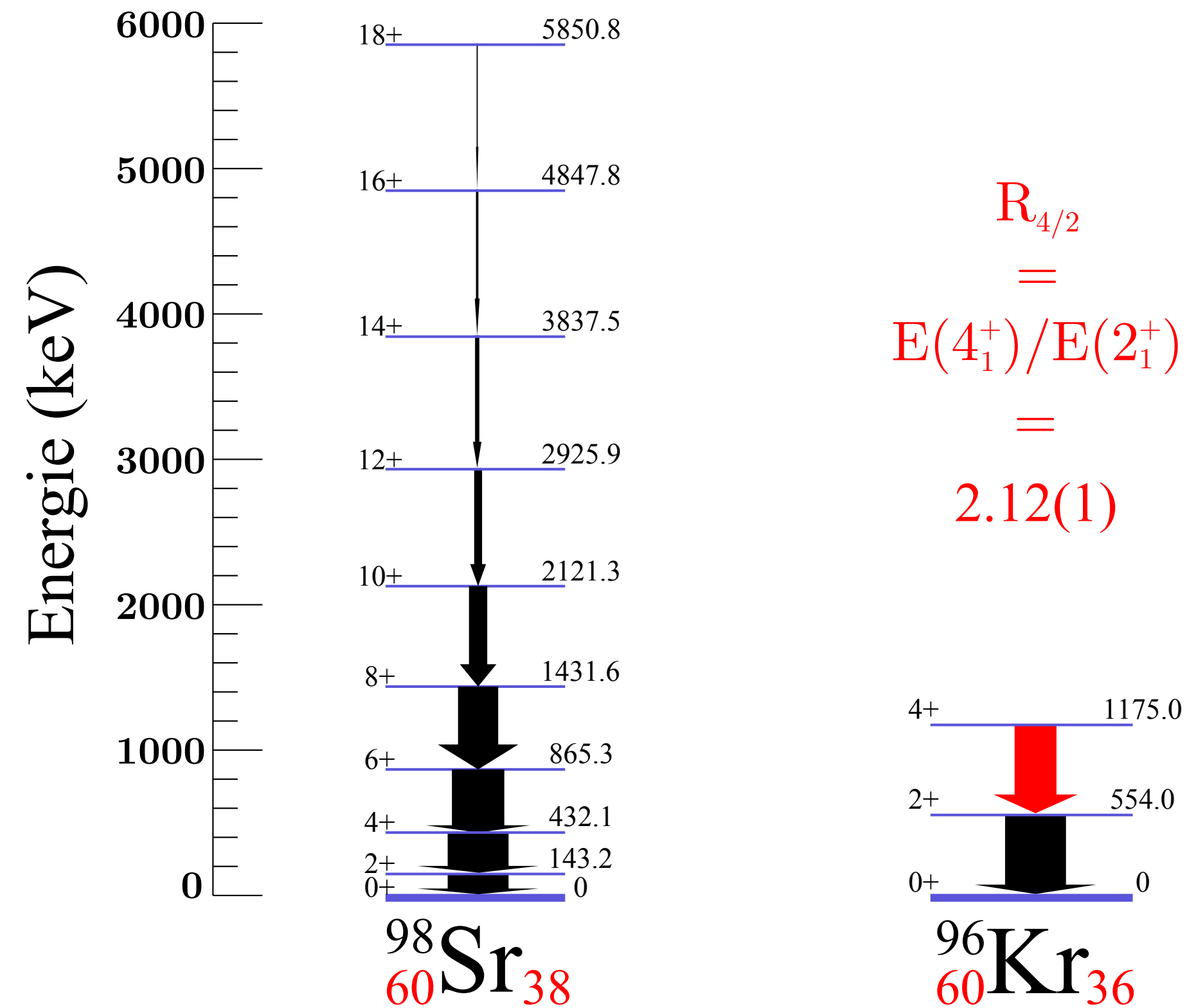
➔ First result from the fission campaigns at GANIL: ^{96}Kr , as the low Z-boundary of this deformation region

➔ First measurement of the 4^+ level in ^{96}Kr

➔ Kr follows an unexpected trend between $R_{4/2}$ and $B(E2)$: hints of oblate/prolate shape coexistence ?



J. Dudouet et al., Phys. Rev. Lett 118, 162501 (2017)

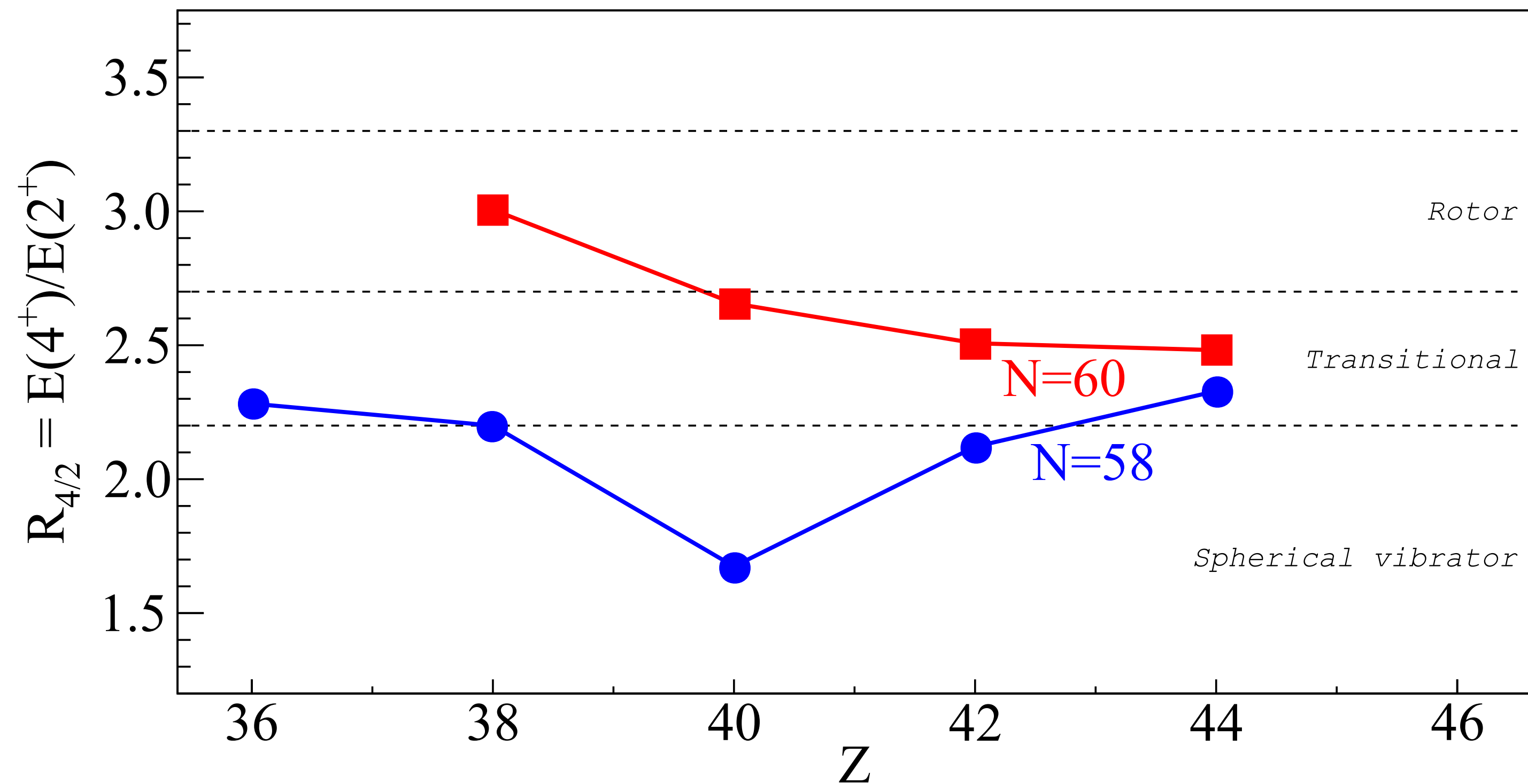


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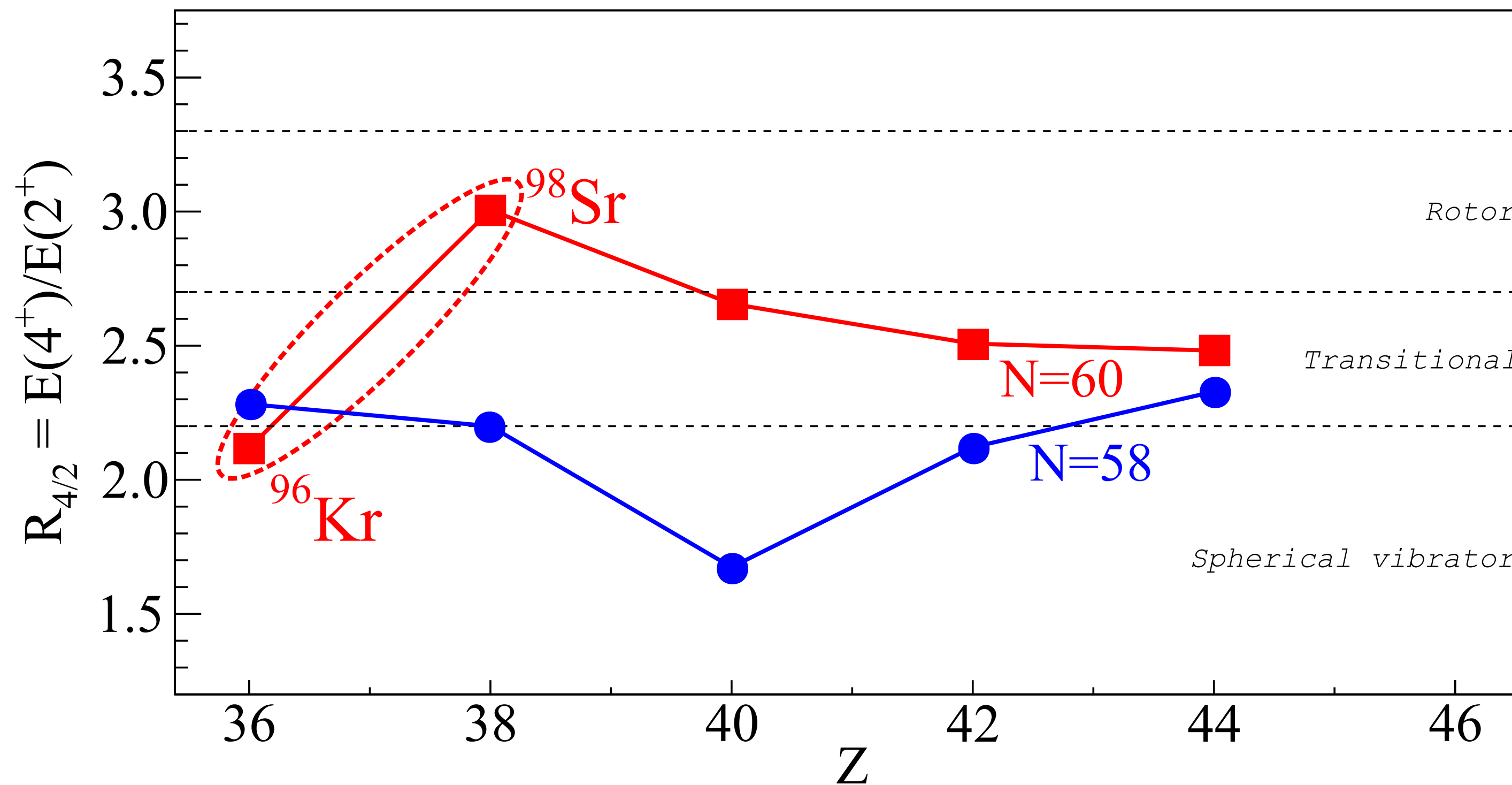
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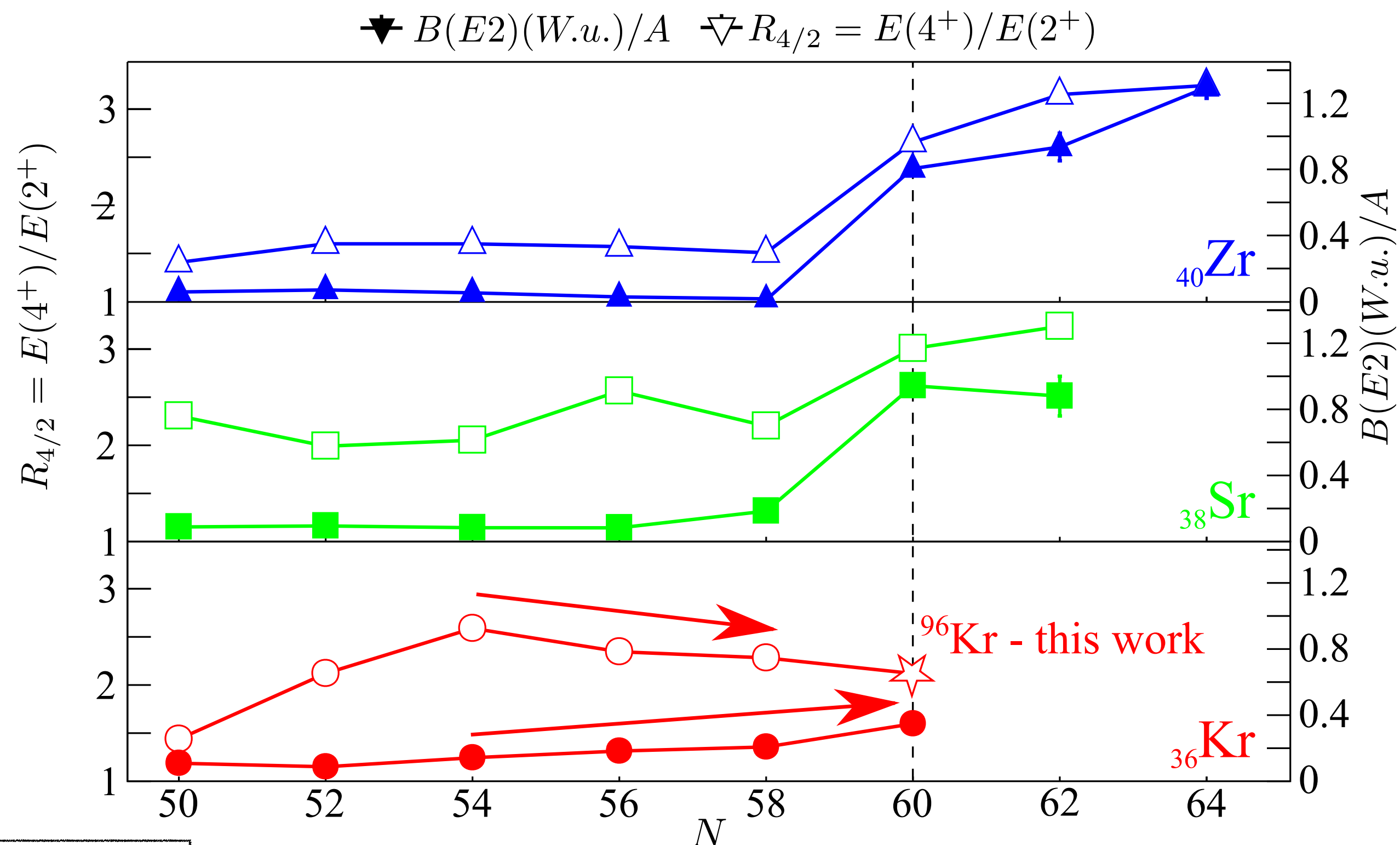
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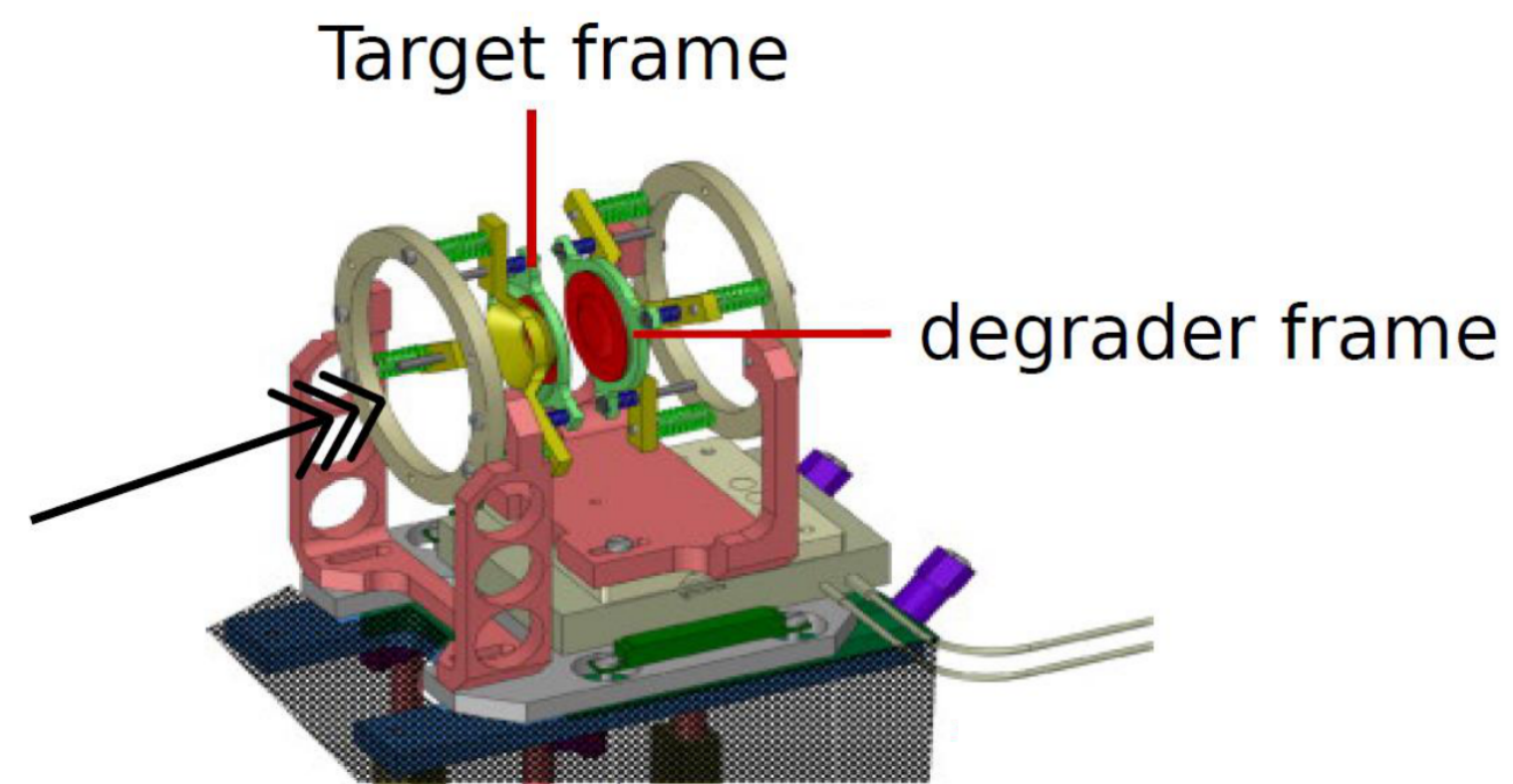


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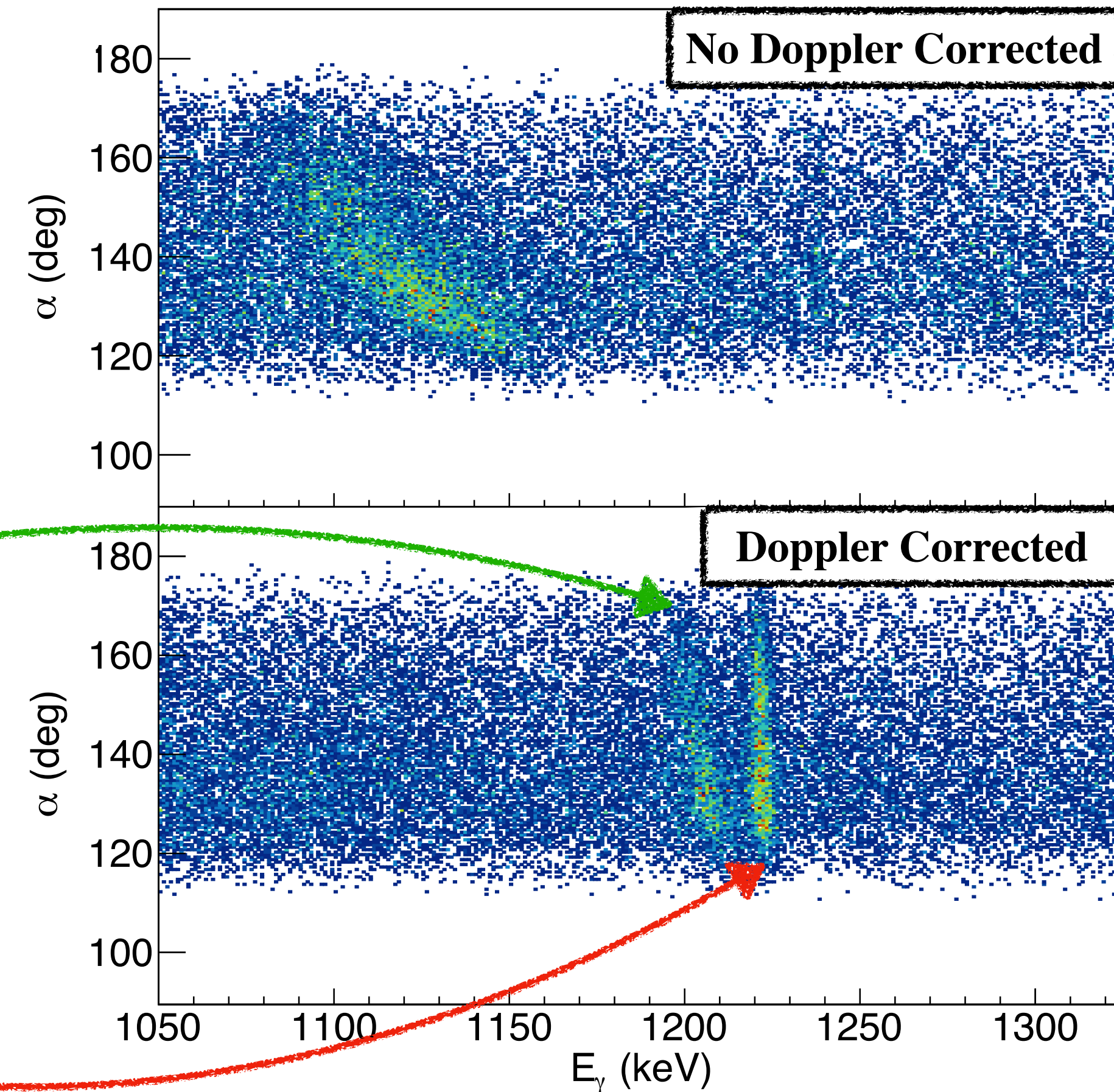
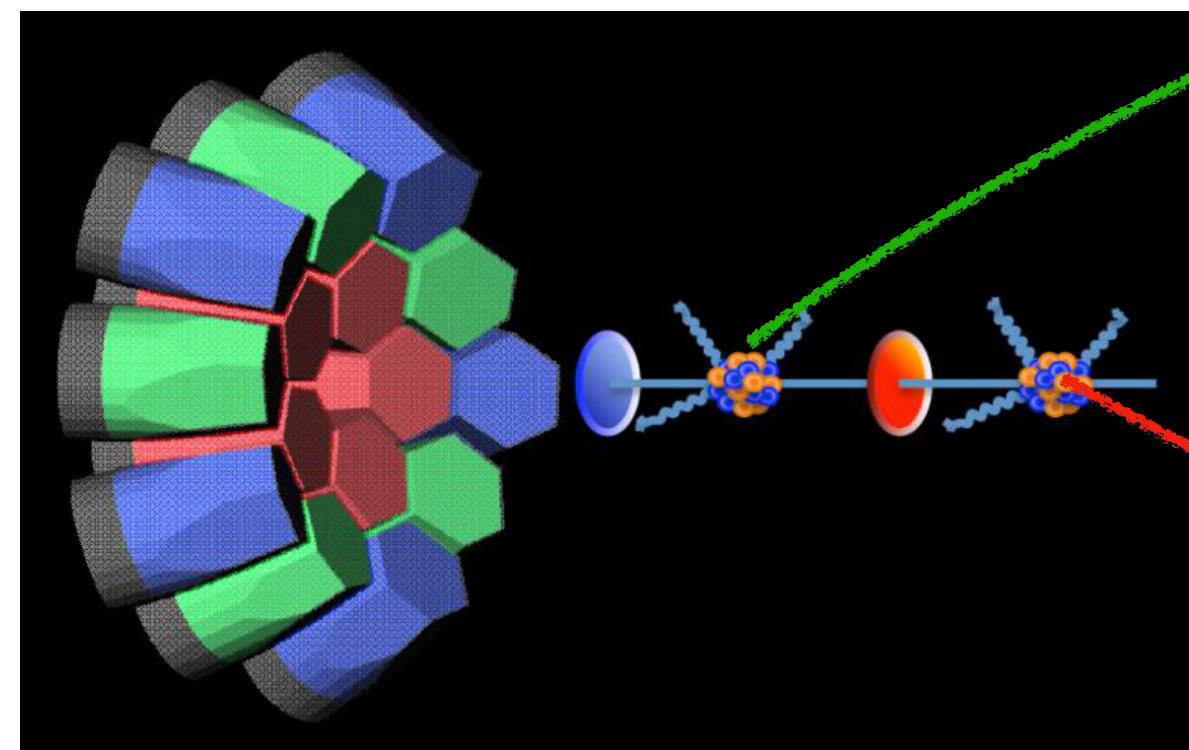
Some physics cases: Lifetimes in neutron rich Zr, Mo and Ru

➔ Lifetime measurements in the Zr, Mo, Ru nuclei using RDDS* method

* Recoil Distance Doppler Shift



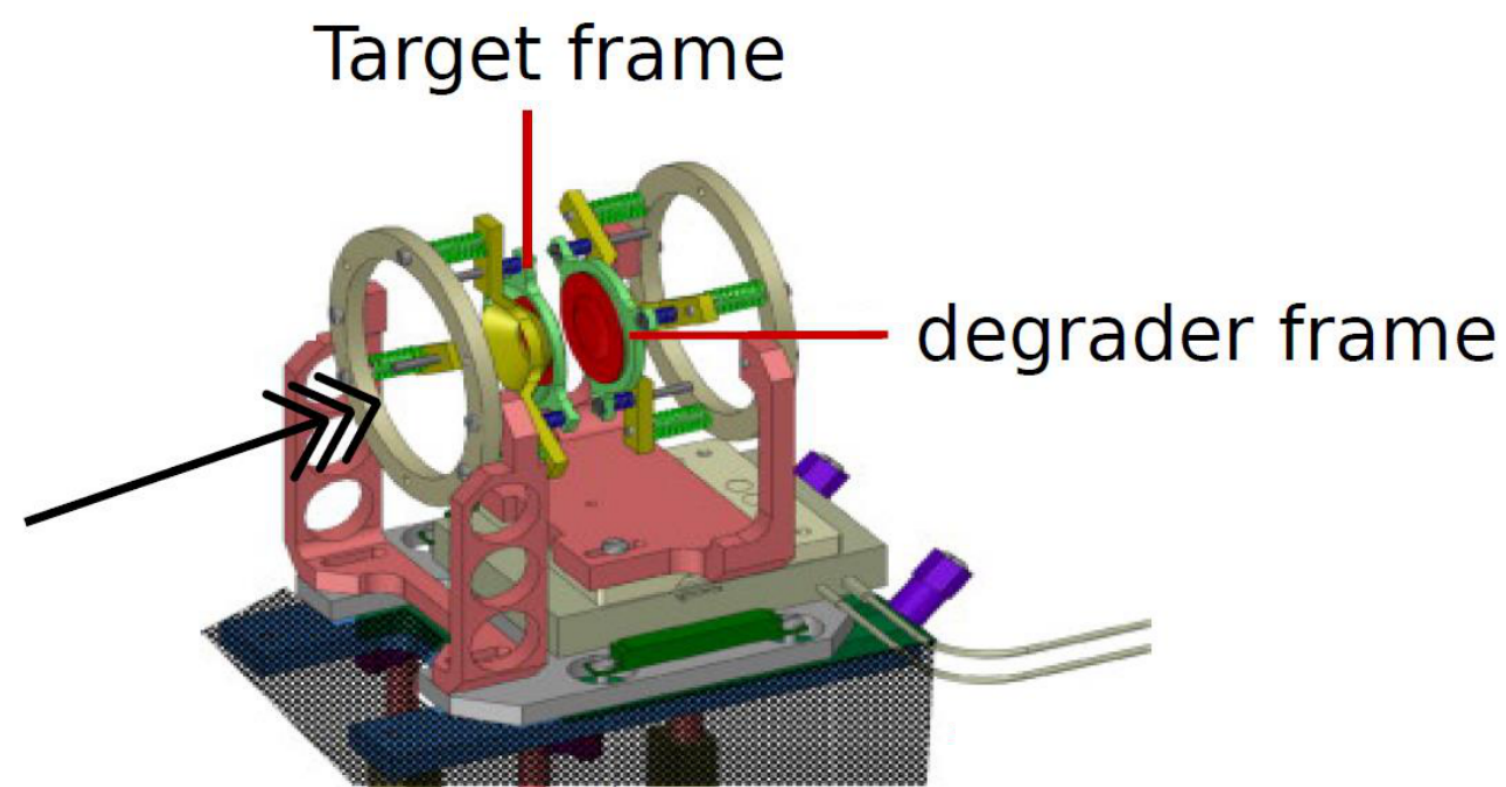
The OUPS Plunger: adapted from S. Ansari PhD thesis



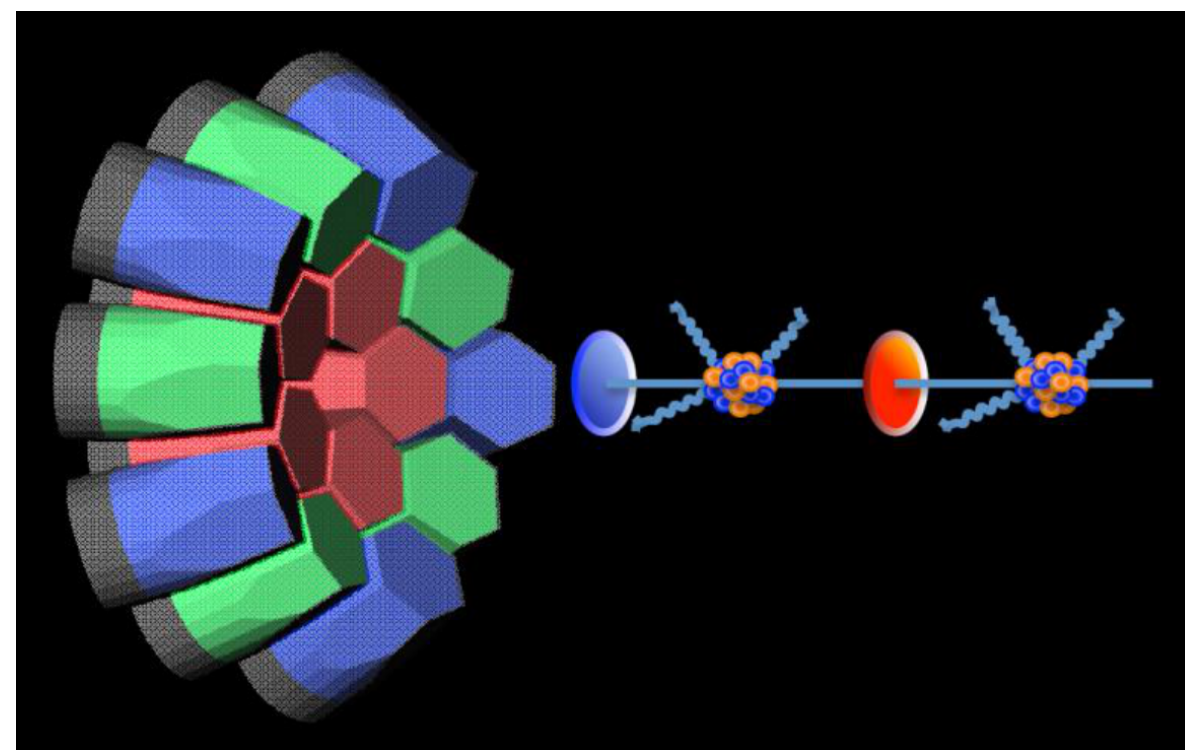
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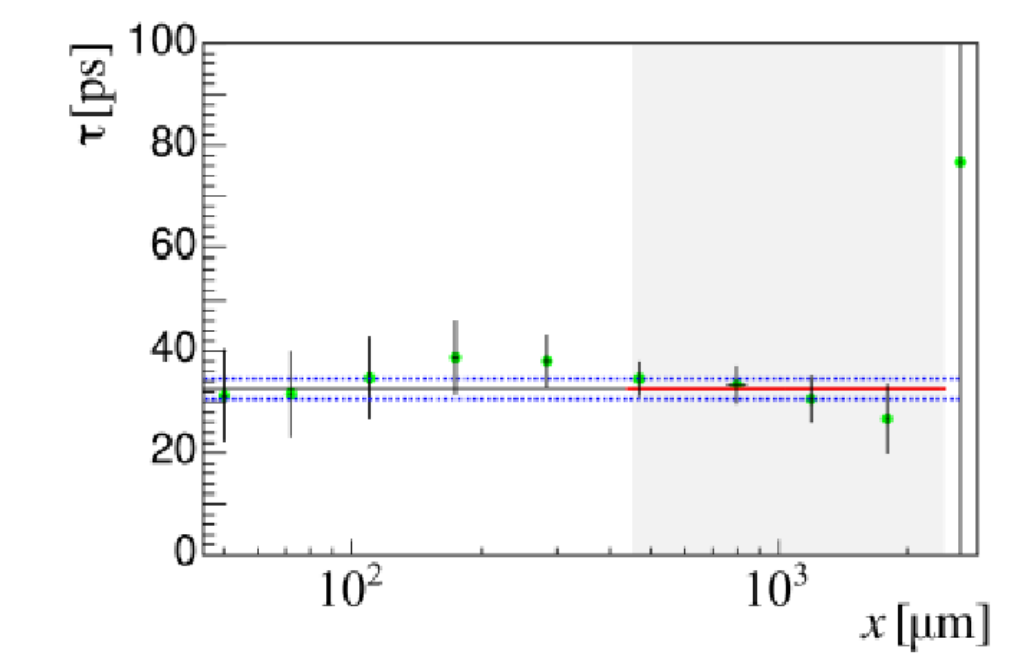
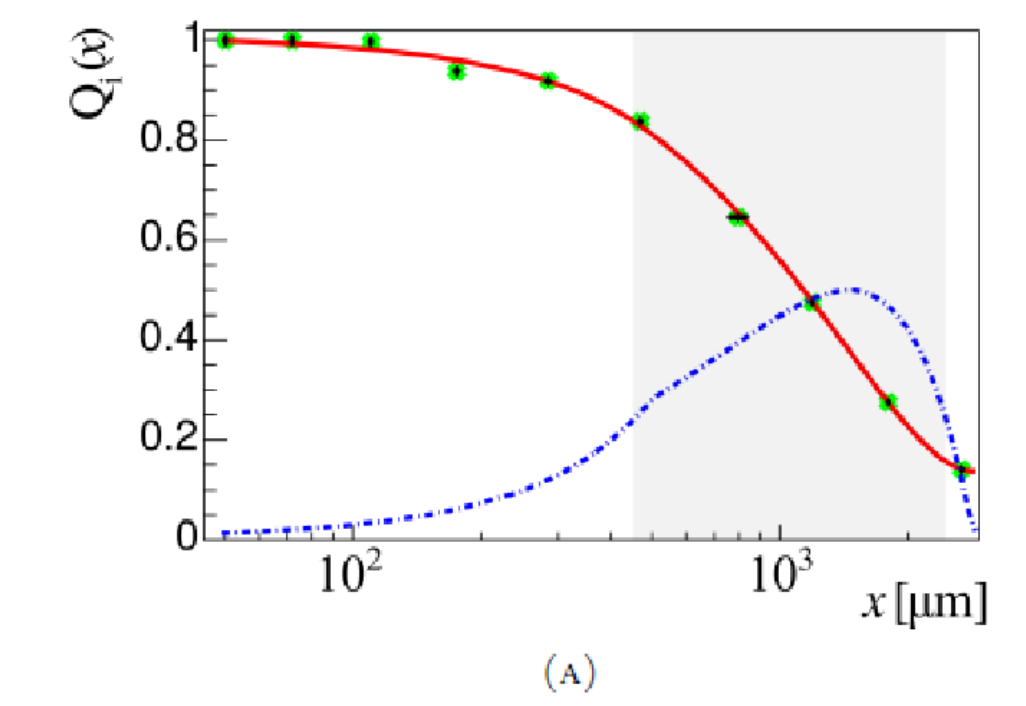
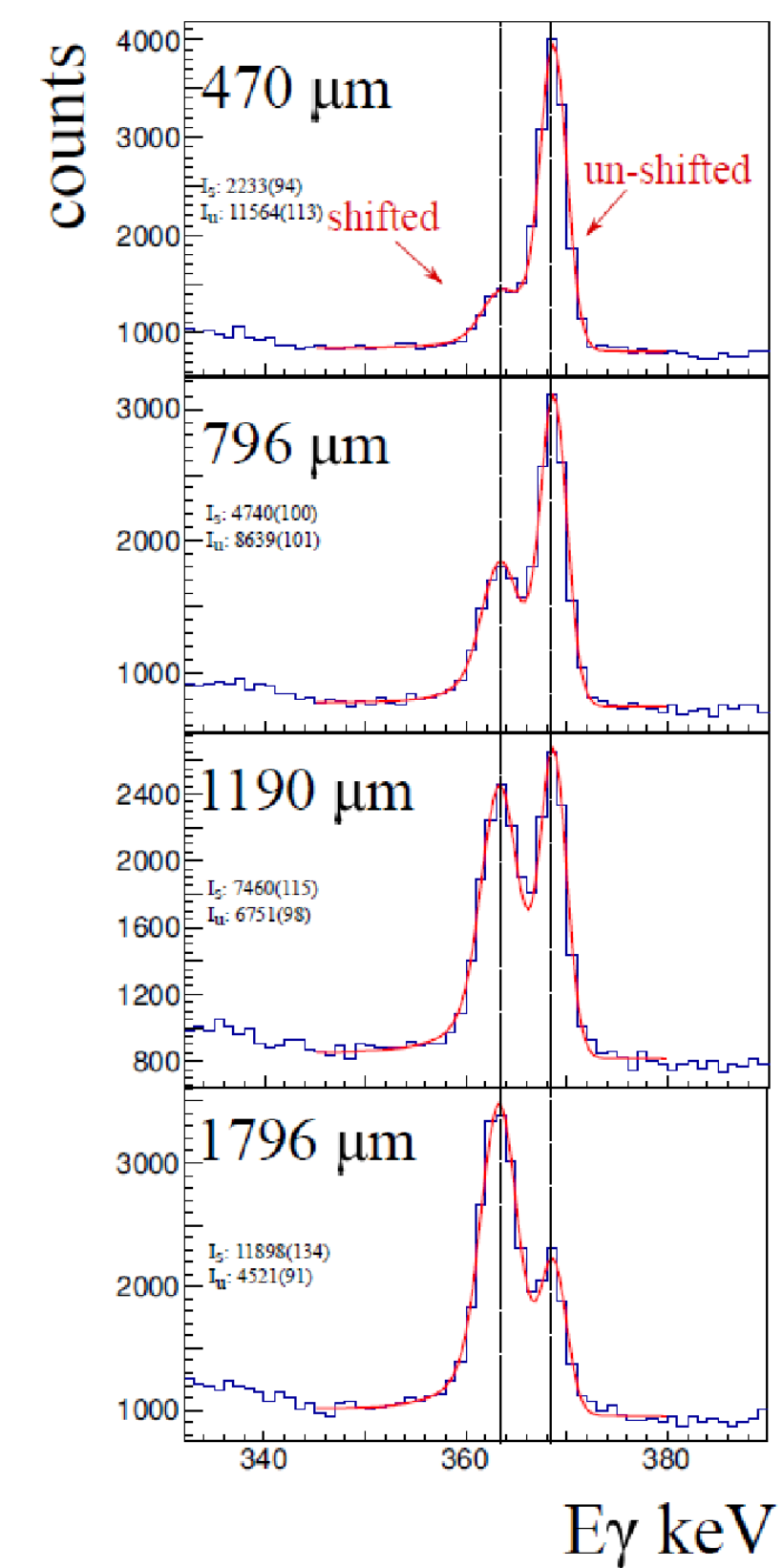
* Recoil Distance Doppler Shift



The OUPS Plunger: adapted from S. Ansari PhD thesis



^{104}Mo : 4^+ state

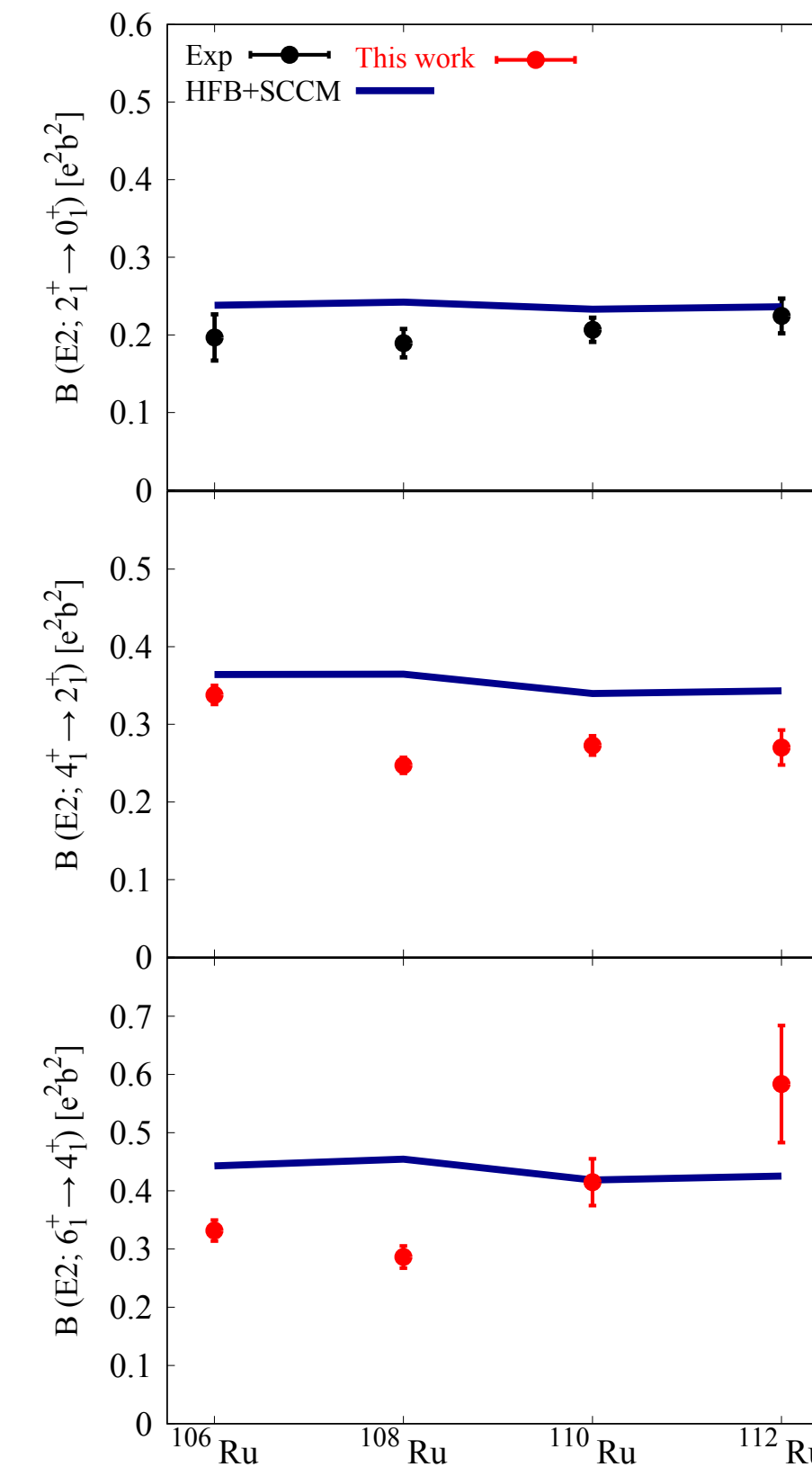
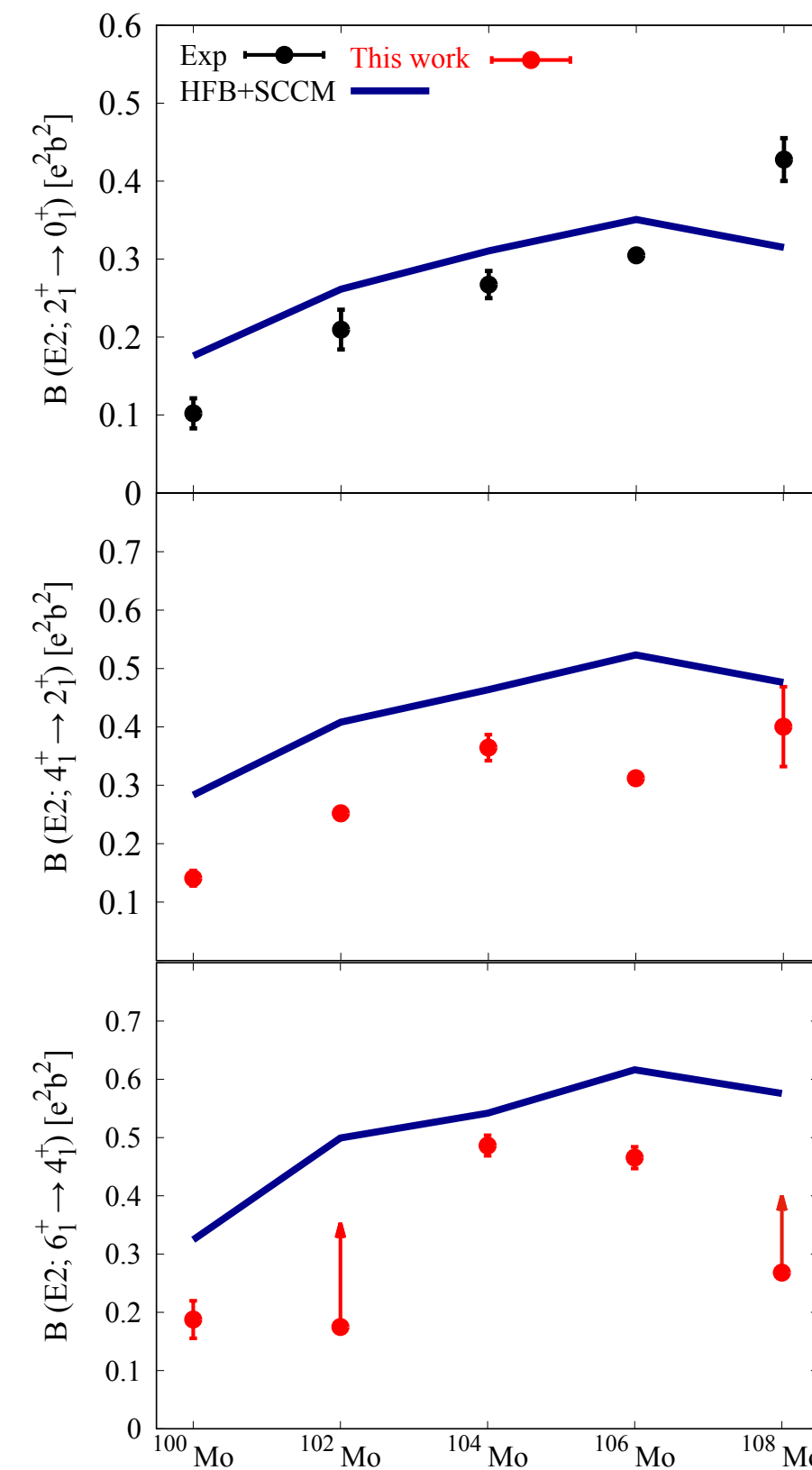
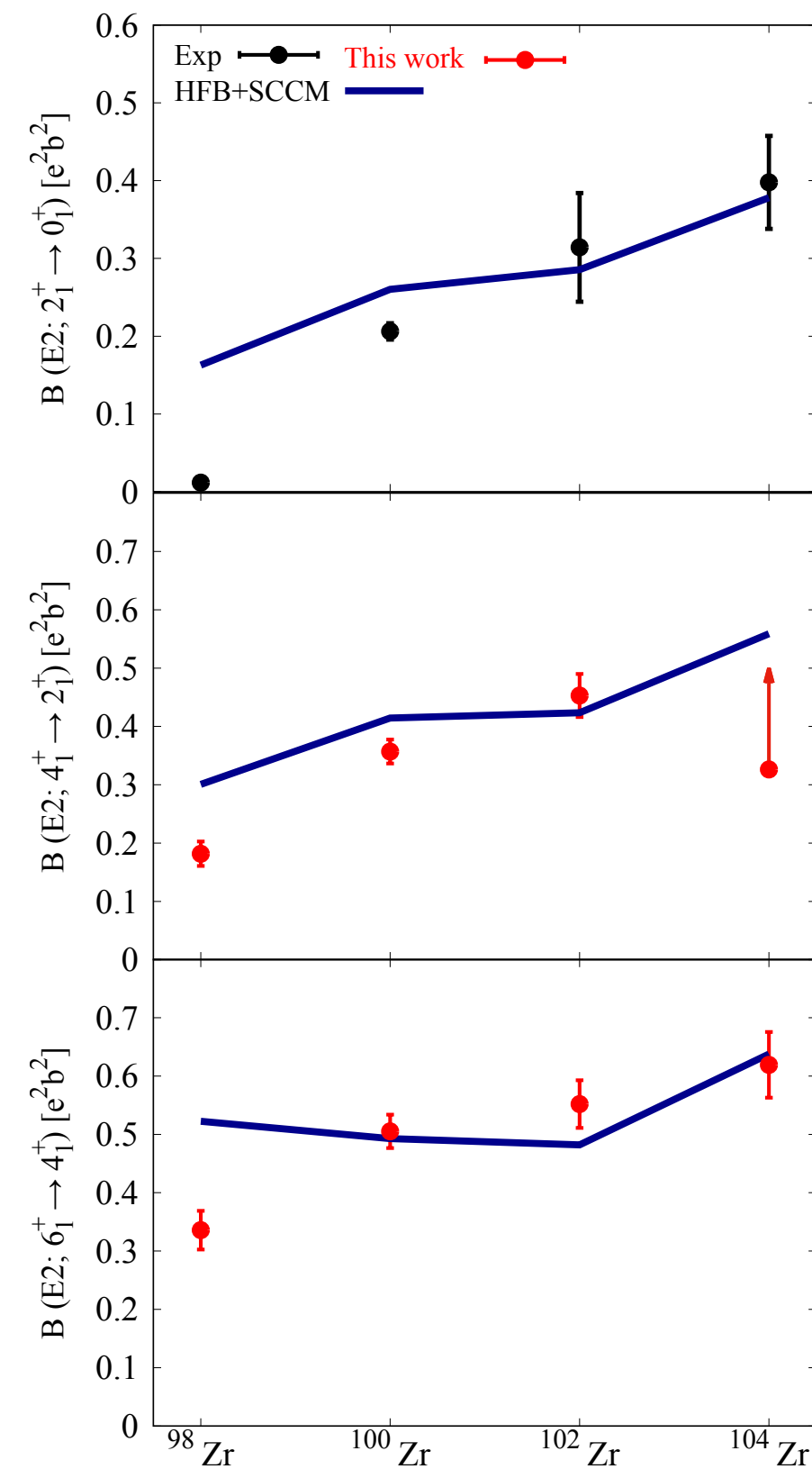


$\tau(4^+) = 32.6(20)$ ps

Some physics cases: Lifetimes in neutron rich Zr, Mo and Ru

➔ Lifetime measurements in the Zr, Mo, Ru nuclei using RDDS

➔ A lot of new lifetimes measured in this region to constrain nuclear models



Adapted from S. Ansari PhD thesis

Some physics cases: Spectroscopy of neutron rich Nb isotopes

Nuclear structure of the neutron rich Nb isotopes:
new insights into the sudden onset of deformation of the
 $A \sim 100$ and $N = 60$ region.

M. Abushawish, E. H. Wang, J. Dudouet, O. Stezowski, A. Navin,
S. Bhattacharyya, J. H. Hamilton *et al.*

See talk of **M. Abushawish**
this afternoon in the parallel session

Conclusions and perspectives

Conclusions

- ➔ A large amount of fission data has been taken at GANIL using AGATA and VAMOS++
- ➔ 10 publications on various physics cases (and more to come)

Perspectives

- ➔ New gap in exoticity needs a factor 10 in statistics
- ➔ Will be investigated at LNL using the AGATA/PRISMA



Merci !

