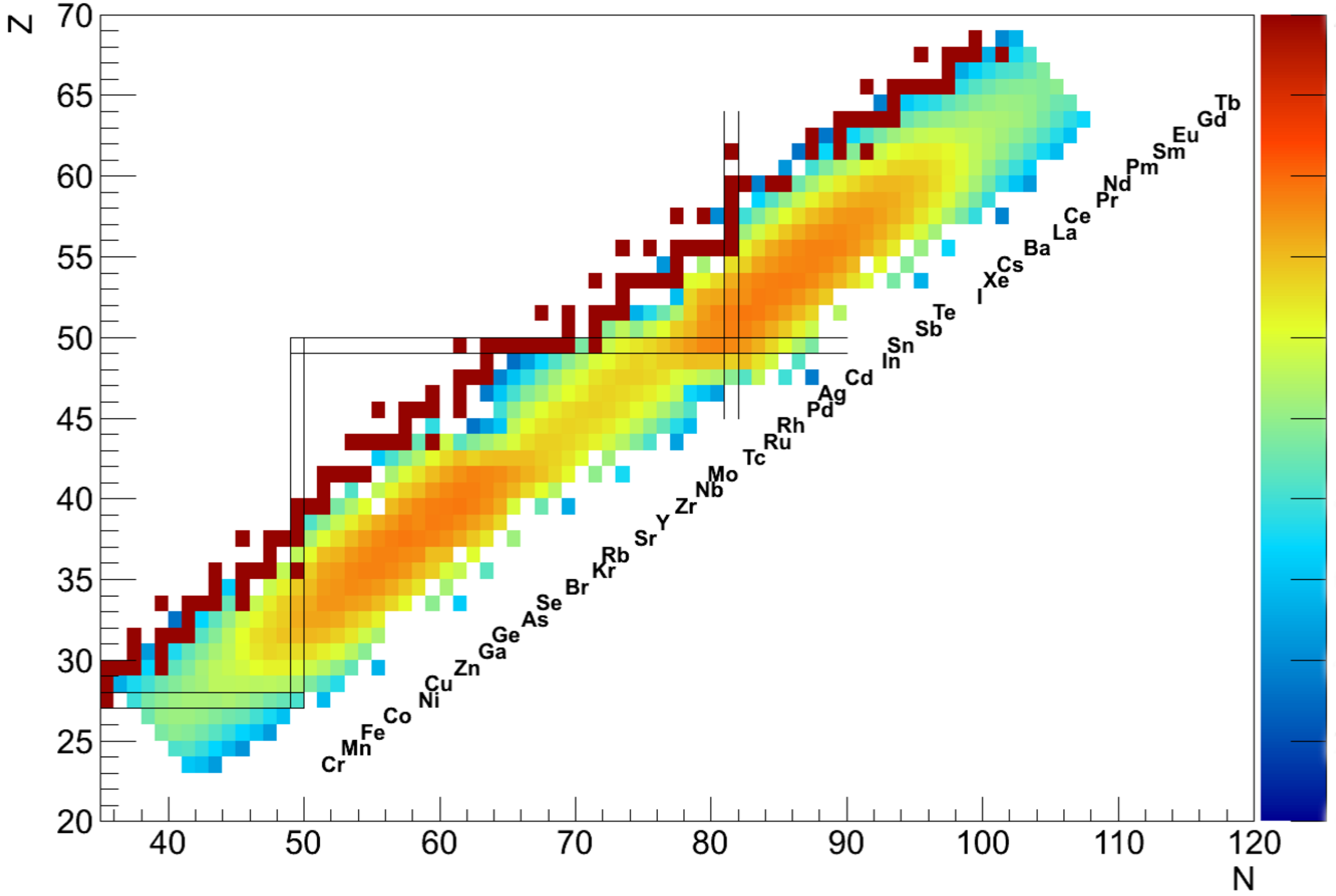
New Fission Studies

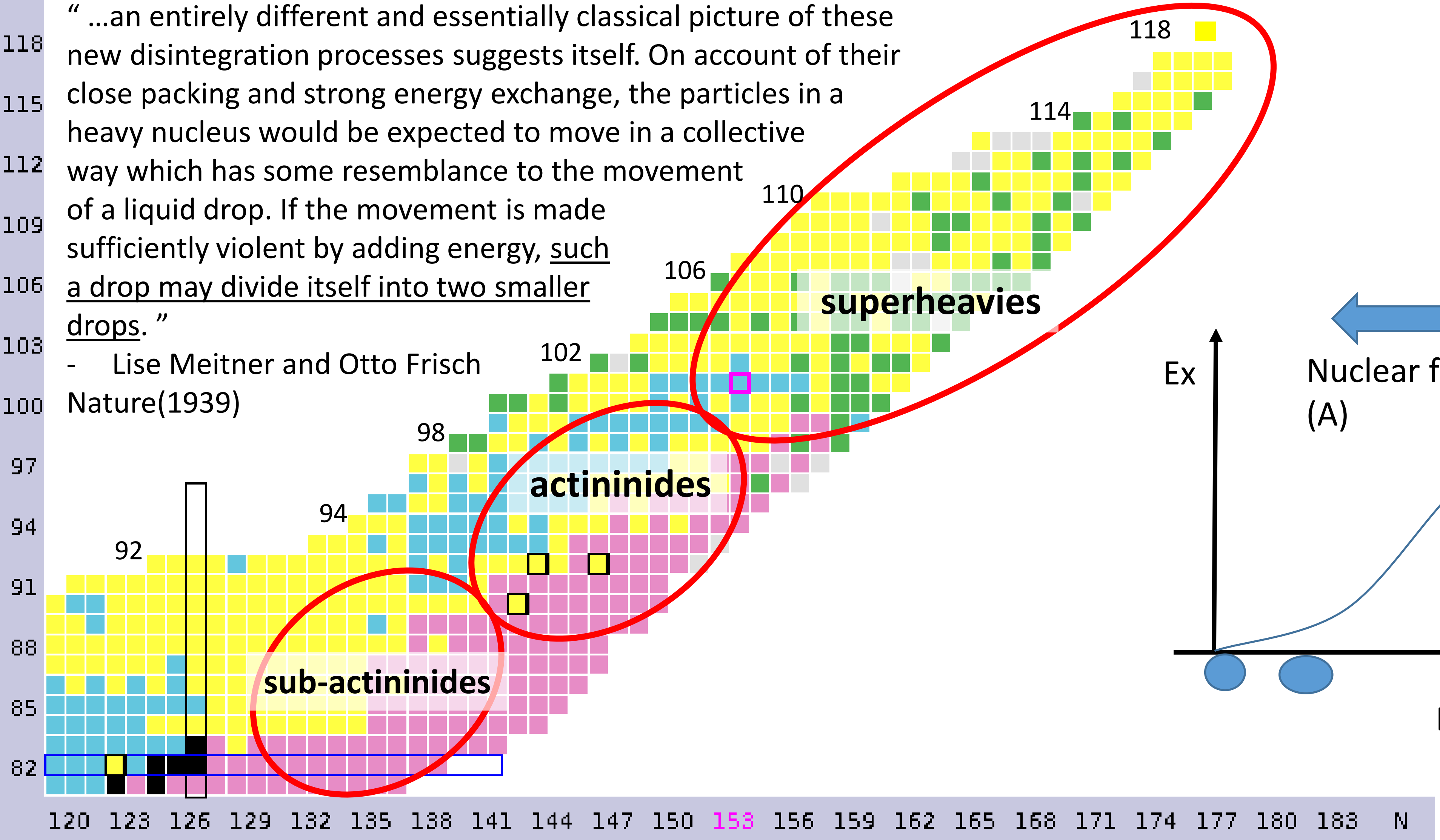
Jonathan Wilson, IJC Lab, Orsay
Erice School (2024)



New Fission Studies

“ …an entirely different and essentially classical picture of these new disintegration processes suggests itself. On account of their close packing and strong energy exchange, the particles in a heavy nucleus would be expected to move in a collective way which has some resemblance to the movement of a liquid drop. If the movement is made sufficiently violent by adding energy, <u>such a drop may divide itself into two smaller drops</u>. ”

- Lise Meitner and Otto Frisch Nature(1939)



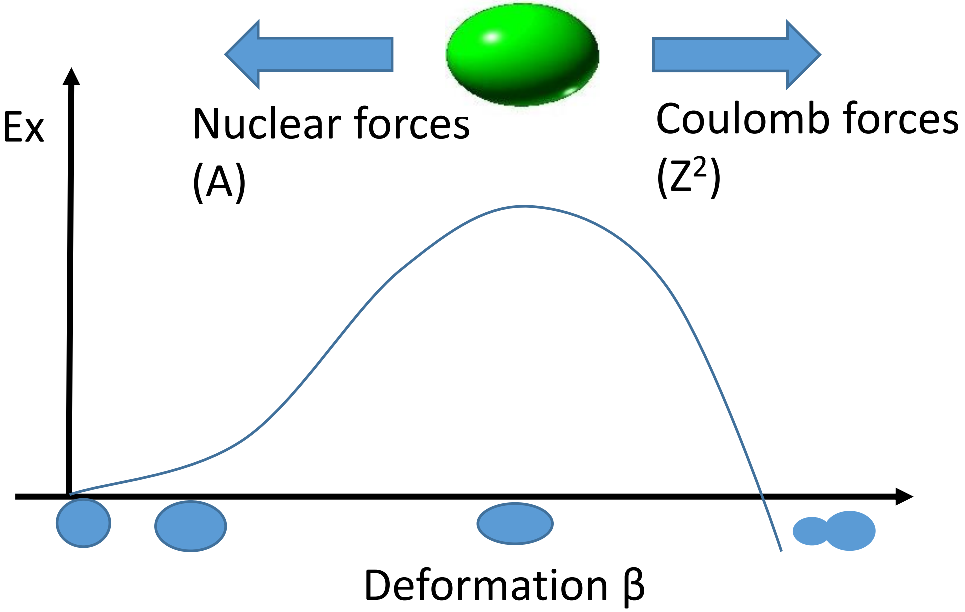
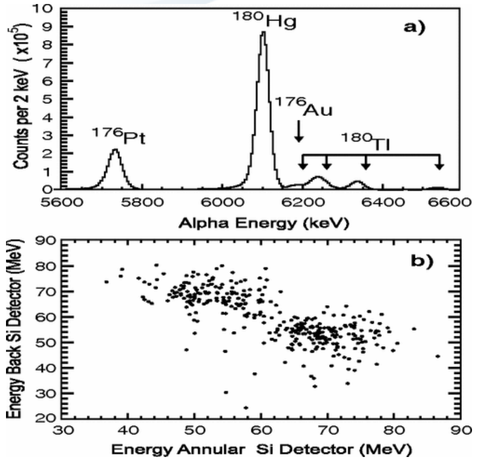


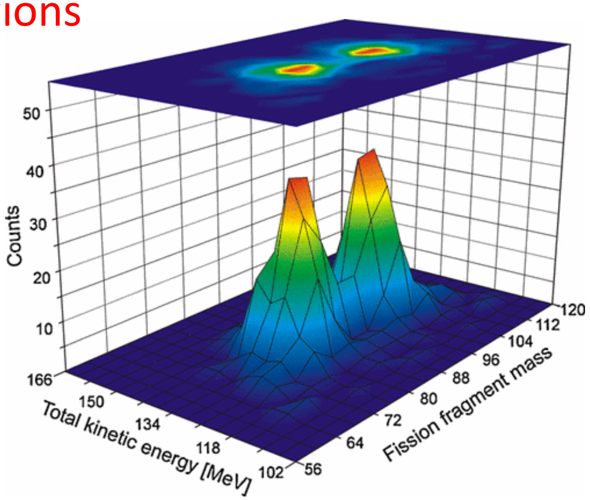
Figure from R. F. Garcia Ruiz et al., Nature 581 396 (2020)

Renewed Interest in Fission

New fission regions

^{180}Hg

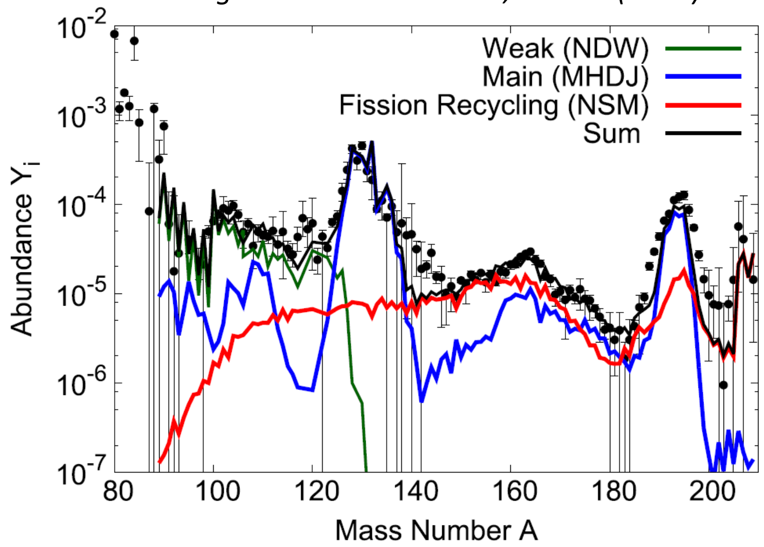




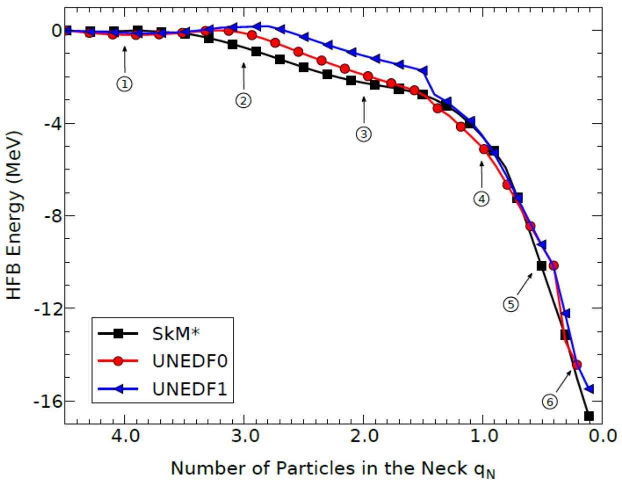
A. N. Andreyev et al. Phys. Rev. Lett. 105, 252502 (2010)

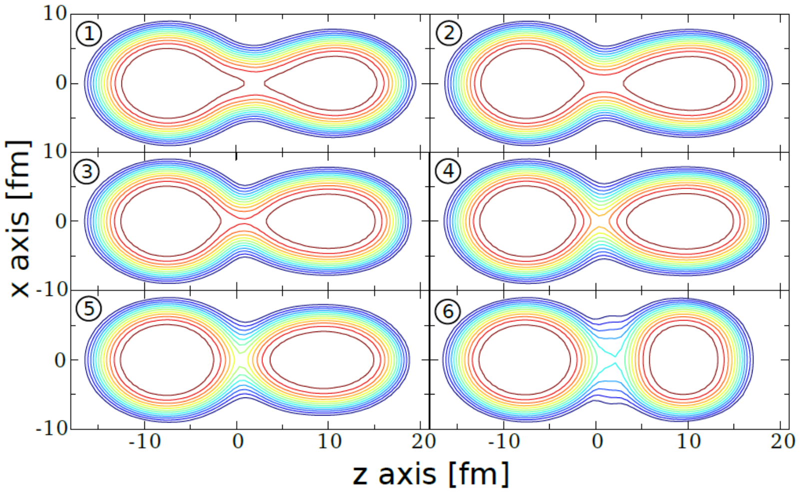
Fission recycling in r-process nucleosynthesis

S. Shibagaki et al. Astro. Journ, 816:79 (2016)



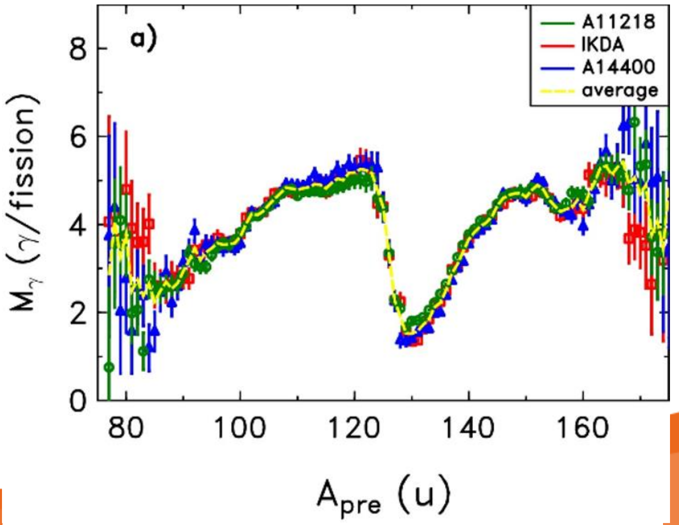
Microscopic theoretical approaches





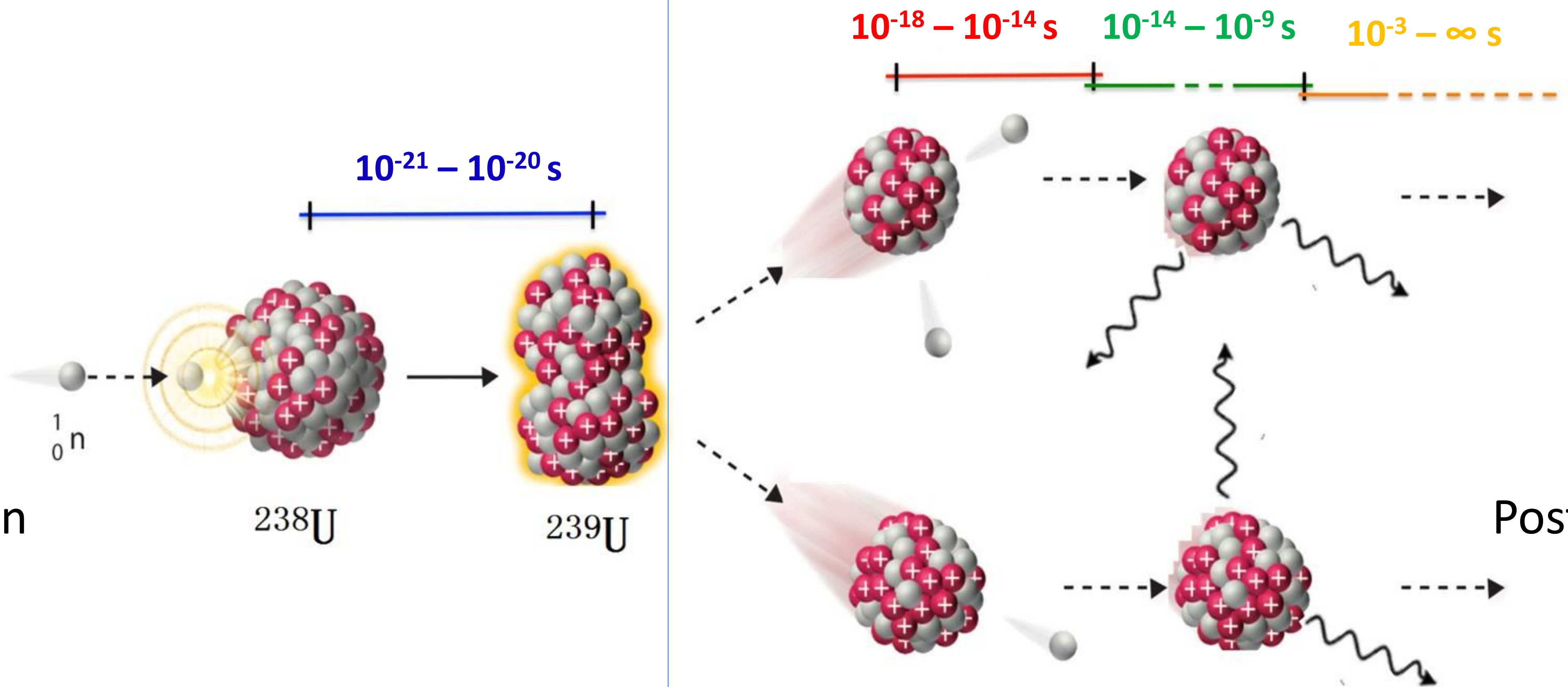
N Schunck, L M Robledo, Prog. Nu.c Part. Phys. (2016)

Prompt neutron/gamma-ray emission in fission



M. Travar et al. Phys. Lett. B 817 136293 (2021)

The de-excitation process in fission



Pre-scission

Post scission

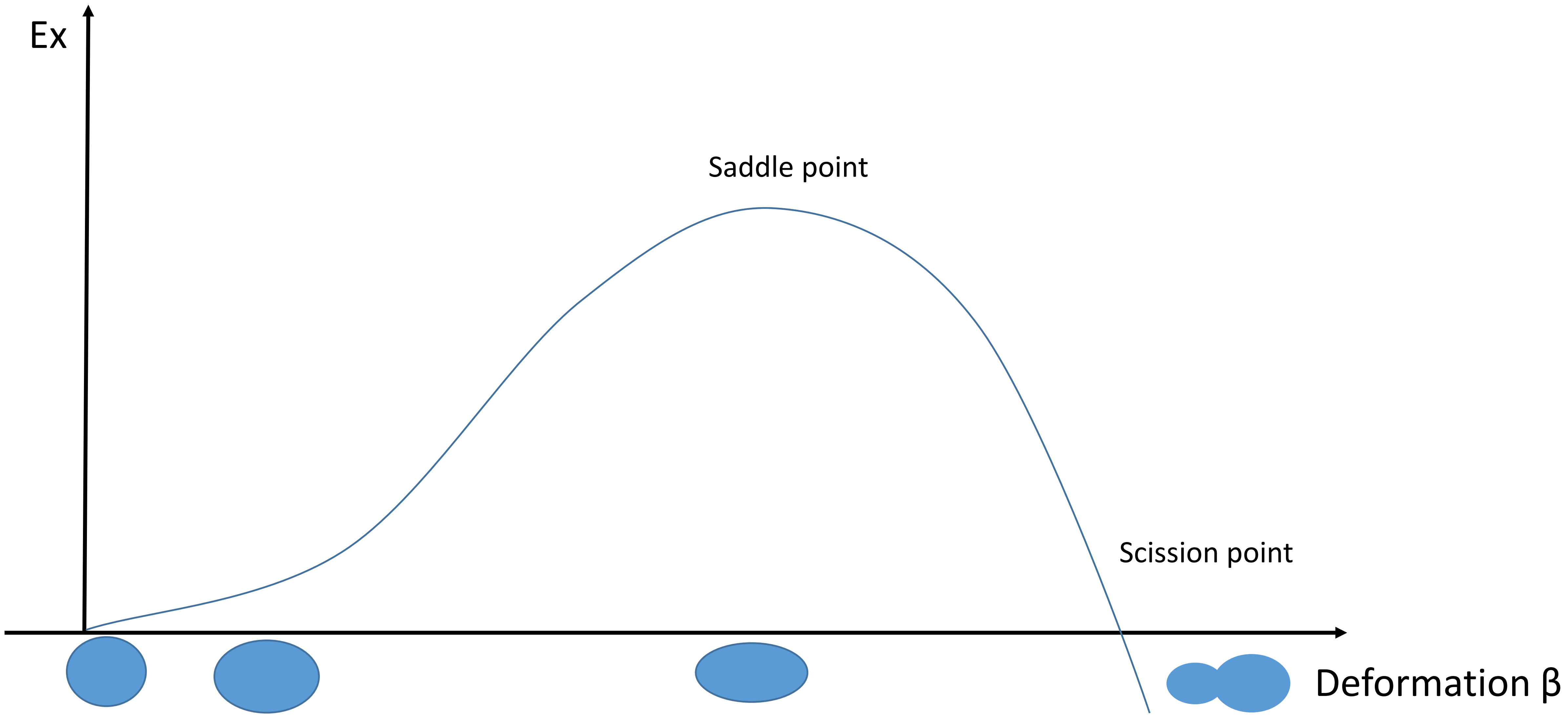
Fragment Kinetic Energy	**Prompt neutrons**	**Prompt gamma rays**	**β, $\bar{\nu}$, γ decay**
~160 MeV	**~6 MeV**	**~8 MeV**	**~20 MeV**

Open problems in fission

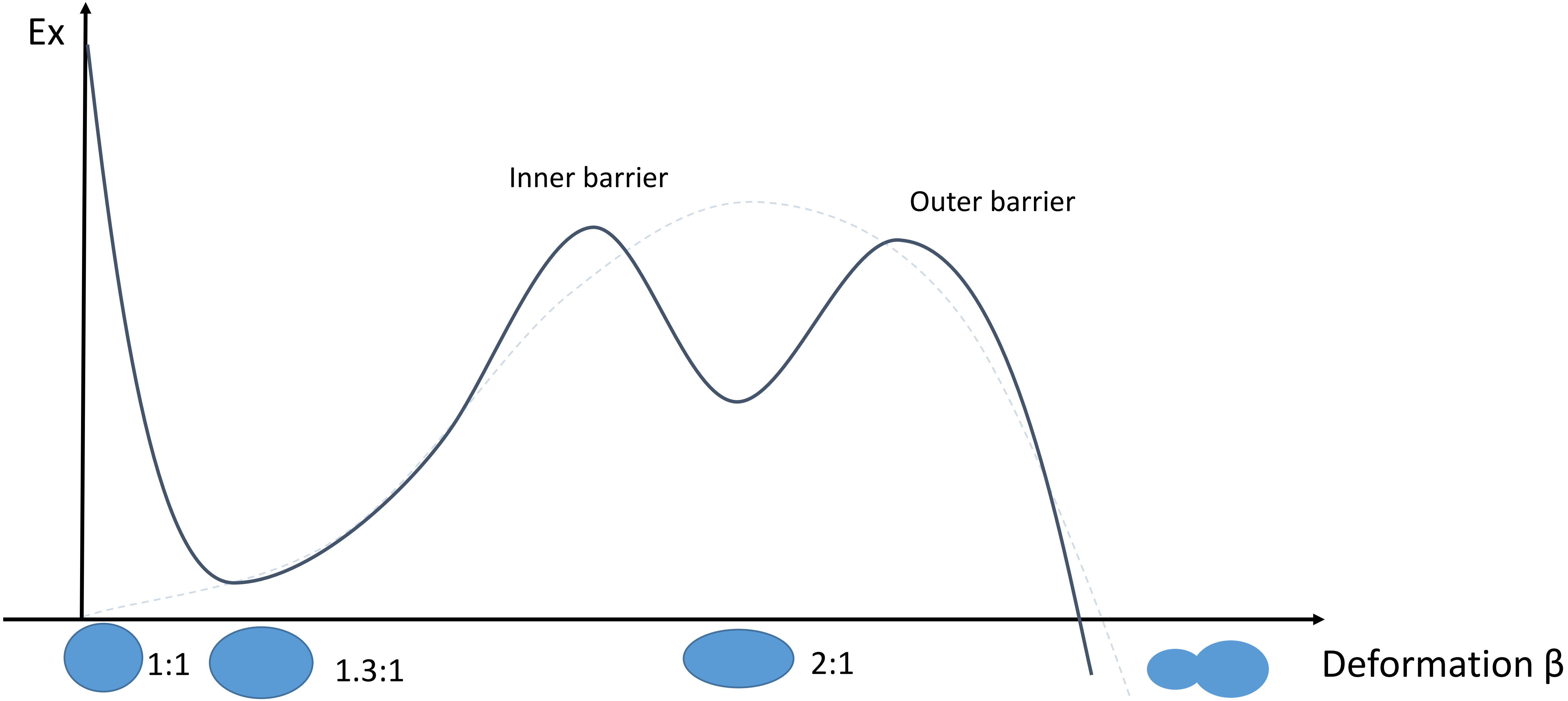
What determines:

- The mass/charge split at scission?
- The energy/angular momentum sharing at scission?
- How these vary with initial A,Z,E*,J?

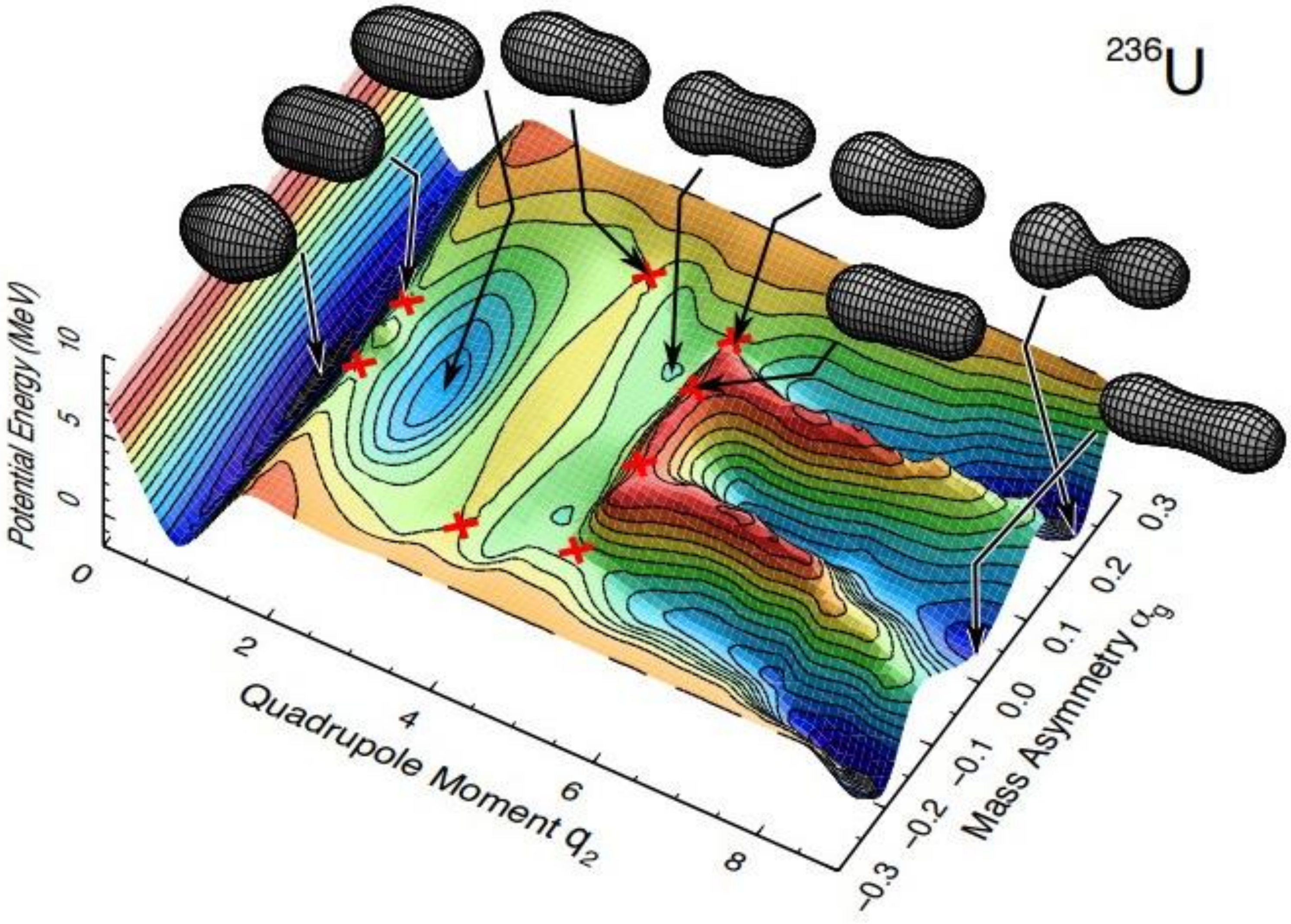
The liquid drop fission barrier



Fission barrier including shell effects

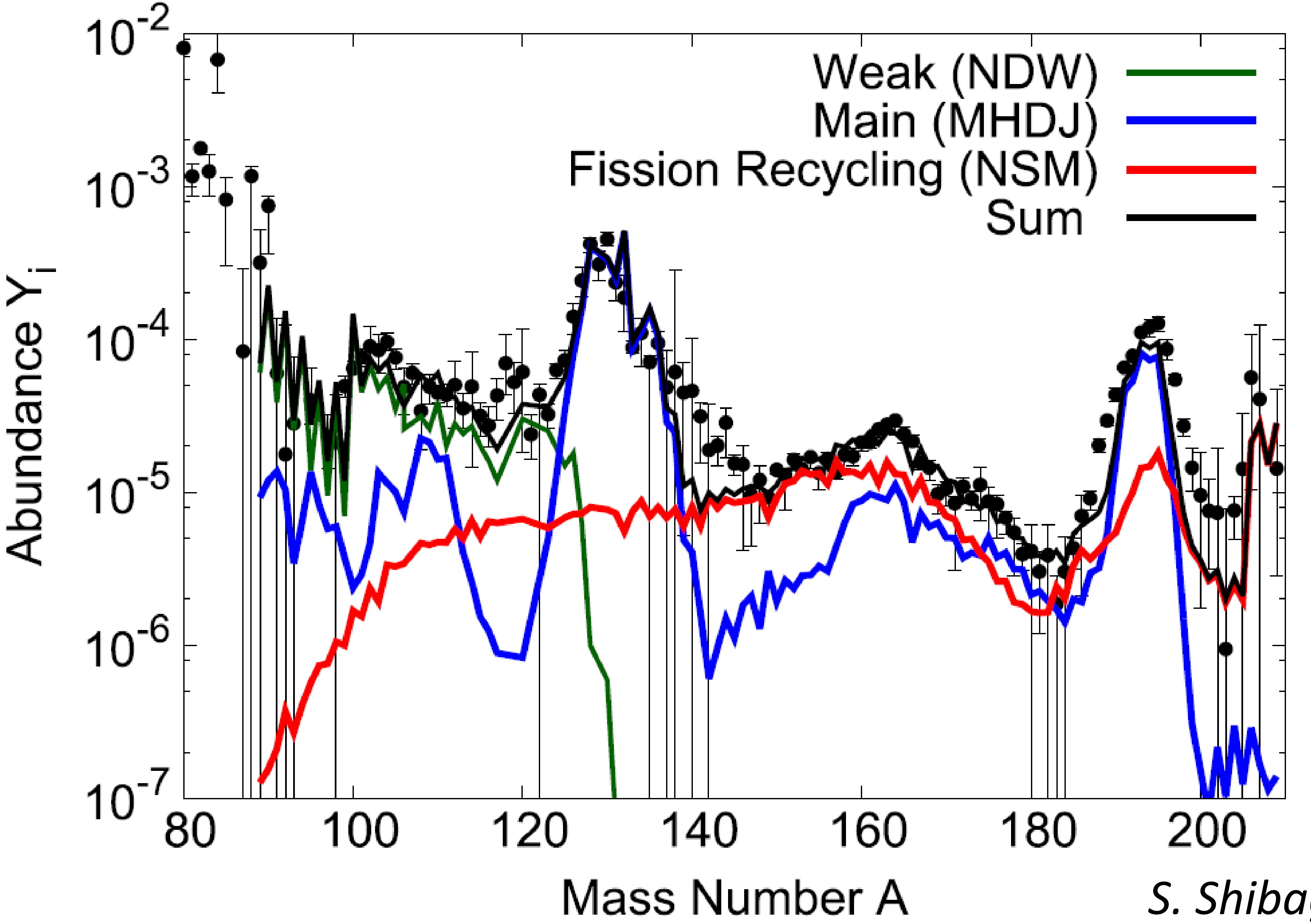


Fission barrier in multi-dimensional deformation space



To better constrain theory and the pathway(s) to fission through the complex potential energy landscapes requires measurements of fragment yields as a function of A,Z, E* and J of fissioning systems.

T. Ichikawa et al. Phys. Rev. C 86, 024610 (2012)

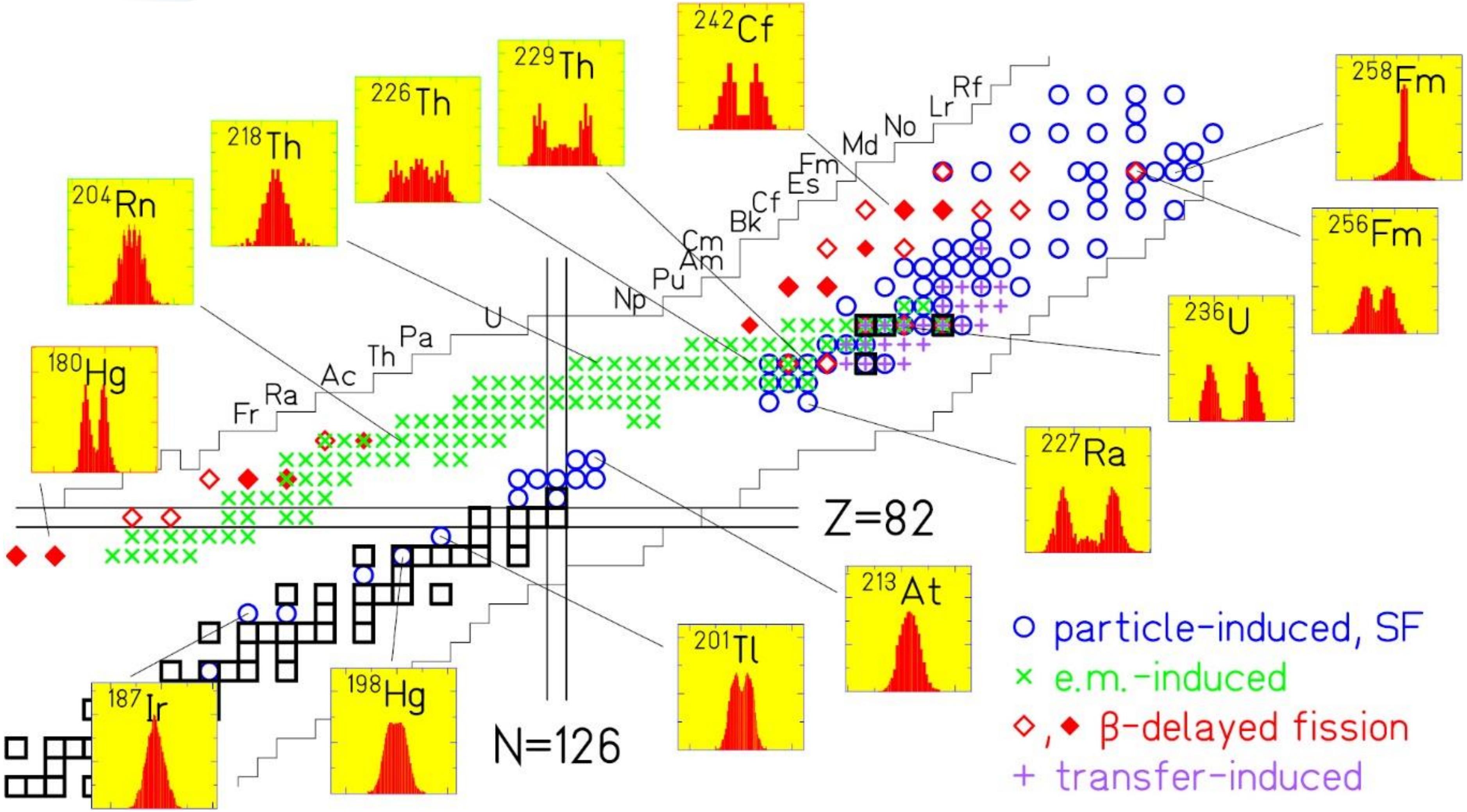


Prediction of FF distributions for very neutron-rich systems is needed (inaccessible to experiment)

Hence models need to be refined over as broad a range of accessible nuclei as possible (sub actinides, proton-rich nuclei, superheavies etc.)

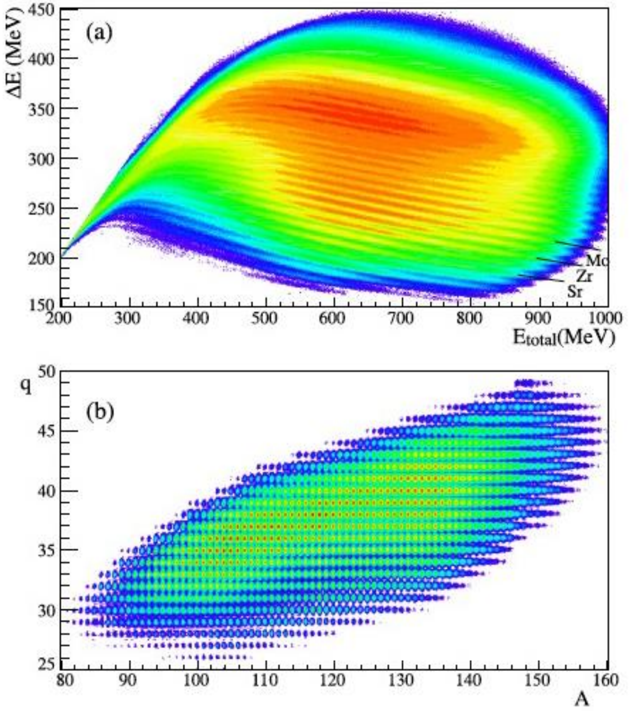
S. Shibagaki et al. Astro. Journ, 816:79 (2016)

Fragment mass/charge measurements in new fission regions



Experimental programs using inverse kinematics (> 6 MeV/A)

SOFIA@GSI
VAMOS@GANIL

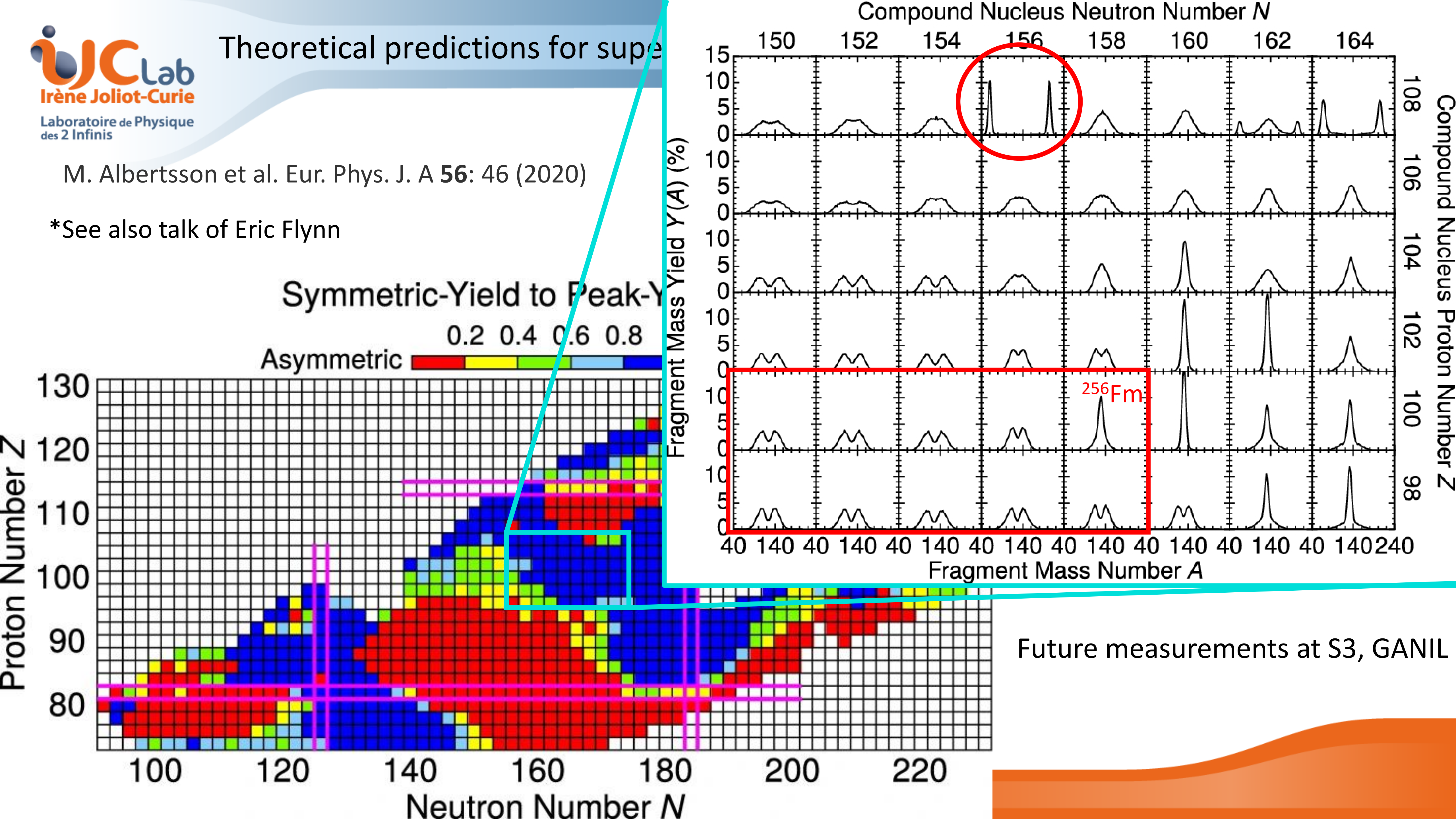


K-H. Schmidt and B. Jurado 2018 Rep. Prog. Phys. 81 106301

Theoretical predictions for supe

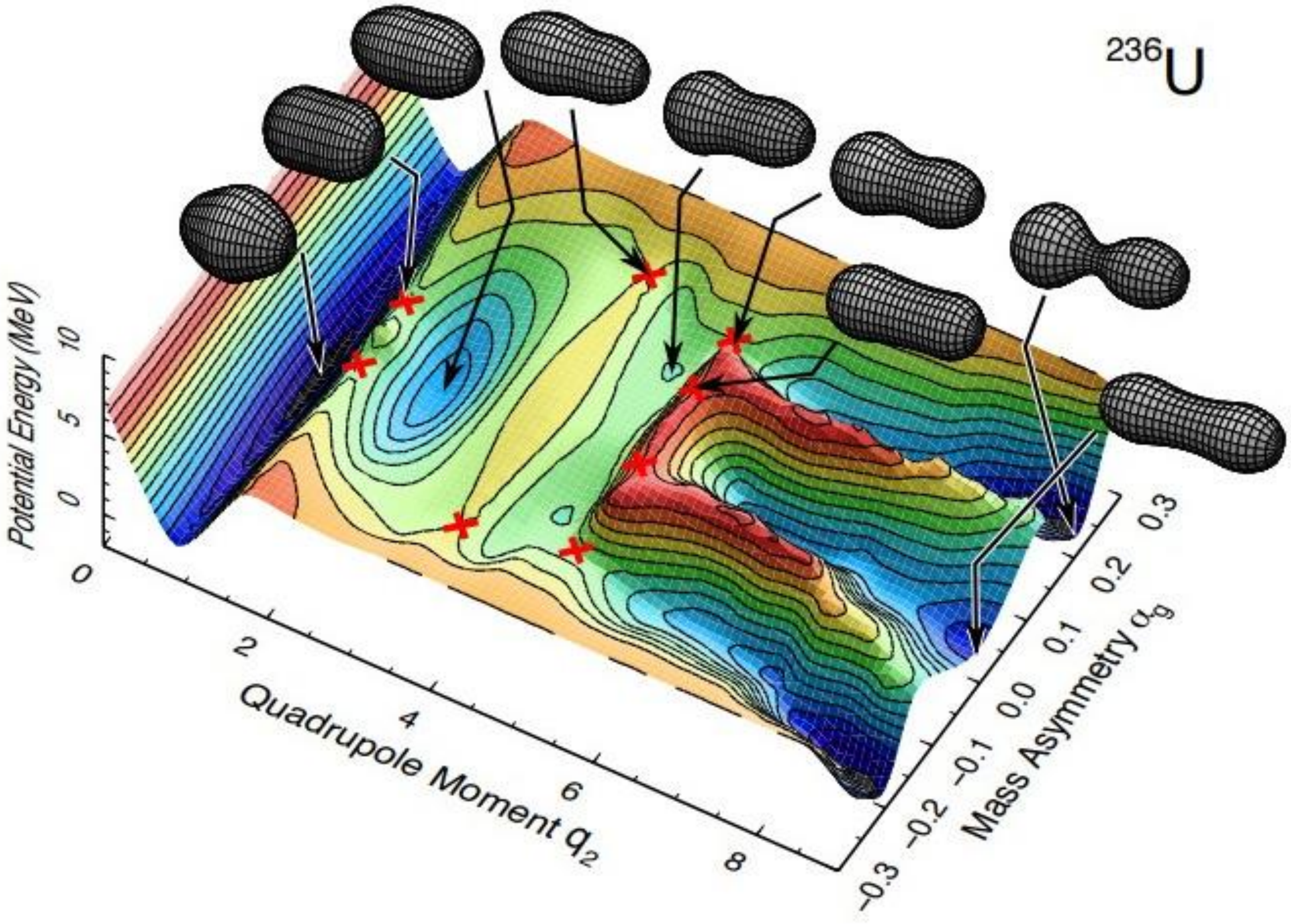
M. Albertsson et al. Eur. Phys. J. A **56**: 46 (2020)

*See also talk of Eric Flynn



Future measurements at S3, GANIL

Fission barrier in multi-dimensional deformation space

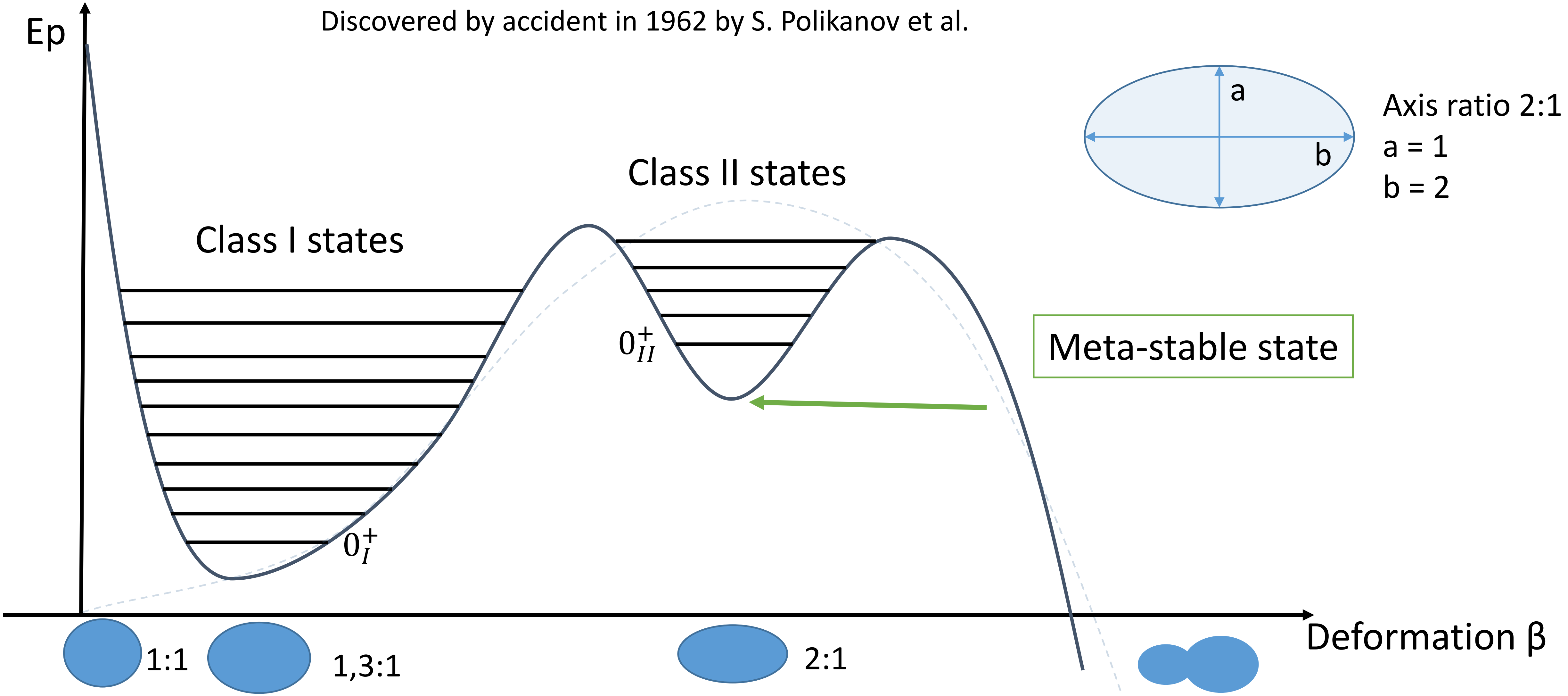


Is there a way to experimentally constrain this landscape?

T. Ichikawa et al. Phys. Rev. C 86, 024610 (2012)

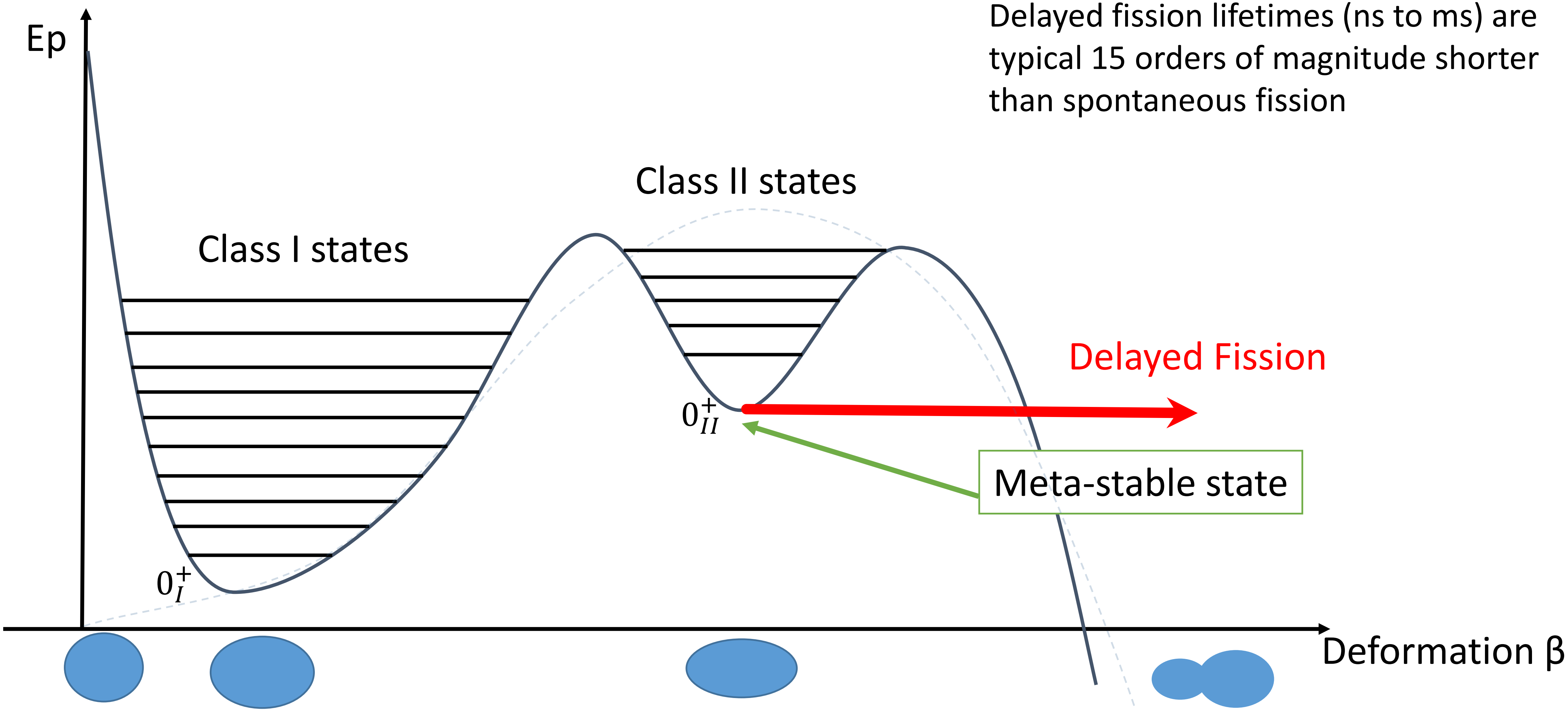
Fission shape isomers

Discovered by accident in 1962 by S. Polikanov et al.



Most shape isomers decay by delayed fission

Delayed fission lifetimes (ns to ms) are typical 15 orders of magnitude shorter than spontaneous fission



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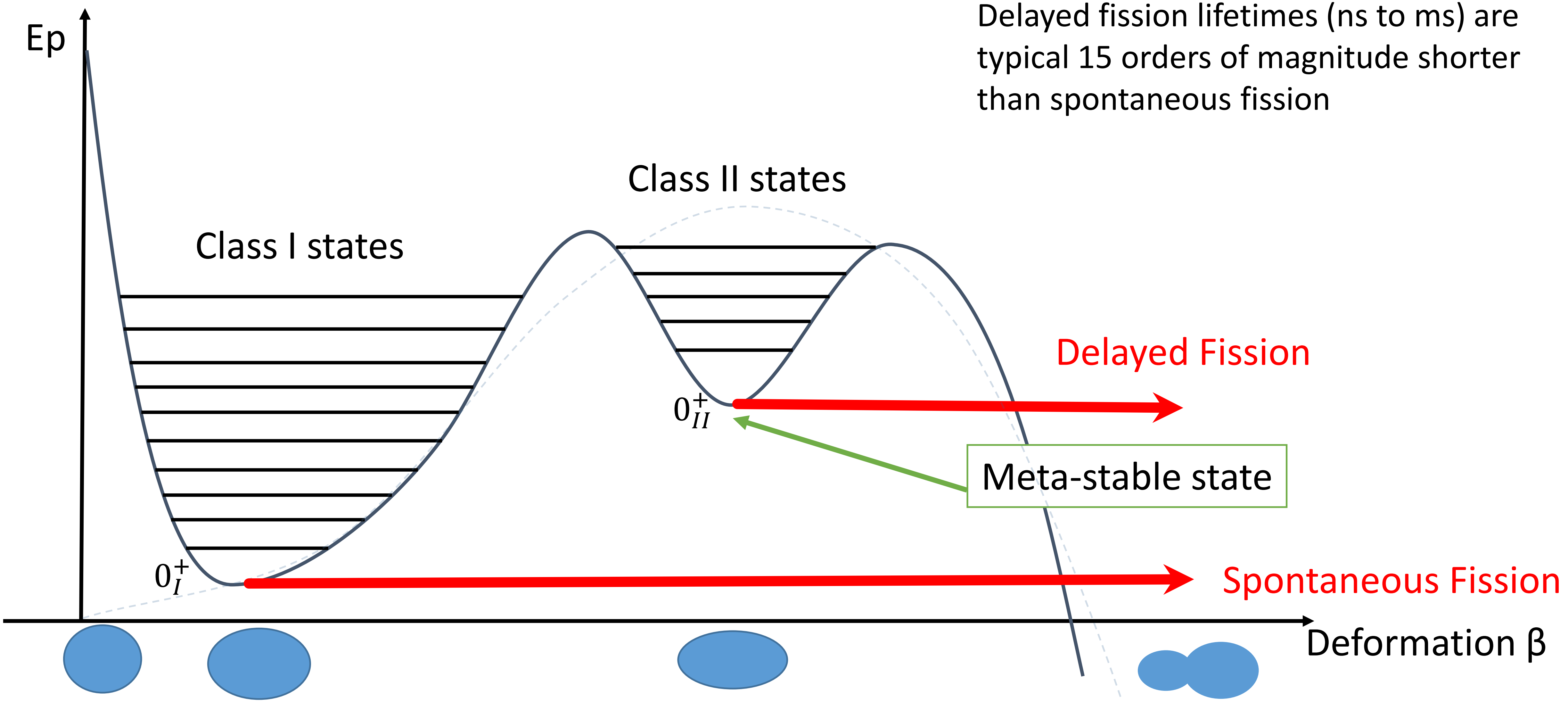
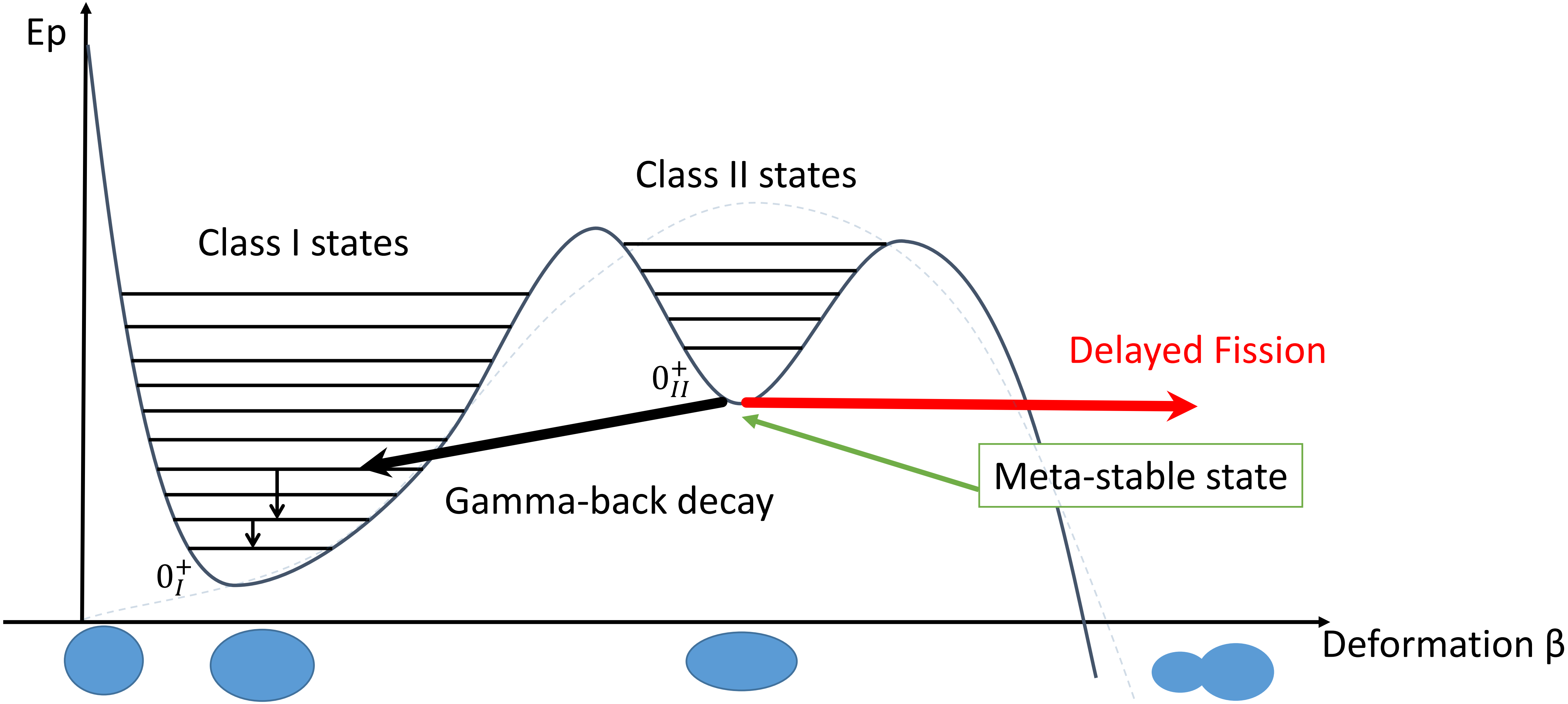
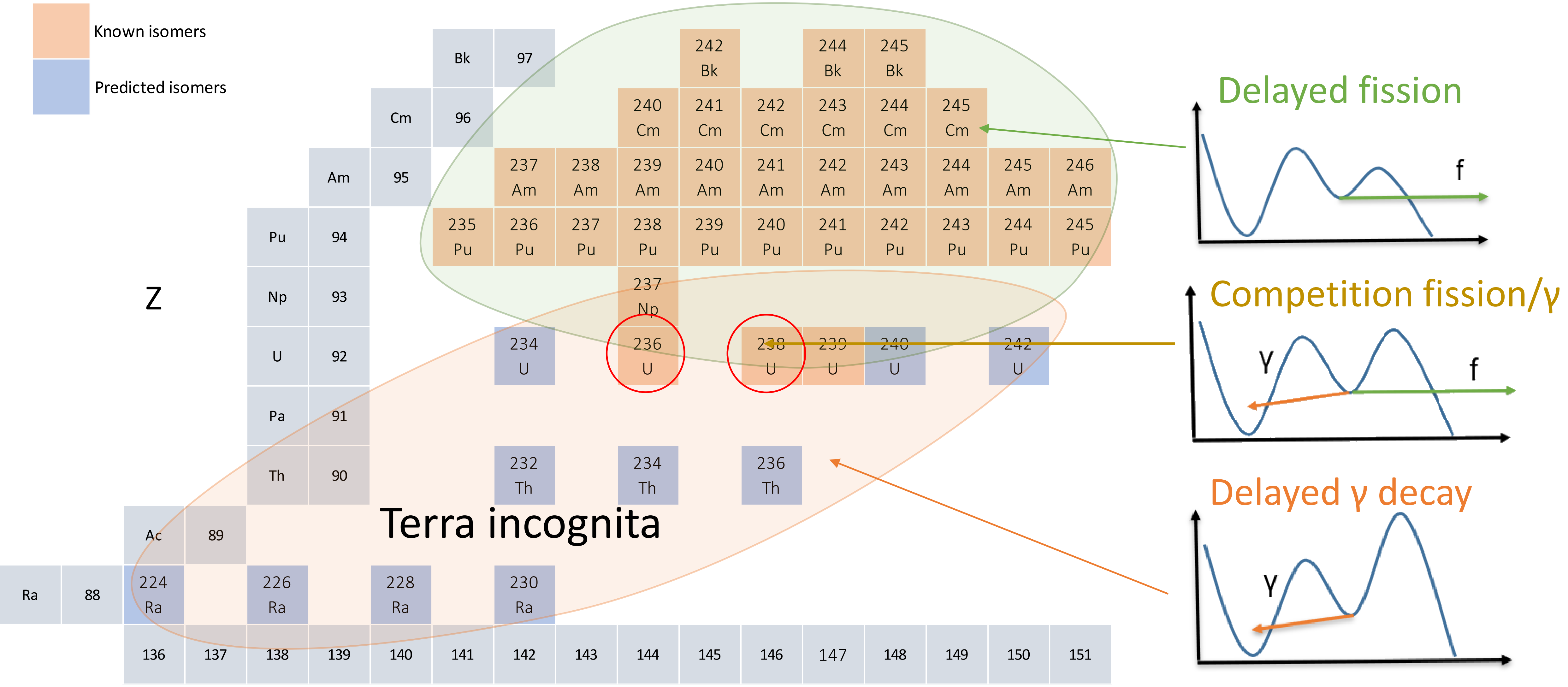


Competing gamma back decay: an even rarer phenomenon

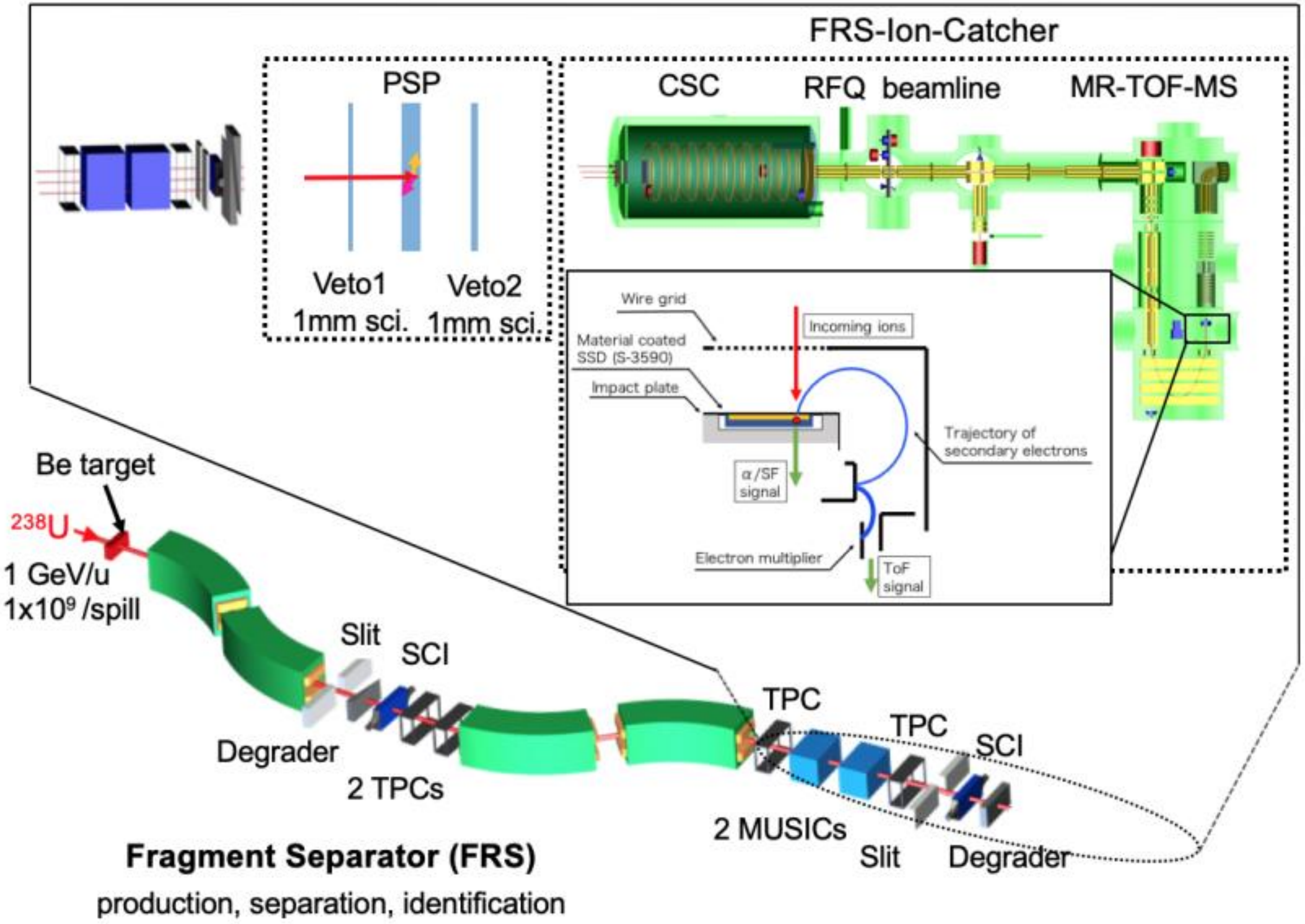


Searching for gamma back decays



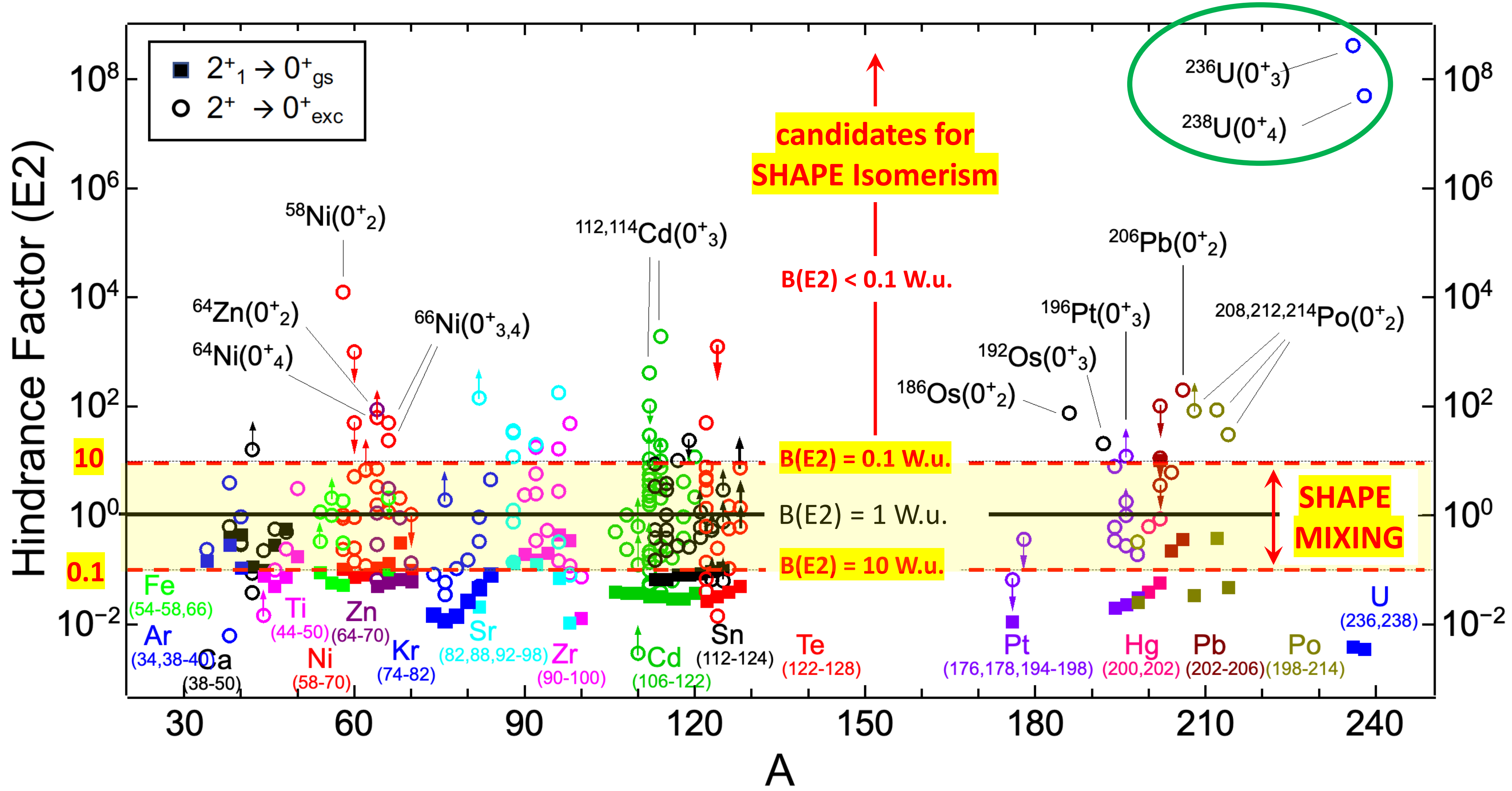
Fission shape isomer studies with the FRS@GSI

J. Zhao and T. Dickel, Proceedings of the FAIR next generation scientists - 7th Edition Workshop 23-27 May (2022)



- Production in inverse kinematics via fragmentation of ^{238}U
- Access to new cases (U, Np, etc.) unavailable for study in direct kinematics

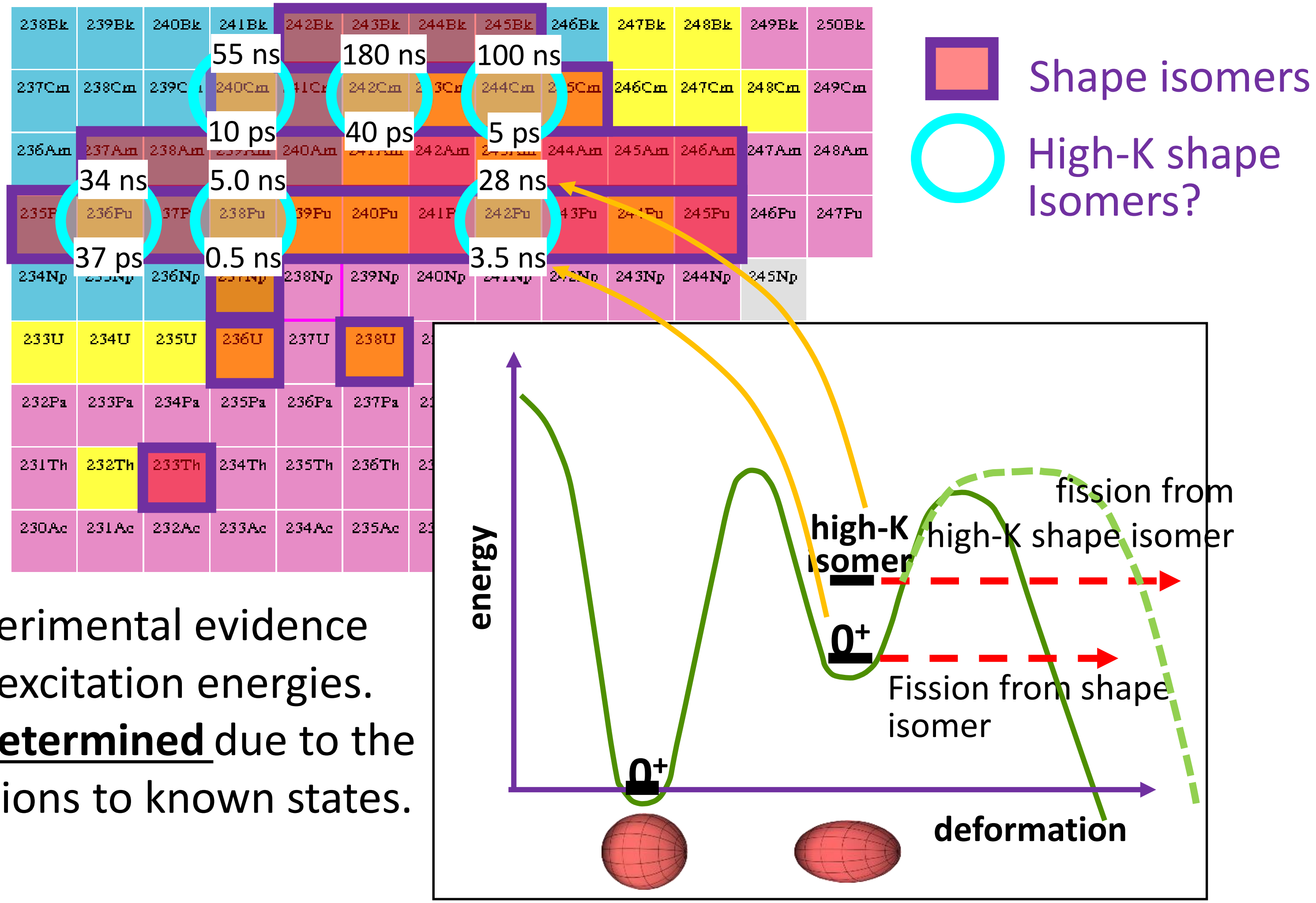
Survey of HINDRANCE (E2) factors for 0^+ states
in the proximity of **Z = 20, 28, 40, 50, 82**



S. Leoni, B. Fornal, N. Marginean and J.N. Wilson EPJ Special Topics 233, pages 1061–1074, (2024)

High-K shape isomers?

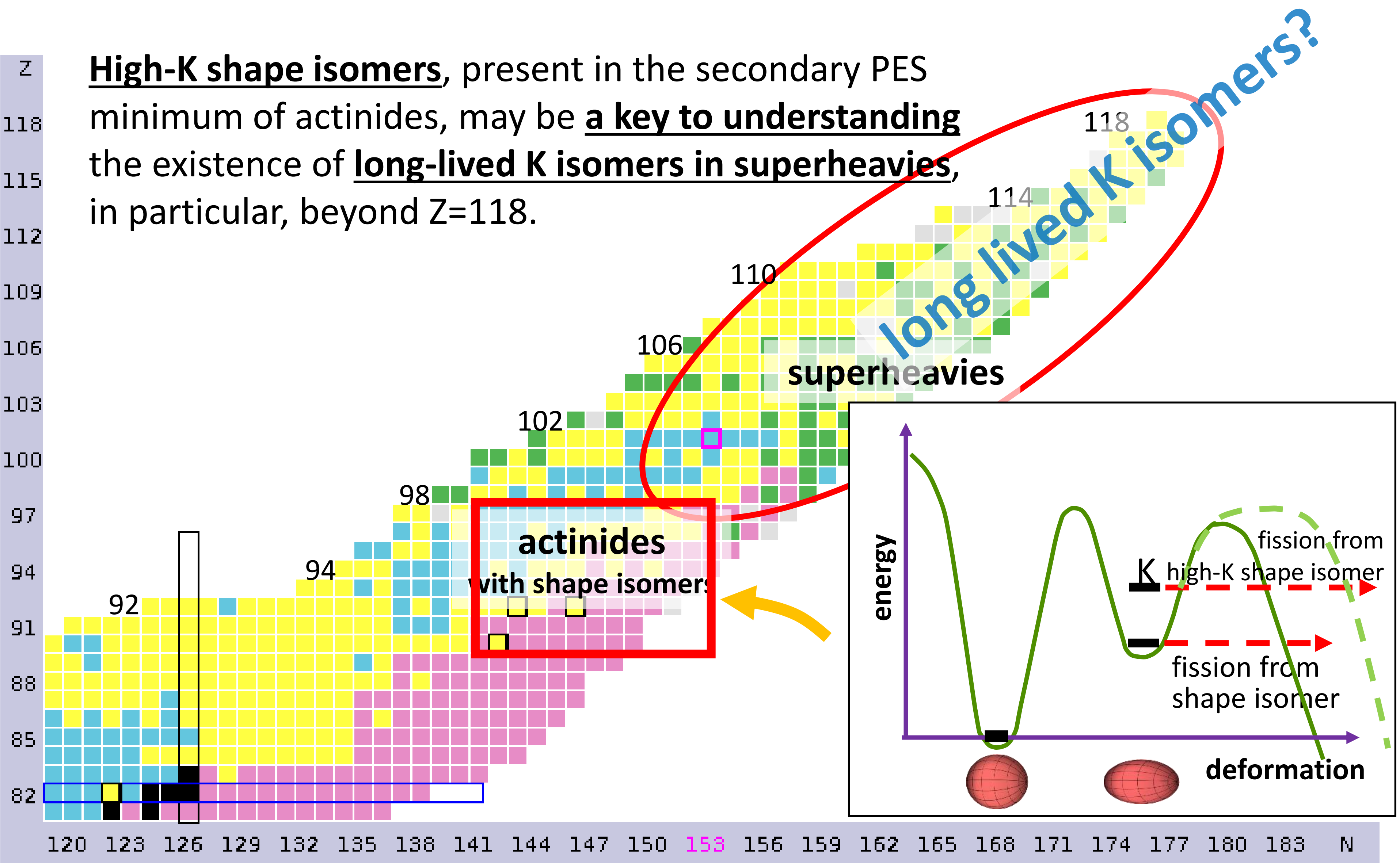
An extra stability against fission!



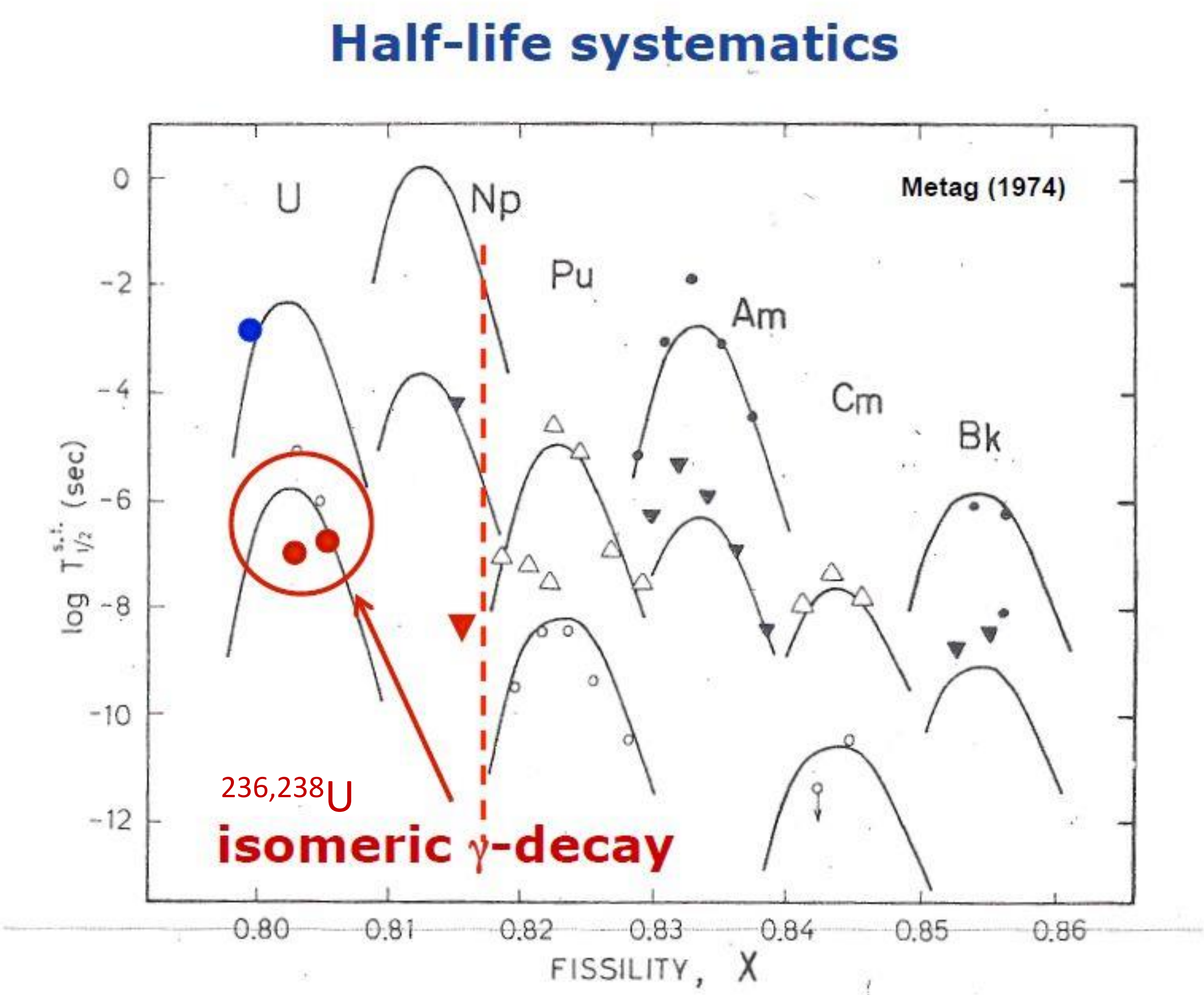
Up to now, for high-K fission isomers experimental evidence includes only half-lives and approximate excitation energies. **<u>Their spins and parities have not been determined</u>** due to the lack of observation of gamma-ray transitions to known states.

High-K shape isomers and their survivability in superheavy nuclei

High-K shape isomers, present in the secondary PES minimum of actinides, may be **a key to understanding** the existence of **long-lived K isomers in superheavies**, in particular, beyond Z=118.



Fission shape isomer half life systematics



Gamma branches were proposed to exist in U nuclei since half lives were shorter than the systematics predicted

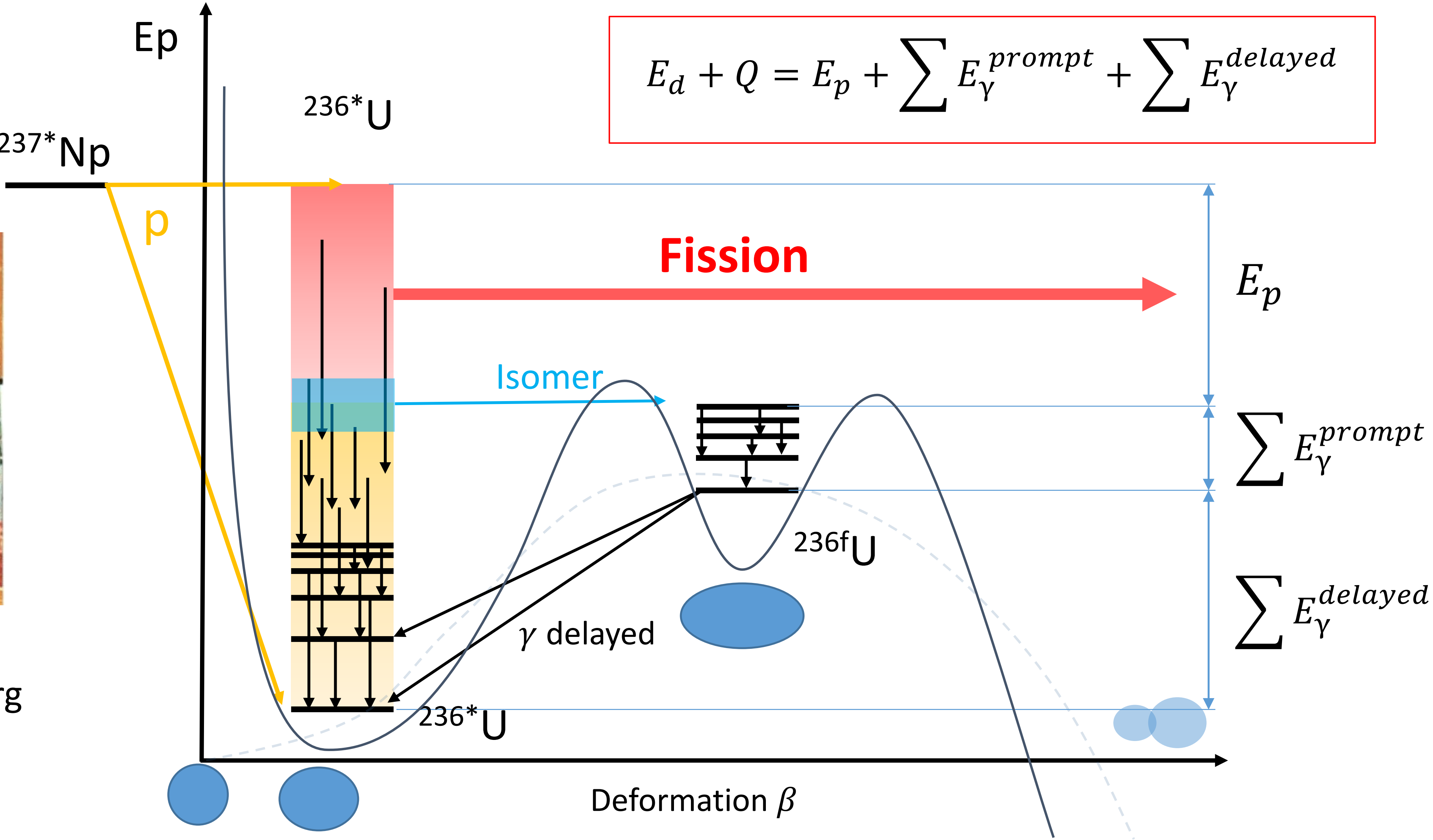
^{238m}U $t_{1/2}$ = 295 ns

^{236m}U $t_{1/2}$ = 120 ns

The ^{236}U case: Selection of the rare back decay events through calorimetry

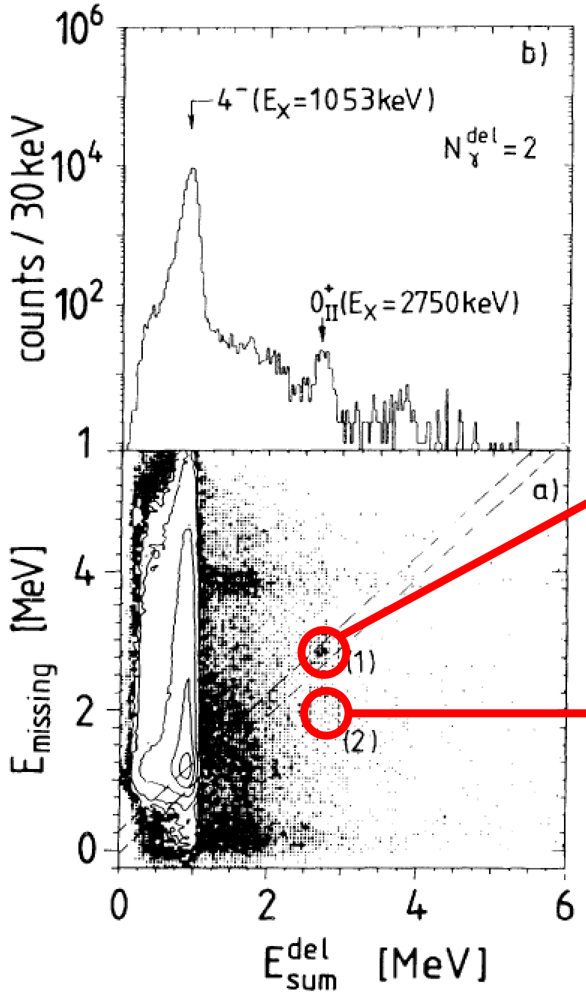
$$E_d + Q = E_p + \sum E_\gamma^{prompt} + \sum E_\gamma^{delayed}$$

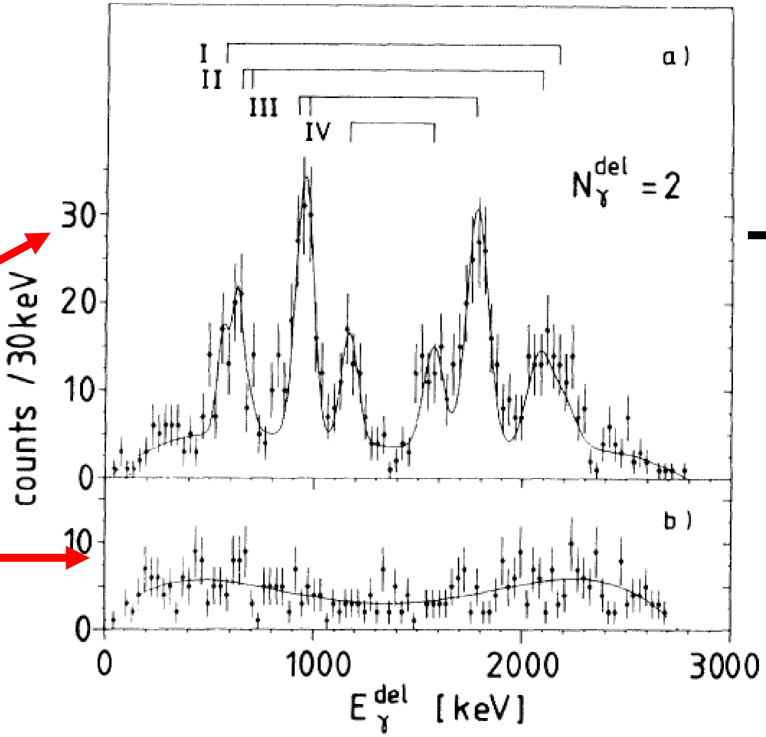
Darmstadt-Heidelberg Crystal Ball (1989)

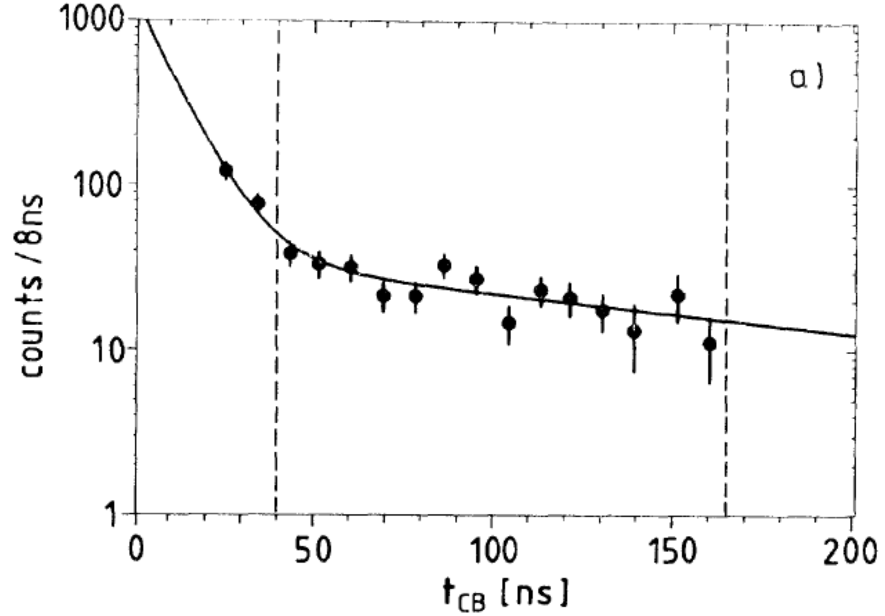


Darmstadt-Heidelberg Crystall Ball (1989) : Detection of ^{236m}U back decay

Gate on $E_{missing} = \sum E^{delayed} \approx 2{,}75\ MeV$





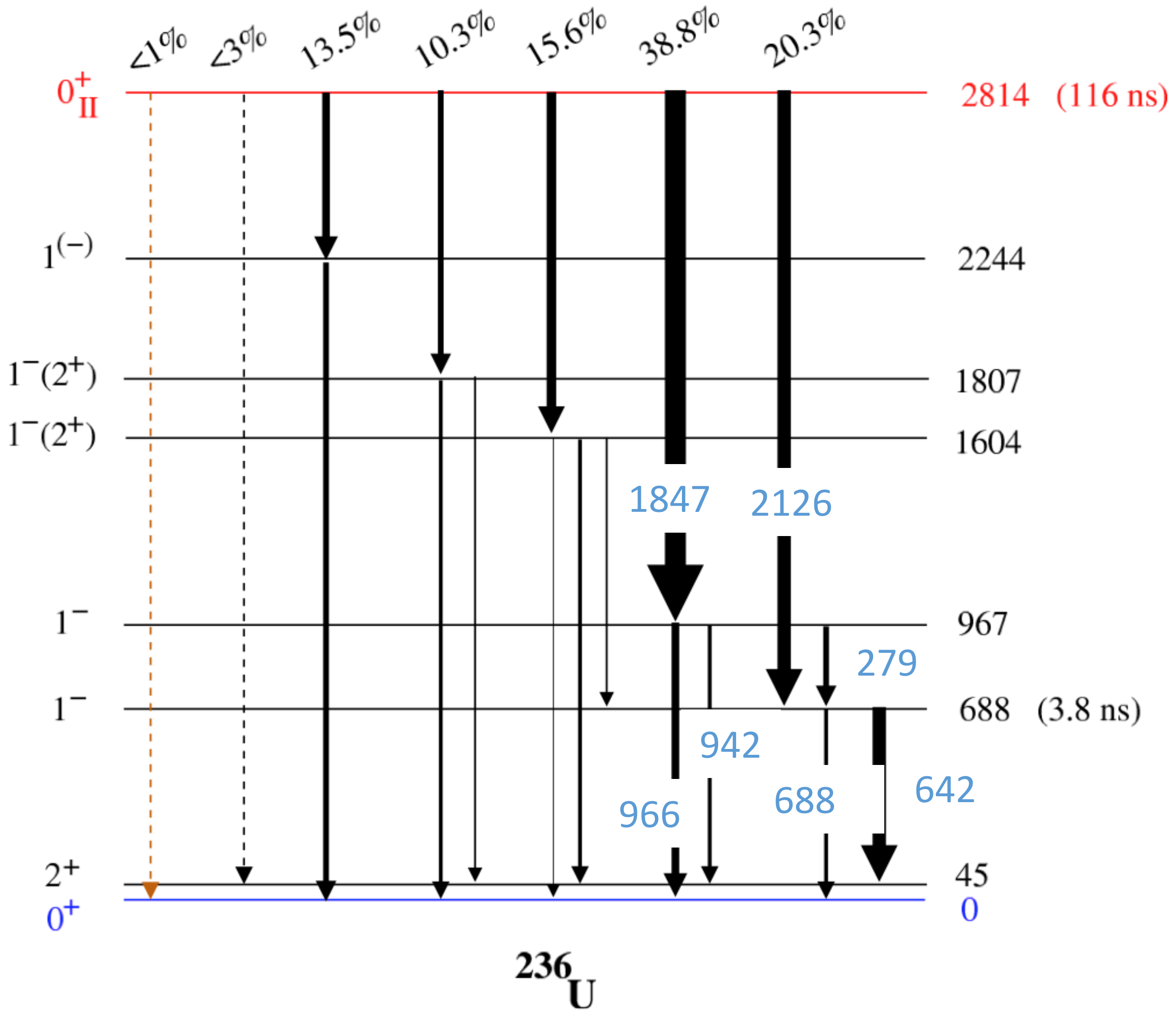


J. Schirmer, J. Gerl, D. Habs, and D. Schwalm, Phys. Rev. Lett. (1989)

Darmstadt-Heidelberg Crystall Ball (1989)

P.Thirolf and D. Habs
Prog. Part. Nucl. Phys. 49 325-402 (2002)

Later re-analysis by P. Reiter PhD thesis



Nu-Ball2+PARIS+DSSD Experiments (2023)

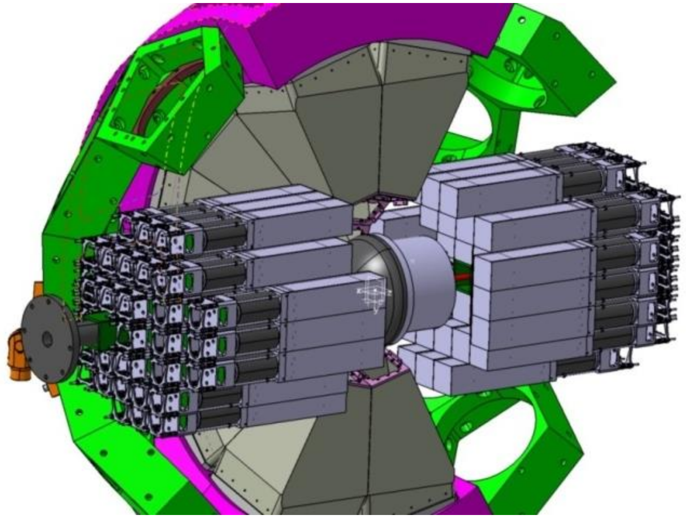
Goals

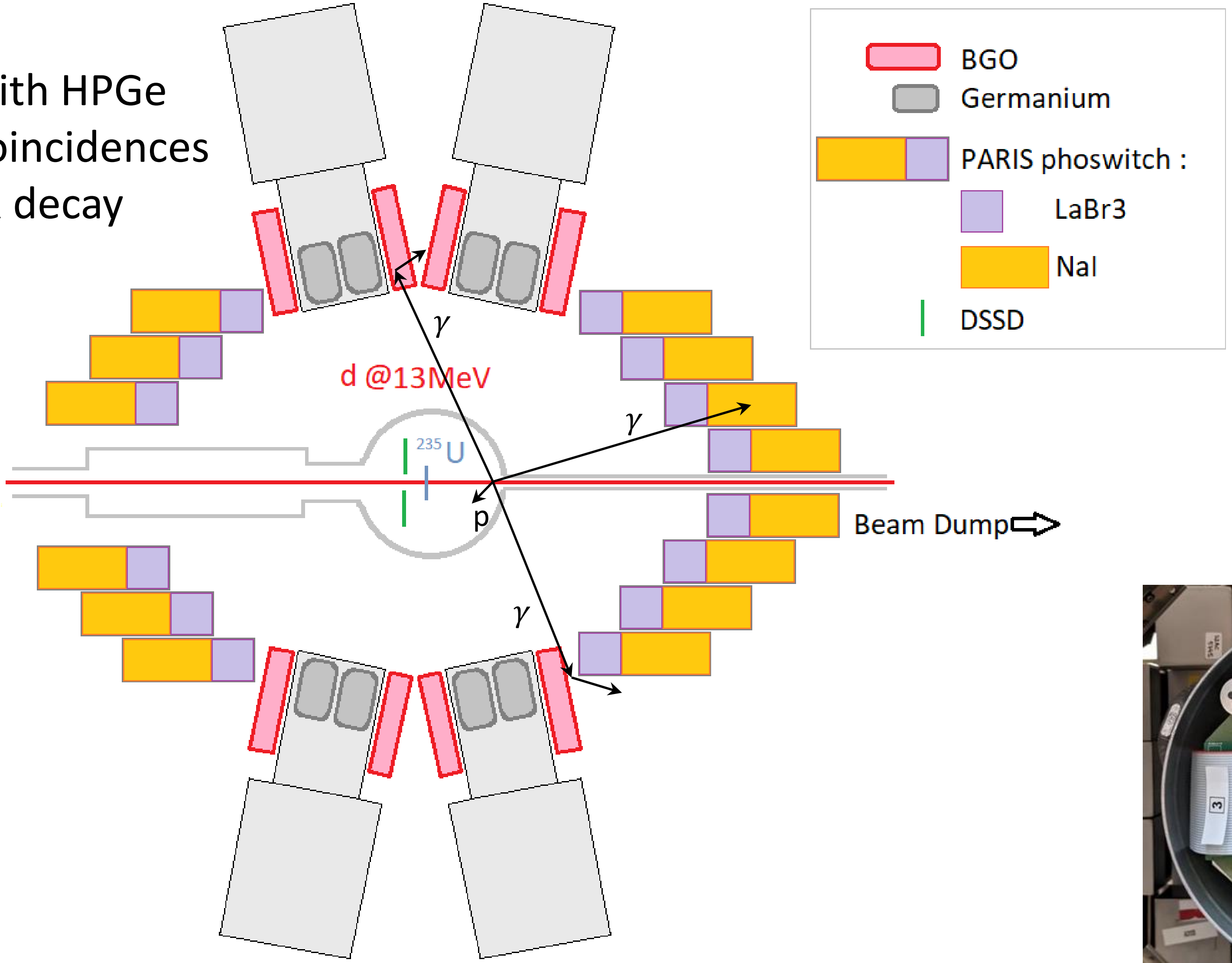
- Explore ^{236m}U back decay with HPGe
- Perform prompt/delayed coincidences
- Search for ^{232}Th SI and back decay

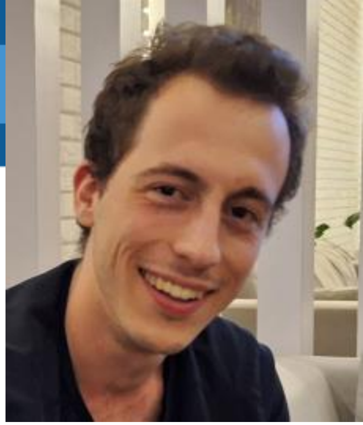
$^{235}U(d,p)^{236}U$

$^{232}Th(d,p)^{233}Th$

Nu-Ball2/PARIS

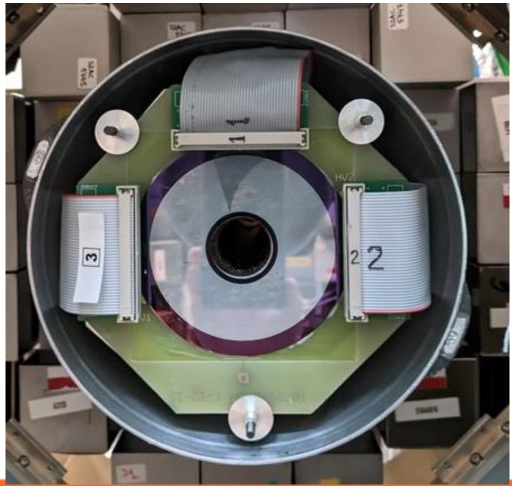




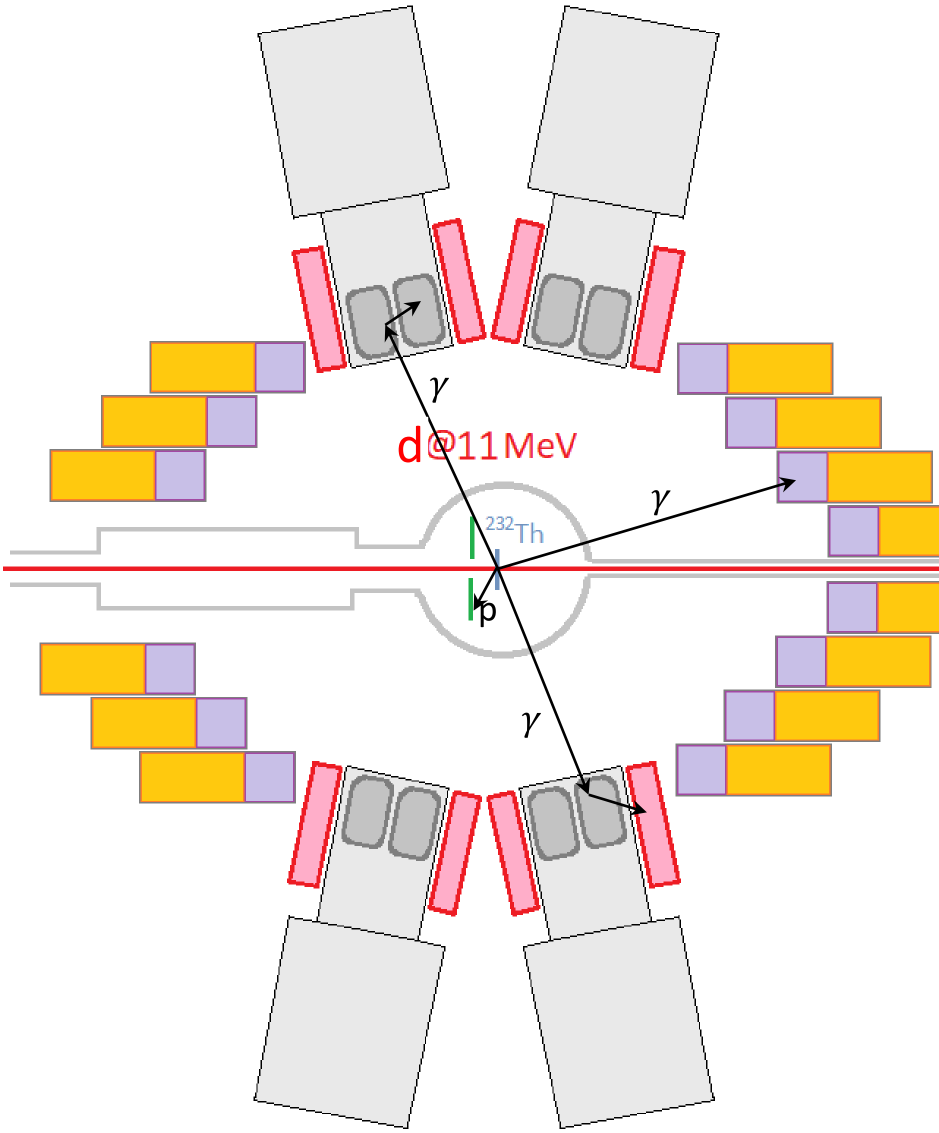


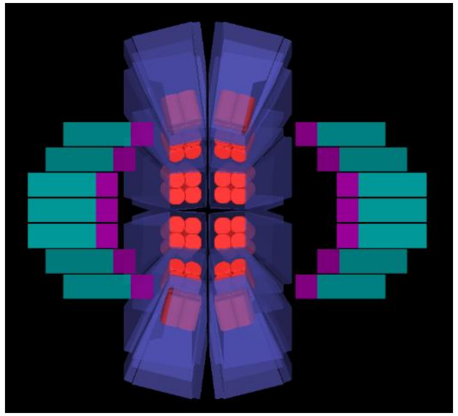
Ph.D thesis Corentin Hiver (2024)

Warsaw DSSD



nu-Ball2 + PARIS + DSSD setup (2023)





Advantages over the Crystal Ball :

- Better energy resolution (HPGe vs NaI)
- Better beam pulsation (2ns wide pulse vs 25 ns)
- Segmented DSSD -> 10kHz vs 800 Hz
- Triggerless -> More flexibility in data analysis

Drawbacks :

Calorimetry full energy efficiency 30% vs 60%
DSSD proton punch-through
UO_2 target vs metal target

Detection of the ^{236}U shape isomer back decay

Expected intensity of the key lines in delayed Ge singles

1847 keV : 3492 counts

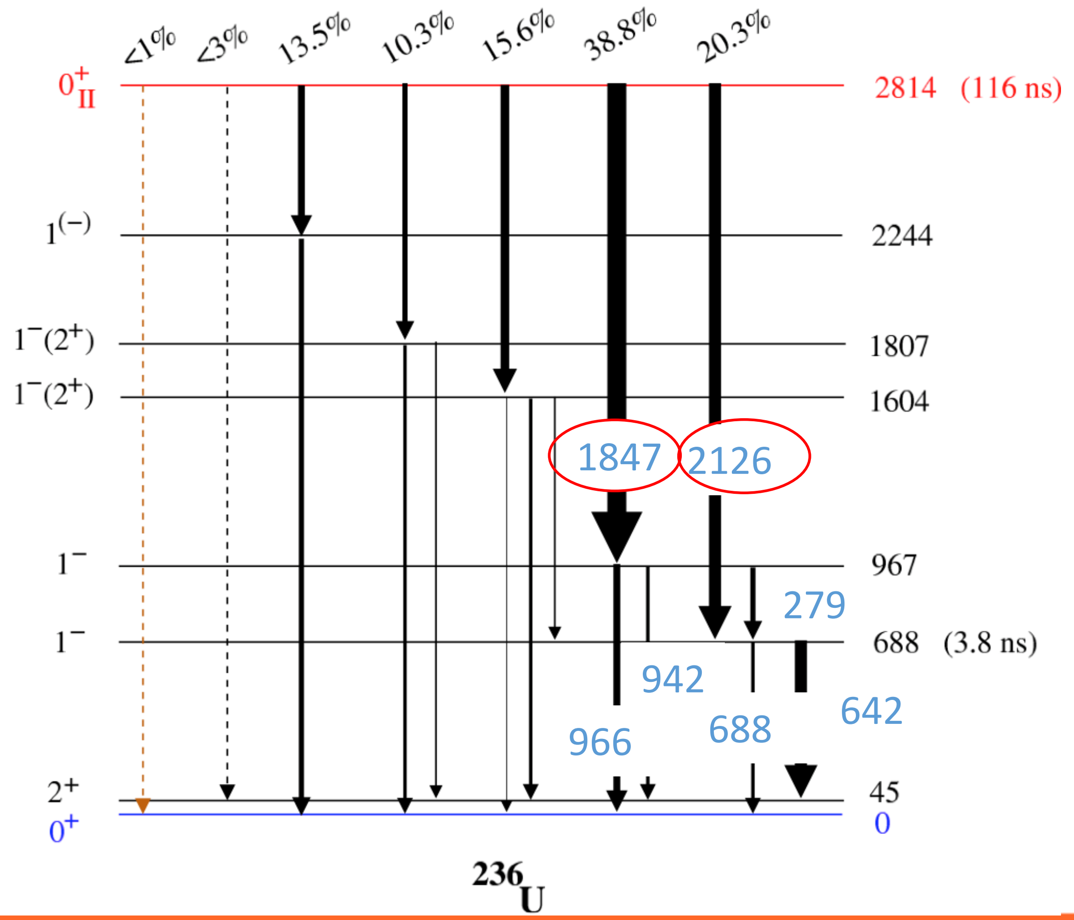
2126 keV : 1671 counts

SI production rates :

- ^{236}U nuclei produced in the experiment: 1.0×10^9
- From Habs et al measurement, $\frac{I(^{236II}U)}{I(^{236I}U)} = 3.10^{-4}$
- Hence we will produce 3.10^5 Shape Isomers

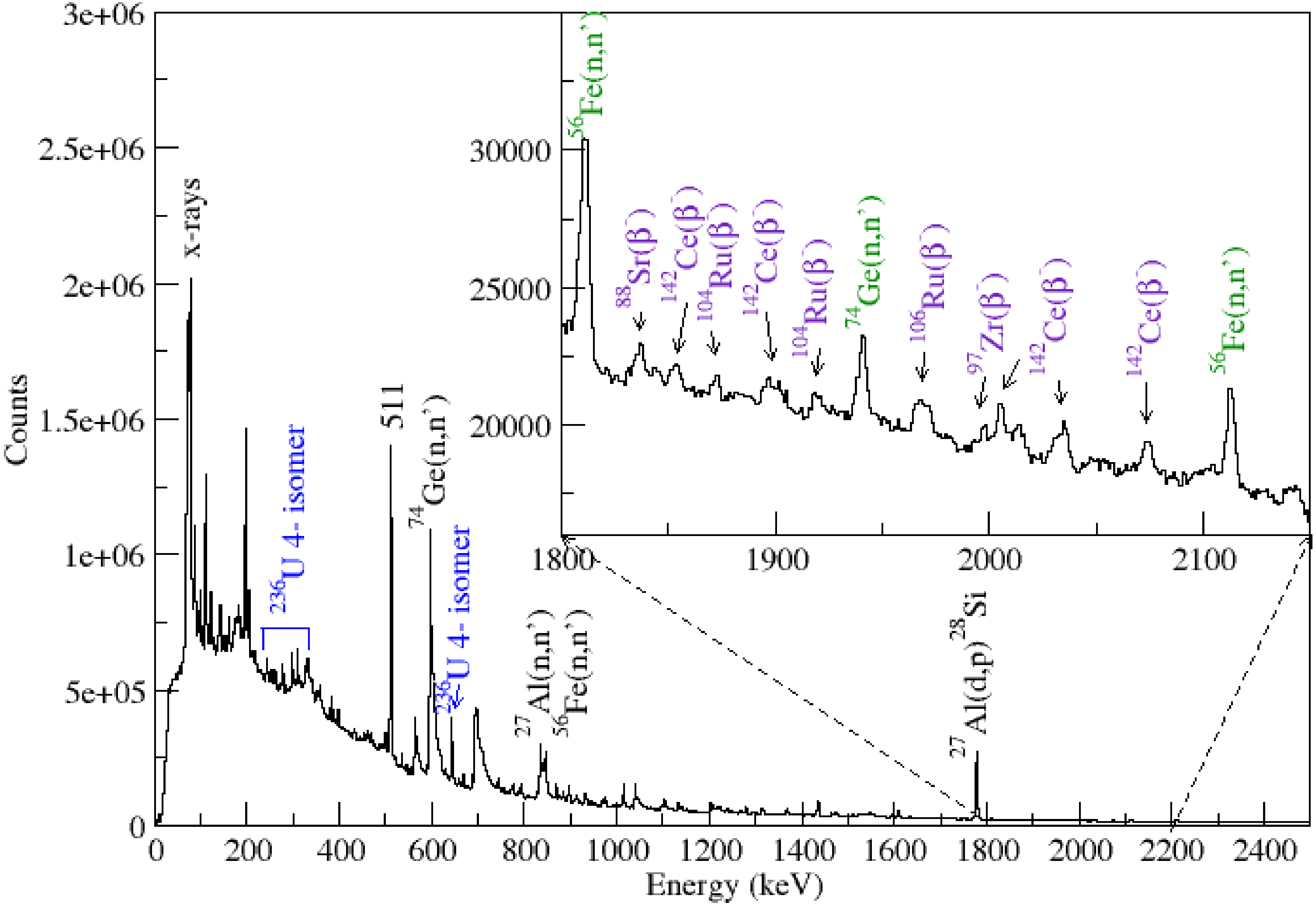
Methodology : Apply stronger and stronger selection criteria:

- Prompt and delayed calorimetry conditions
- Particle gate
- Excitation energy conditions



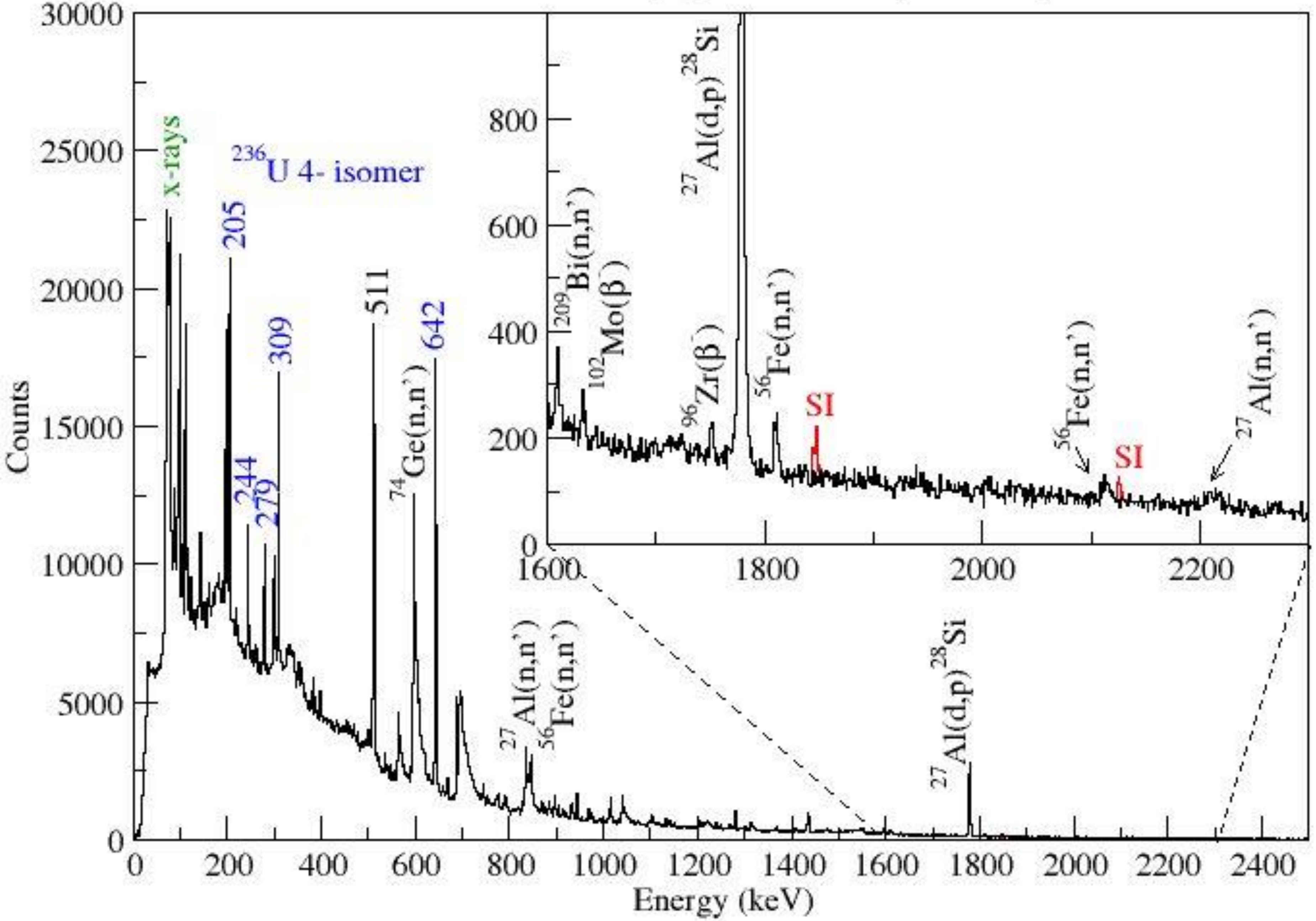
Delayed γ's

$M\gamma_{prompt} >= 1, M\gamma_{delayed} >= 2$



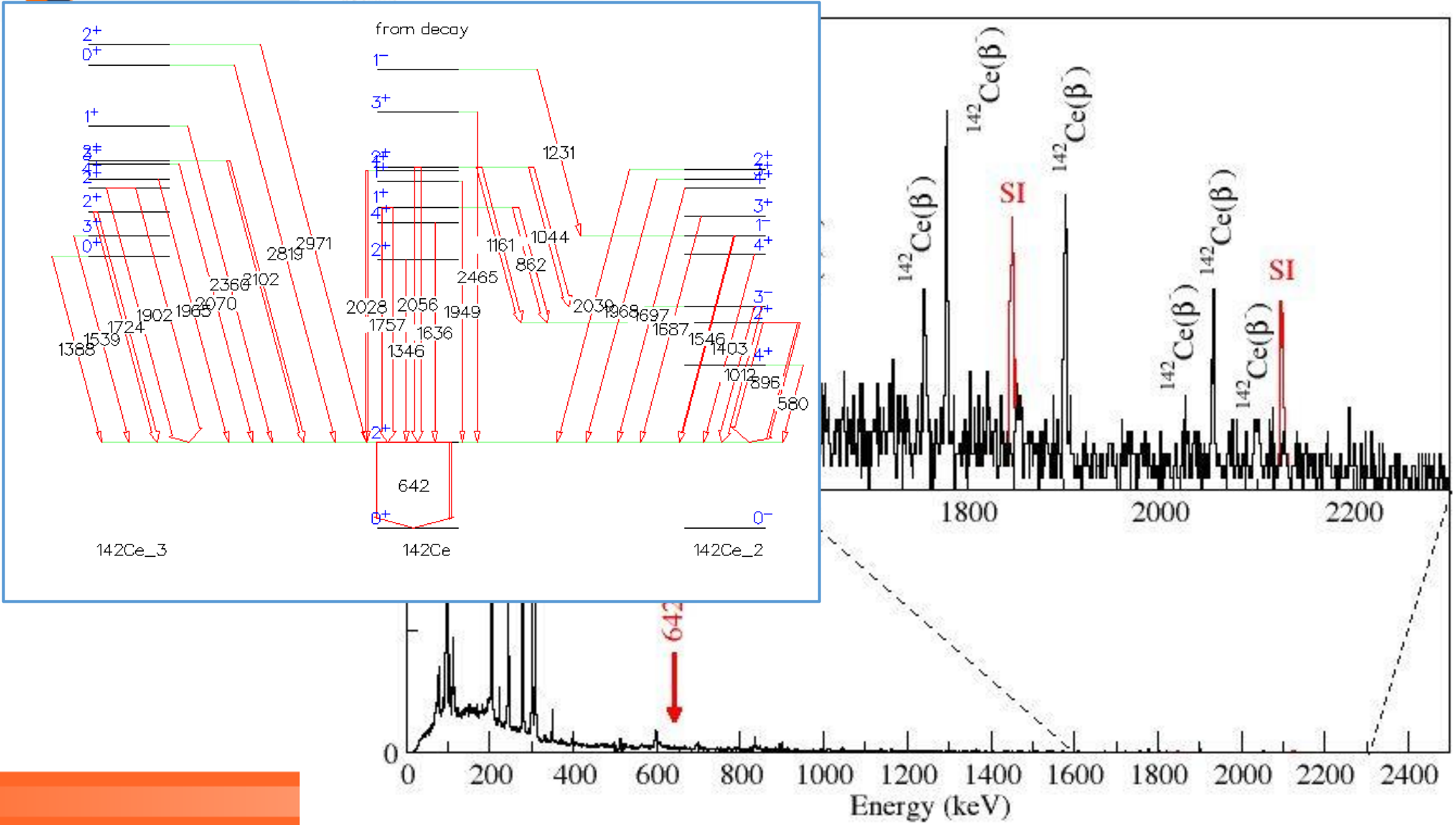
Delayed γ + Proton + Calorimetry

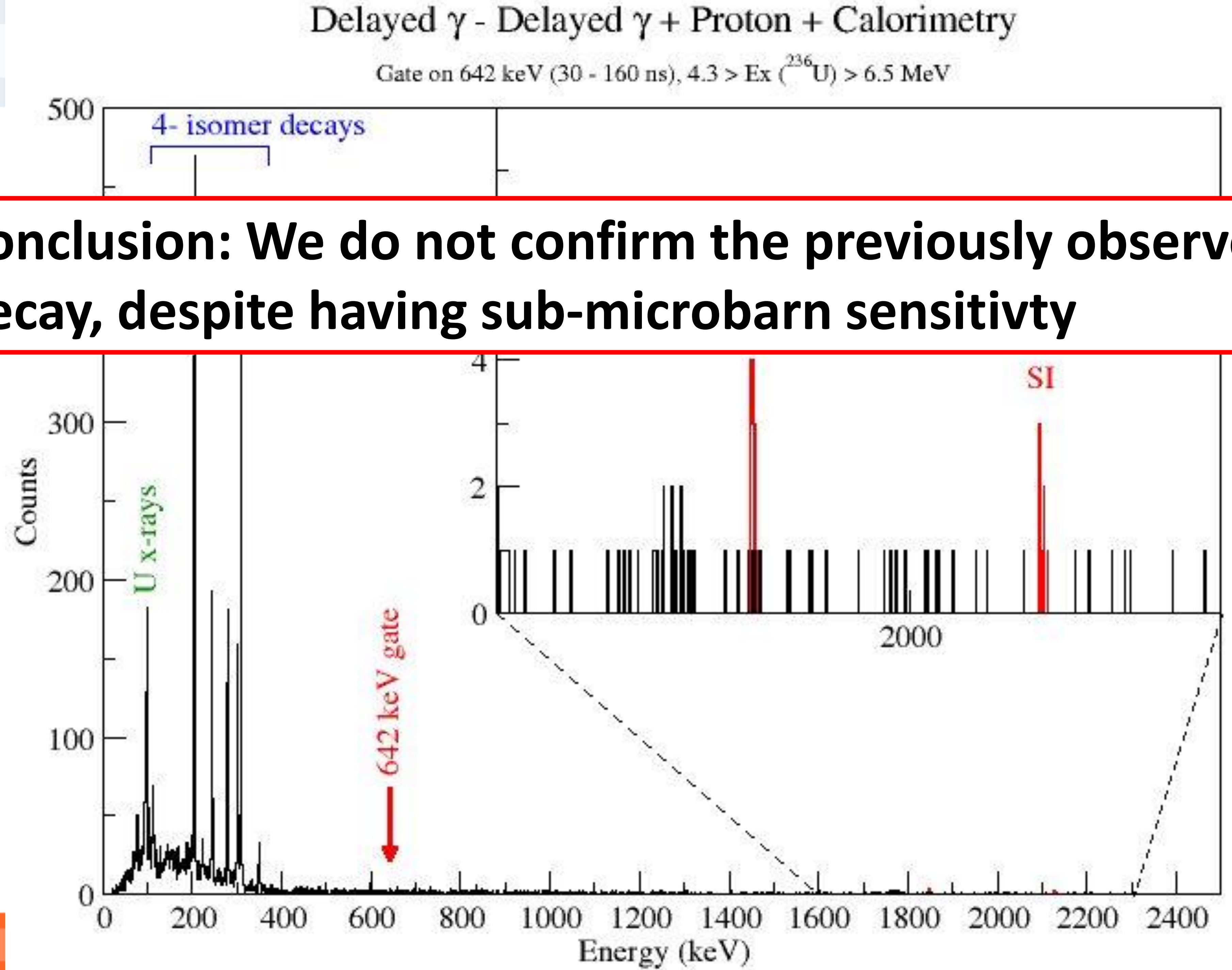
4.3 > E_x (^{236}U) > 6.5 MeV, 1 >= $M\gamma_{prompt}$ <= 4, 2 >= $M\gamma_{delayed}$ <= 4, $E_{delayed}$ < 3 MeV



Delayed γ - Delayed γ + Calorimetry

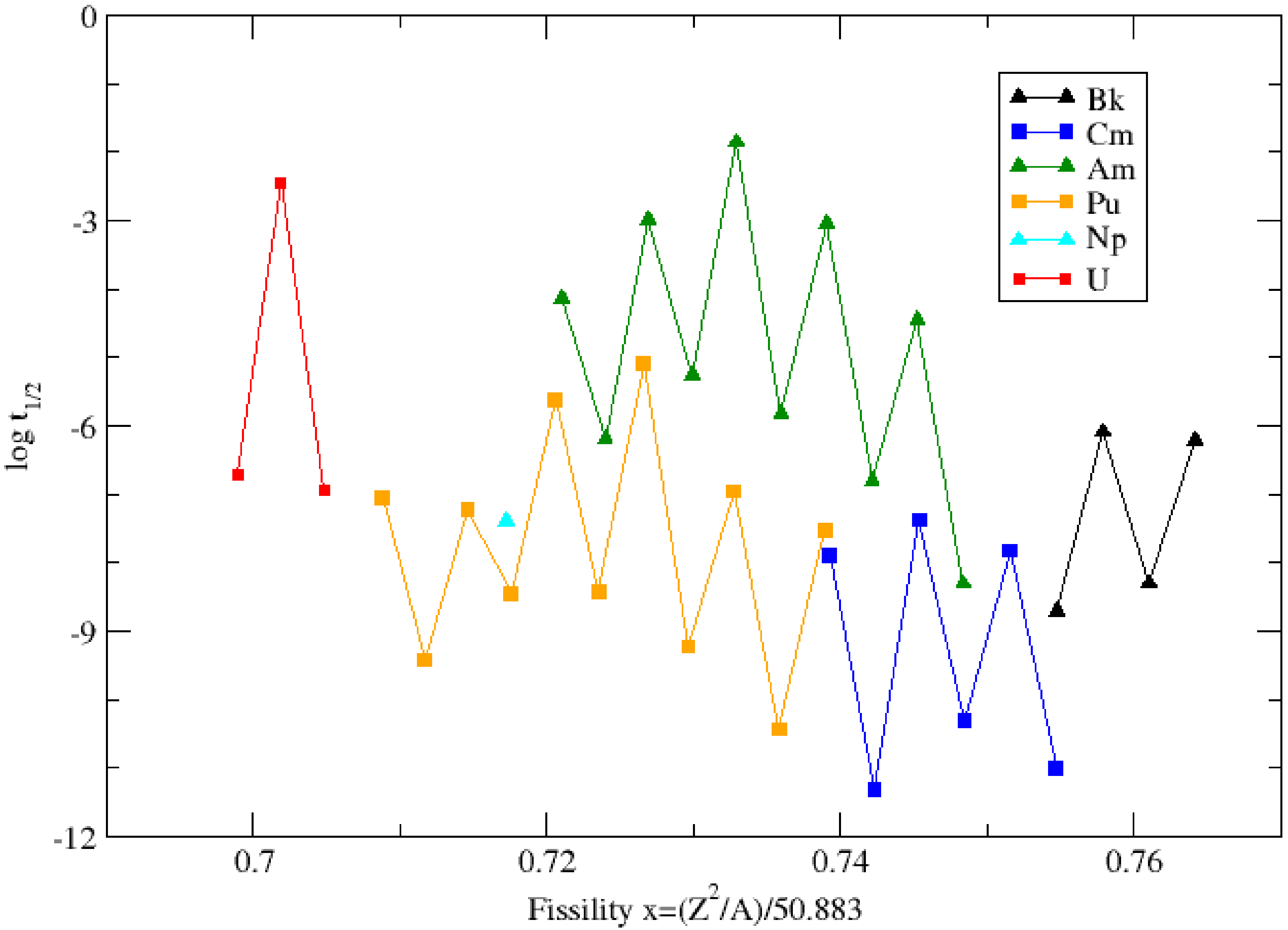
Gate on 642 keV (30 - 160 ns), $M\gamma_{prompt}$ >= 1





Conclusion: We do not confirm the previously observed back decay, despite having sub-microbarn sensitivty

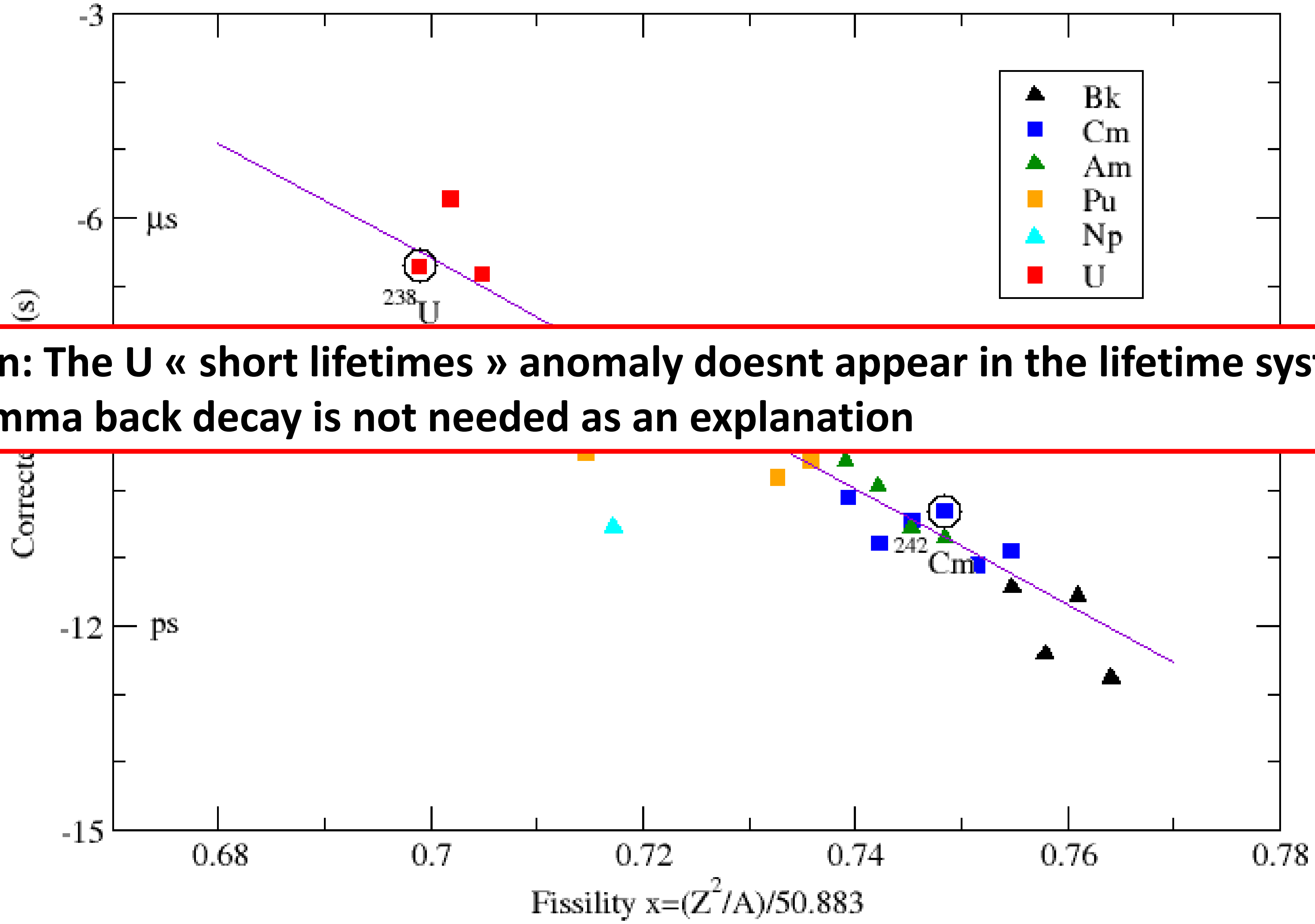
Systematics of shape isomer lifetimes: REVISITED!



Method: « Correct » the $t_{1/2}$'s for

- Specialisation energy (×10^3)
- Distance from N=144 closed shell (×10)

Systematics of shape isomer lifetimes: REVISITED!



Conclusion: The U « short lifetimes » anomaly doesnt appear in the lifetime systematics
Hence gamma back decay is not needed as an explanation

Prompt emission in fission

How is the available exciation energy and angular momentum shared at scission?

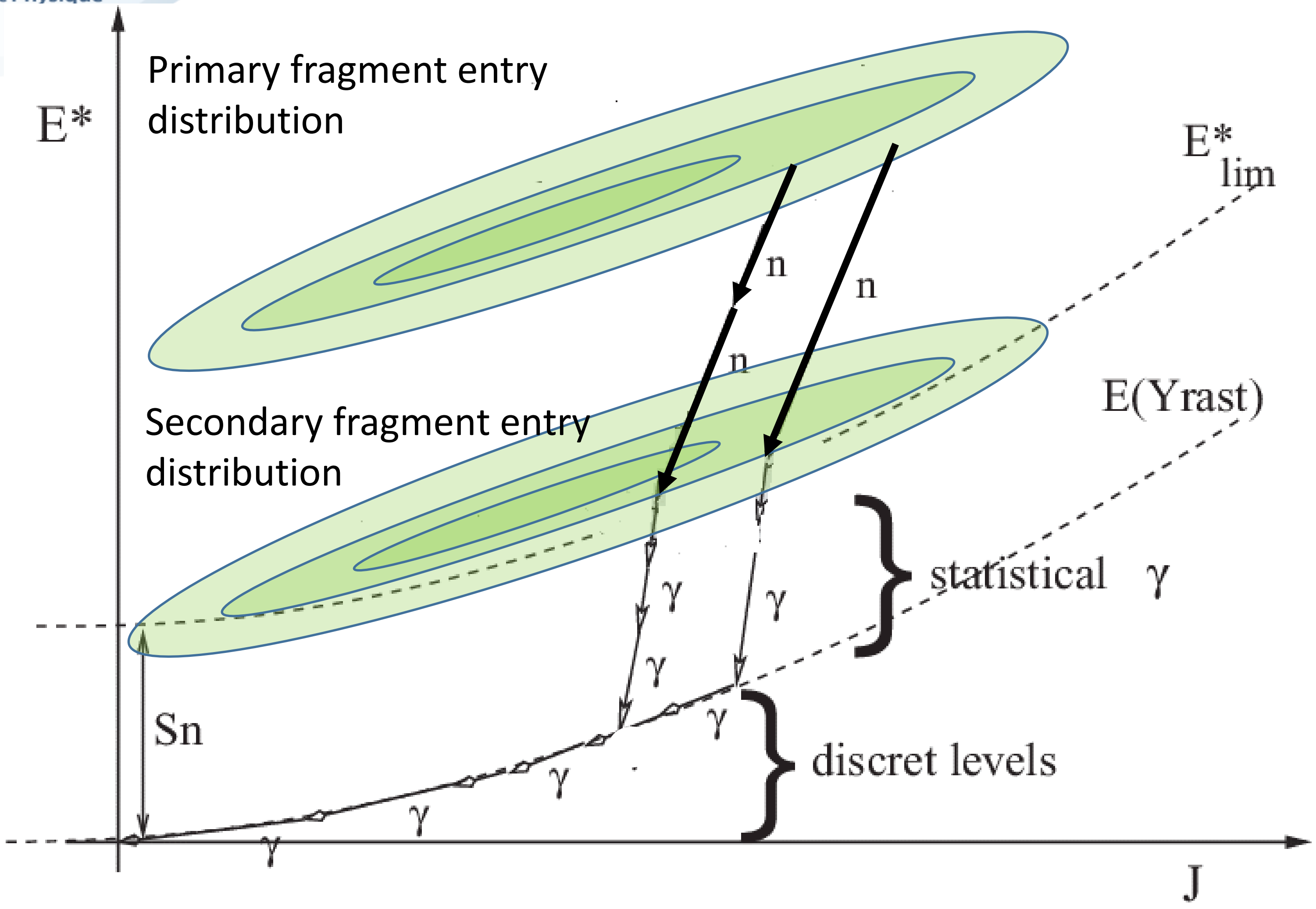
$$Q = TKE + TXE$$

Coulomb repulsion of fragments (180 MeV)

Remaining energy available for prompt emission (25-30 MeV)

Fission fragment decay

S. Leoni, C. Michelagnoli, J. N. Wilson
Gamma-ray spectroscopy of fission fragments with state-of-the-art techniques
La Rivista del Nuovo Cimento
45 461–547 (2022)



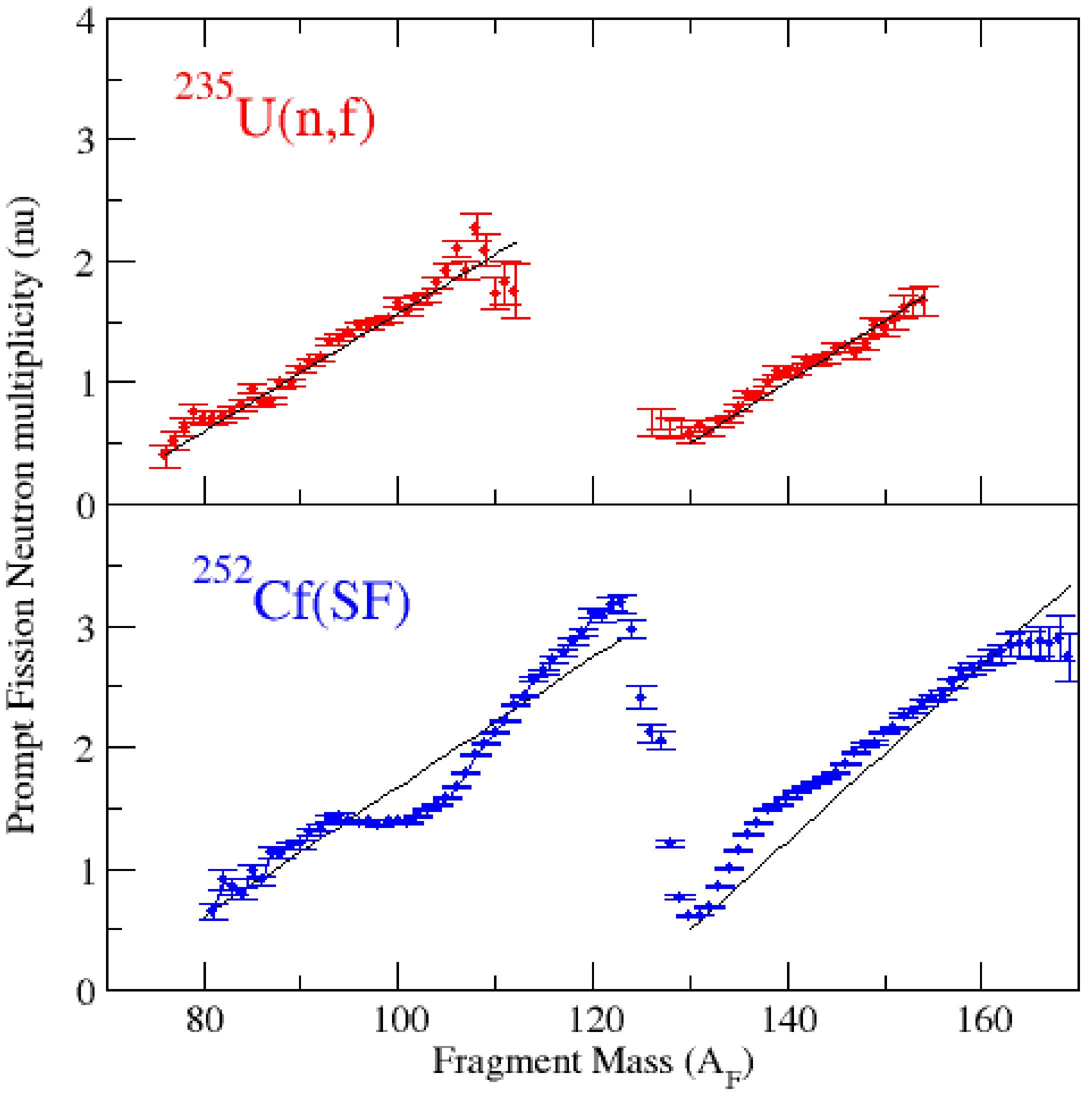
- Excitation energy evacuated by neutrons
- Angular momentum evacuated by gammas

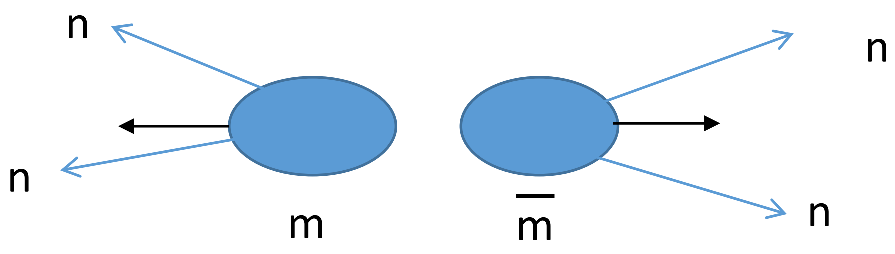
(mostly)

$\langle M_\gamma \rangle$ (one fragment) ~ 3.5 - 4

$\langle \nu \rangle$ (one fragment) ~ 1 - 2

Prompt neutron multiplicity vs fragment mass (A)





Prompt neutron multiplicity measurements: Exploit the kinematic boost of neutrons in the lab frame in the direction of fragment velocity

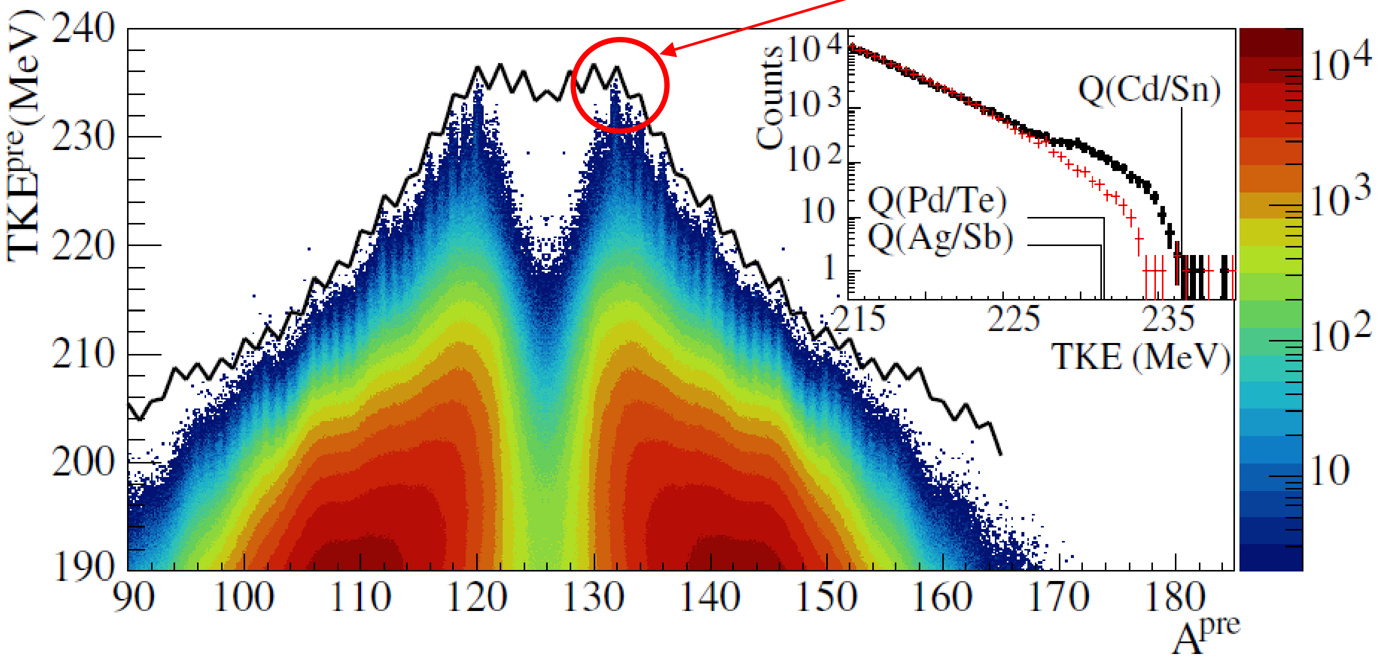
Prompt neutron multiplicities are related to energy sharing at scission

Variation of a factor 4-6 between lowest and highest

Study of neutronless fission emission in ^{252}Cf

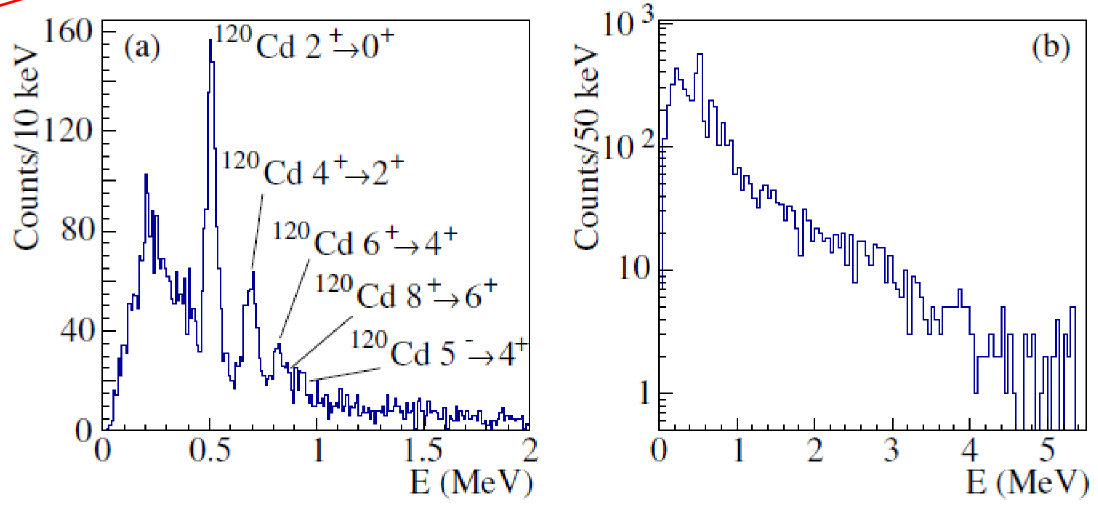
Setup: Ionisation chamber with ^{252}Cf sample surrounded by NaI detectors

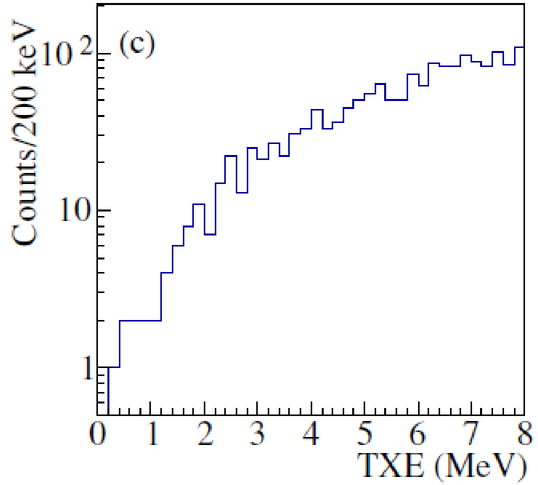
Selection of « cold » neutronless fission events



A. Franchetau et al., Phys. Rev. Lett. 132, 142501 (2024)

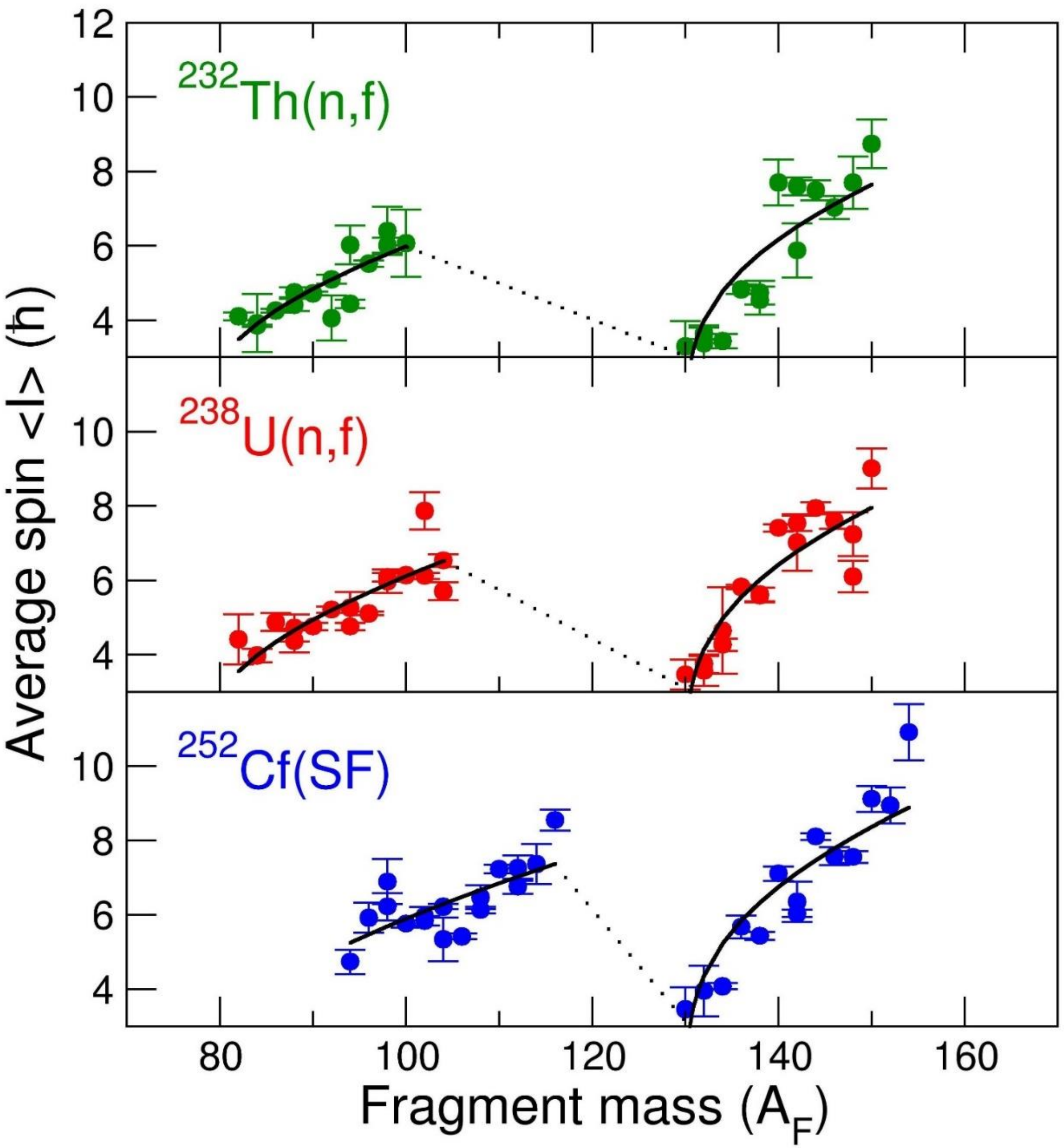
Selection of the ^{120}Cd/^{132}Sn pair





Result: First measurement of the E_x distribution at scission in a single fragment

Average spin <I> vs fragment mass (A)



- 30 even-even nuclei measured for each system
- Definitive saw-tooth patterns
- Slope and curvature. Heavy peak has higher spins

Remarks

- No notable dependence on the partner nucleus

e.g.

^{140}Xe + ^{90}Kr
^{140}Xe + ^{96}Sr
^{140}Xe + ^{112}Ru

25% difference in mass

Each nucleus does not care who it emerged with!

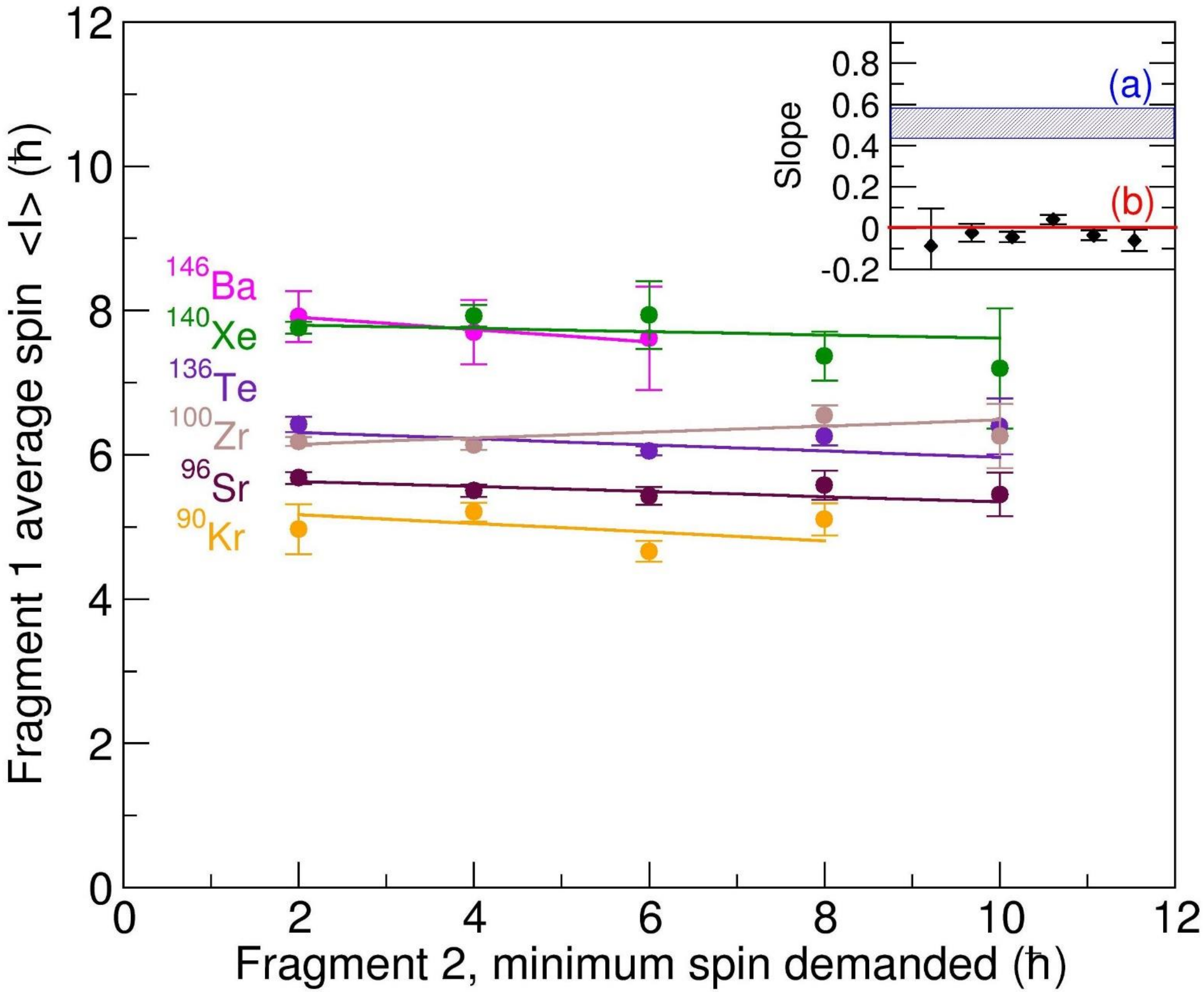
- Certain partners have large asymmetries in <I>

e.g. ^{150}Ce has double the <I> of ^{86}Se

- Highly asymmetric distribution

J.N. Wilson et al. Nature 590 566 (2021)

Correlation between fission fragment spin magnitudes



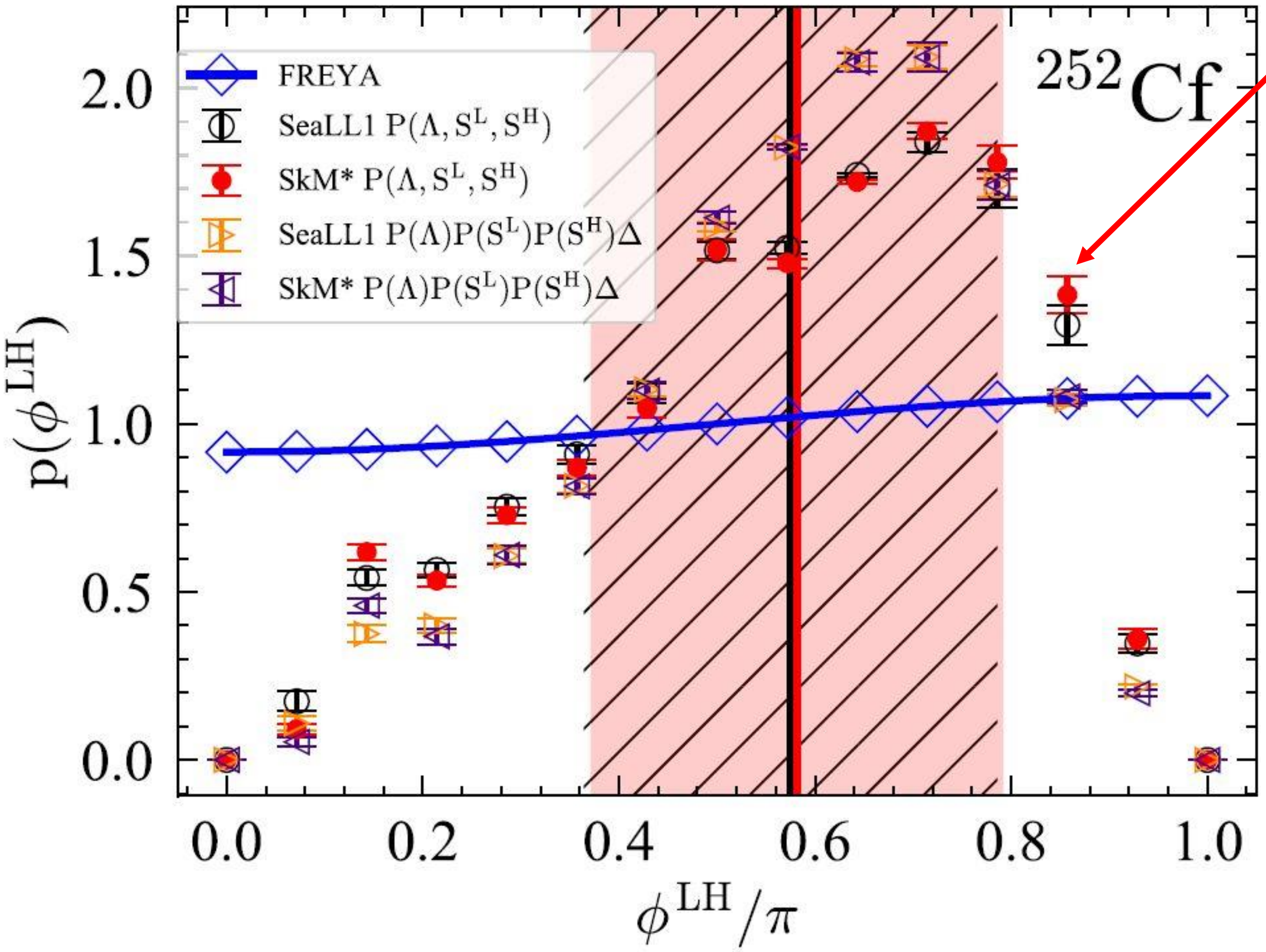
Correlated spins

Uncorrelated spins

$$\vec{S}_1 + \vec{S}_2 + \vec{S}_o = 0$$

Correlation between the fragment spin *directions?*

TDDFT, A. Bulgac, I. Abdurrahman, K. Godbey, and I. Stetcu, Phys. Rev. Lett. 128, 022501 (2022)



J. Randrup and R. Vogt, Phys. Rev. Lett.127, 062502(2021)

Theoretical predictions strongly disagree

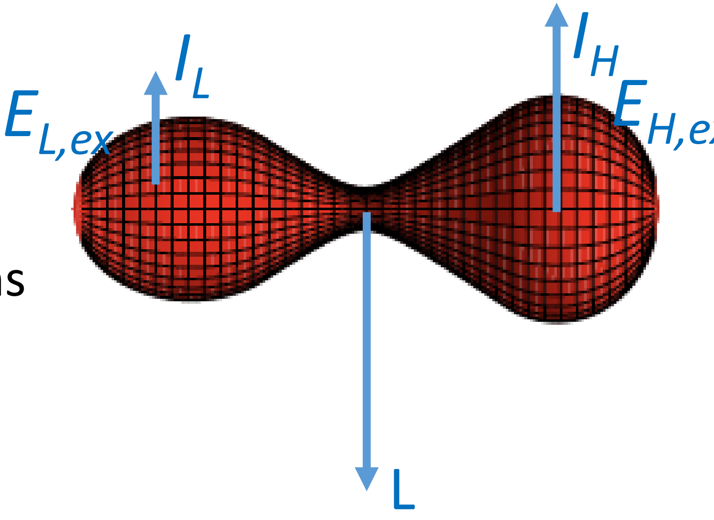
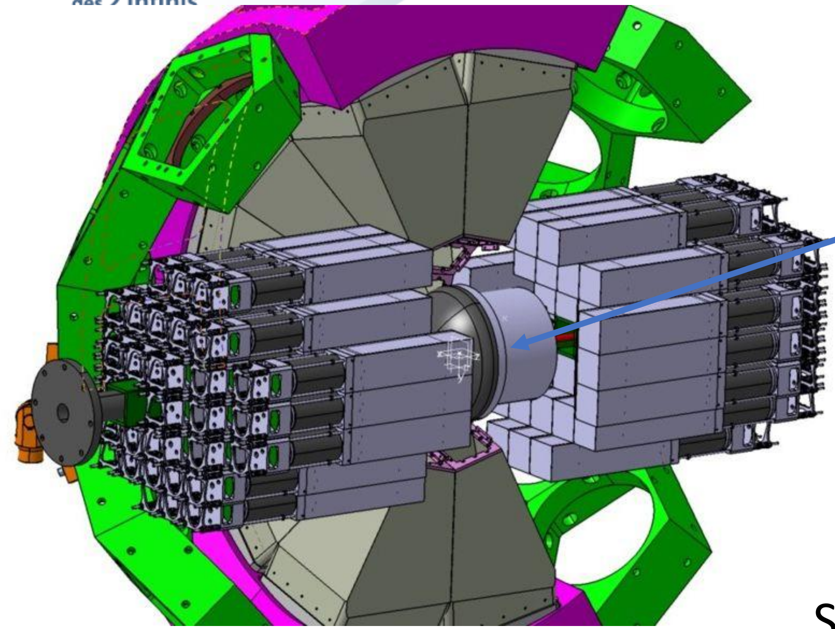
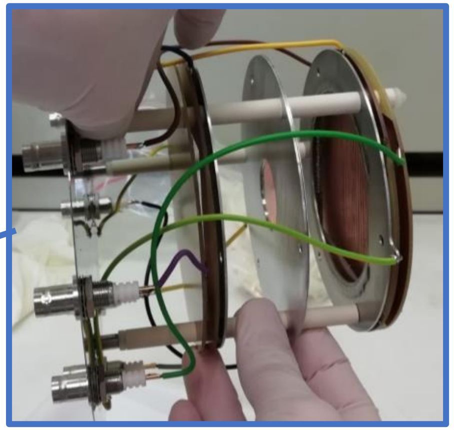


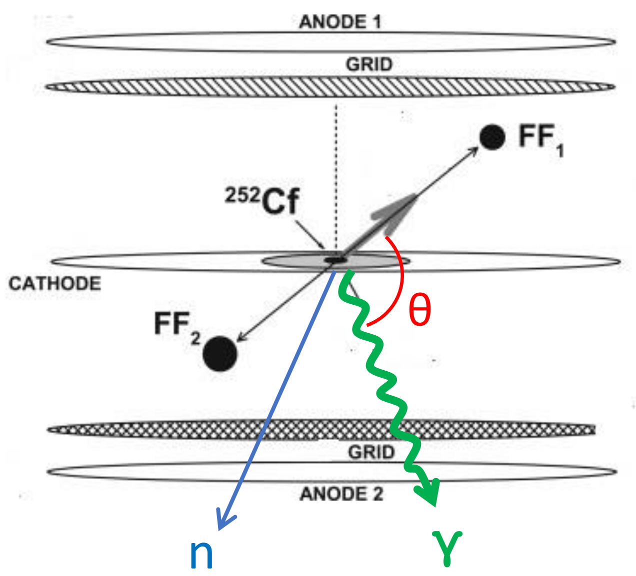
Image courtesy of S. Aberg

<u>However, directional correlations can be determined by experiment!</u>

v-ball2 + 4π ^{252}Cf source + Segmented Ionisation chamber







FROZEN project
M. Lebois

A. Göök et al.
JRC-Geel

Measurment of correlations between multiple fission observables are key to obtaining interesting new results (in our opinion)

Simultaneous event-by-event measurement of:

- Prompt/delayed fission gamma rays and neutron(s) (via TOF)
- Fragment Kinetic Energies, Fragment A/Z and partner A/Z
- Fission axis direction and all directional correlations
- Prompt/Delayed gamma sum energy and multiplicity

Analysis is ongoing

Conclusions

- There are still many interesting and important experimental measurements that need to be performed
- Both inverse and direct kinematics experimental approaches useful

- Suggestions for new experimental studies…

1) Yield distributions in new fission regions, especially the super heavy nuclei

2) Revisting of the fission shape isomers with modern state-of-the-art techniques

3) Studies of prompt emission in fission (Ionization chambers coupled to high performance arrays)

4) Studies of E*, J dependence of fission observables of neutron induced fission at NFS@GANIL (5 – 40 MeV)

The nu-Ball2 collaboration, July (2024)

IJC Lab, CEA DAM
Subatech, CENBG, IPHC,
GANIL, LPC Caen

University of Milano
INFN Legnaro

IFJ-PAN Krakow
University of Warsaw

University of Oslo

JRC-Geel
Leuven

University of Surrey, NPL
University of Manchester

TU Darmstadt
IFK- Koln

University of Novi Sad

University of Madrid
IFIC Valencia

ELI-NP, Bucharest

University of Sofia

Riken