

**P(ND)<sup>2-3</sup> Perspectives on Nuclear Data for the Next Decade**  
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# **Microscopic Theory of Angular Momentum Distributions Across the Full Range of Fission Fragments**

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In collaboration with

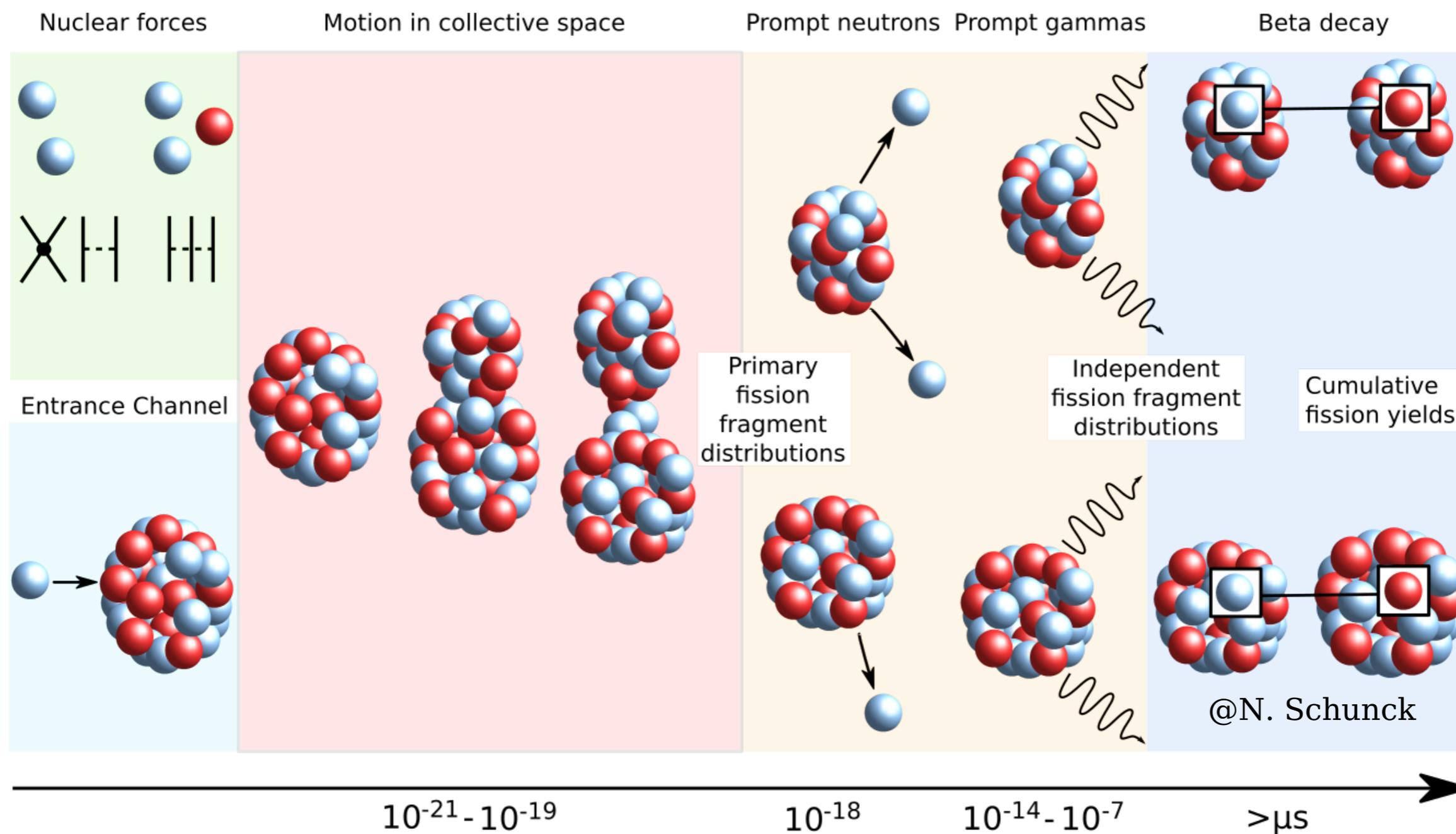
**Nicolas Schunck, LLNL, USA**

**Marc Verriere, CEA, France**



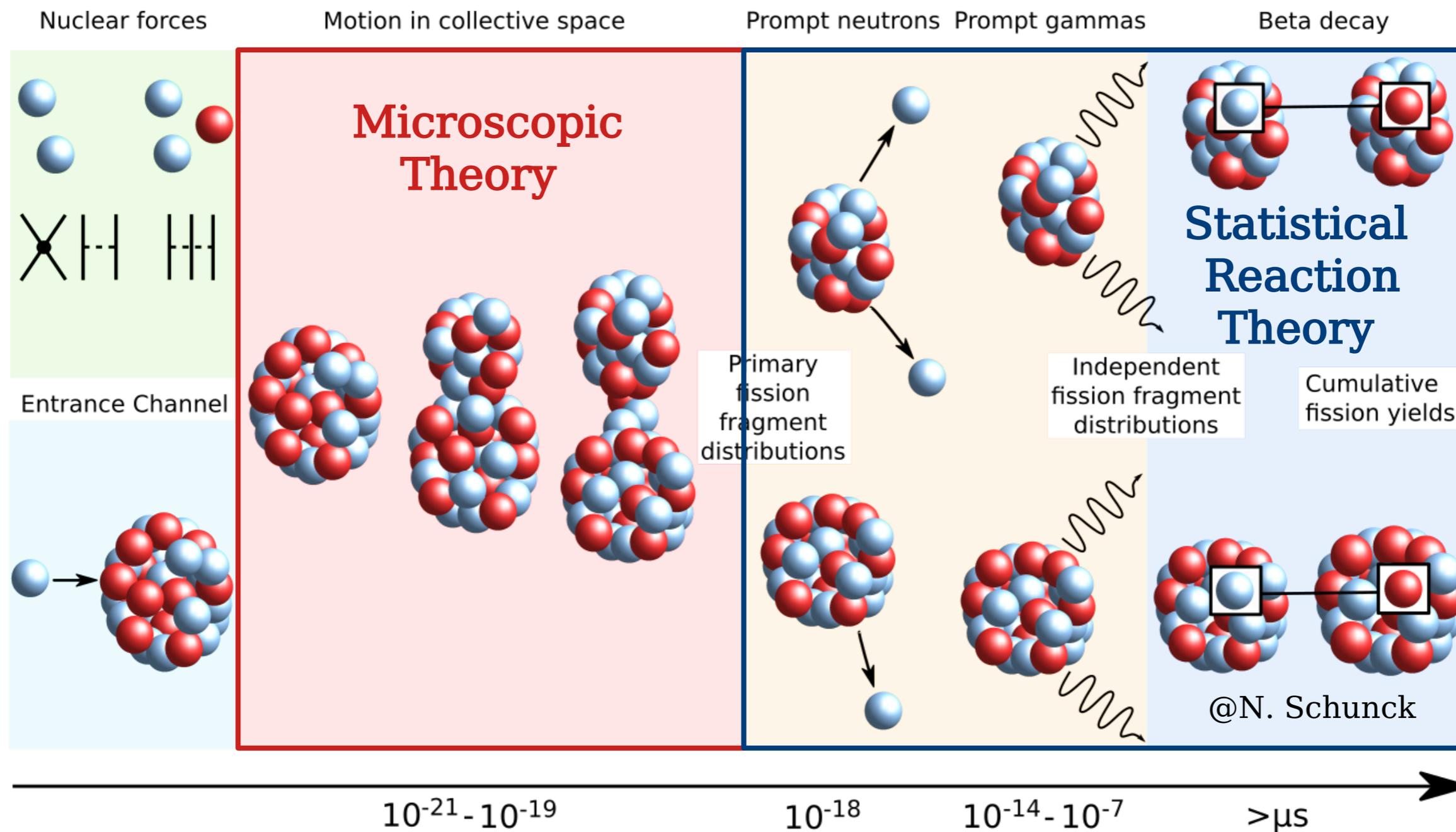
# Introduction

## Fission: A Longstanding Puzzle for Nuclear Theory



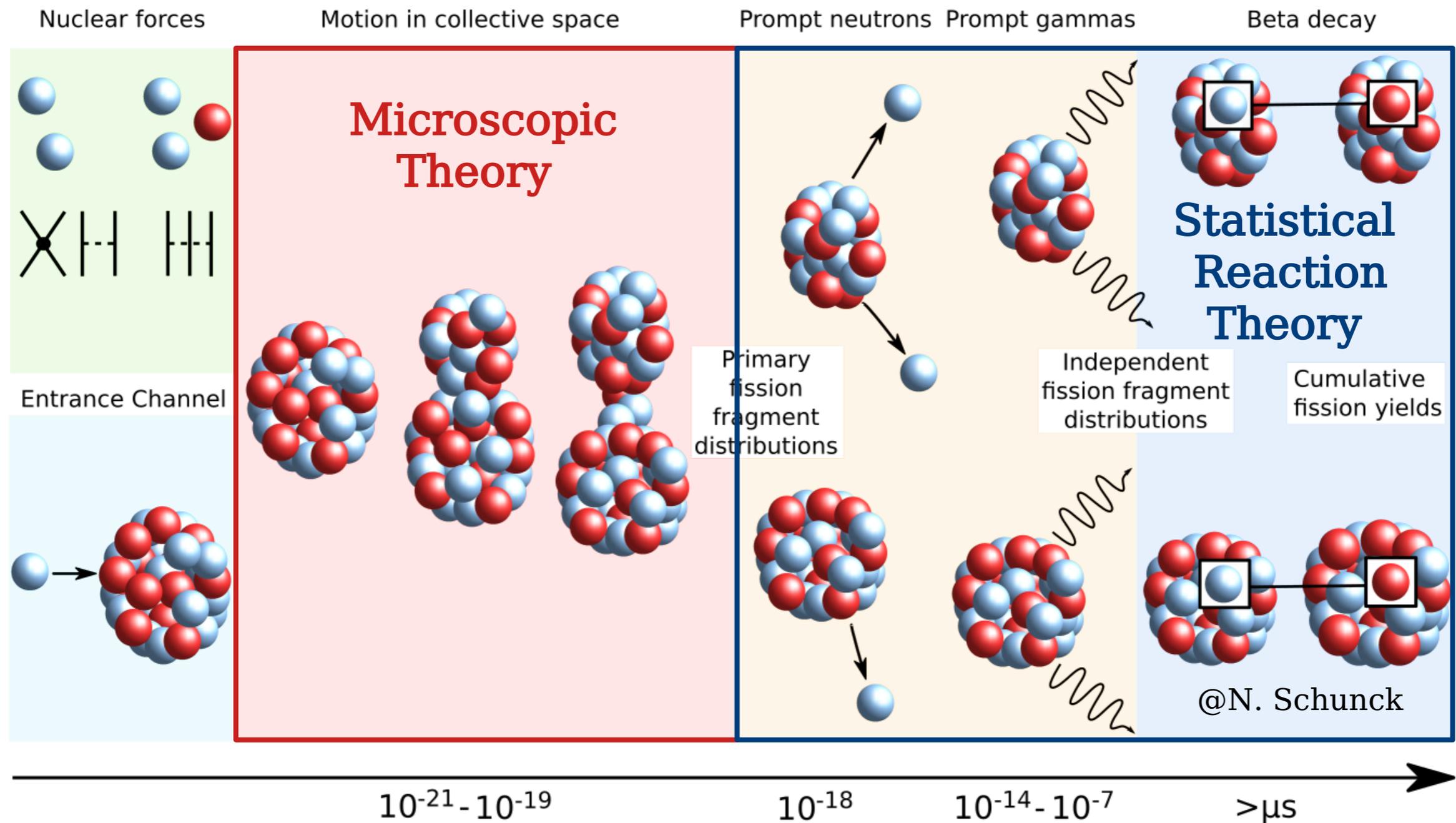
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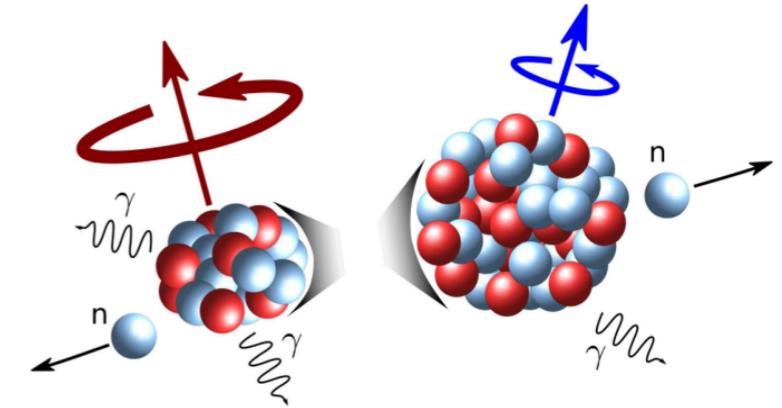


Microscopic theory can now predict **initial conditions** for primary FFs.

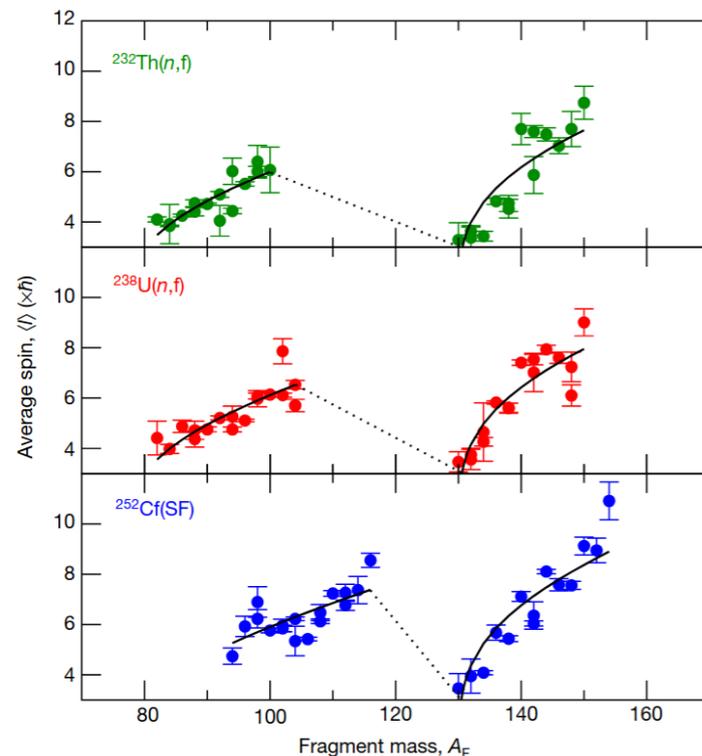
# Introduction

## Angular Momentum of Fission Fragments (FFs)

- FFs at scission are hot, deformed, and rotating
  - High excitation energy (up to 30 MeV)
  - Large deformation, typically different than the g.s.
  - Distribution of angular momentum (AM)
- Angular momentum of FFs influences the decay process
- Recently, the study of AM of FFs experienced a *renaissance*



Wilson *et al.*, Nature **590**, 566 (2021).



- A. Bulgac *et al.*, PRL **126**, 142502 (2021).
- P. Marević *et al.*, PRC **104**, L021601 (2021).
- J. Randrup and R. Vogt, PRL **127**, 062502 (2021).
- I. Stetcu *et al.*, PRL **127**, 222502 (2021).
- A. Bulgac *et al.*, PRL **128**, 022501 (2022).
- J. Randrup, PRC **106**, L051601 (2022).
- G. Scamps, PRC **106**, 054614 (2022).
- G. Scamps *et al.*, PRC **108**, L061602 (2023).
- T. Dossing *et al.*, PRC **109**, 034615 (2024).
- G. Scamps *et al.*, arXiv:2512.02207v1 (2025).
- ... and others

Most studies still focus on the **most likely fragmentation**.

# Introduction

What Are We Trying to Achieve?

## Objectives:

1) Establish a microscopic framework for predicting AM distributions in the **full range** of FF masses and charges.

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- 3) **Verify the results** against experiment and theory (the sawtooth pattern, lack of correlation in magnitude, ...).
- 4) Use the results to **inform phenomenological models** (deformation effects, isobaric dependence, ...).
- 5) Assess how microscopic AM distributions **impact the FF decay process** (neutron and photon spectra).

# Theoretical Framework

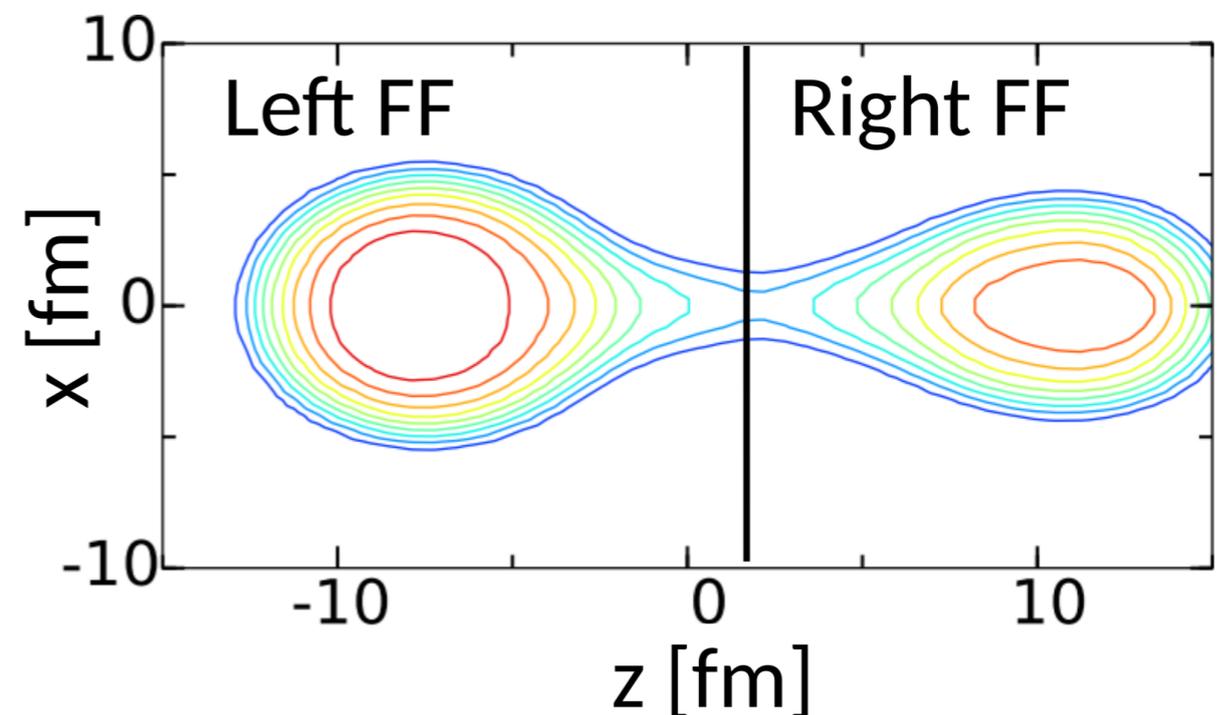
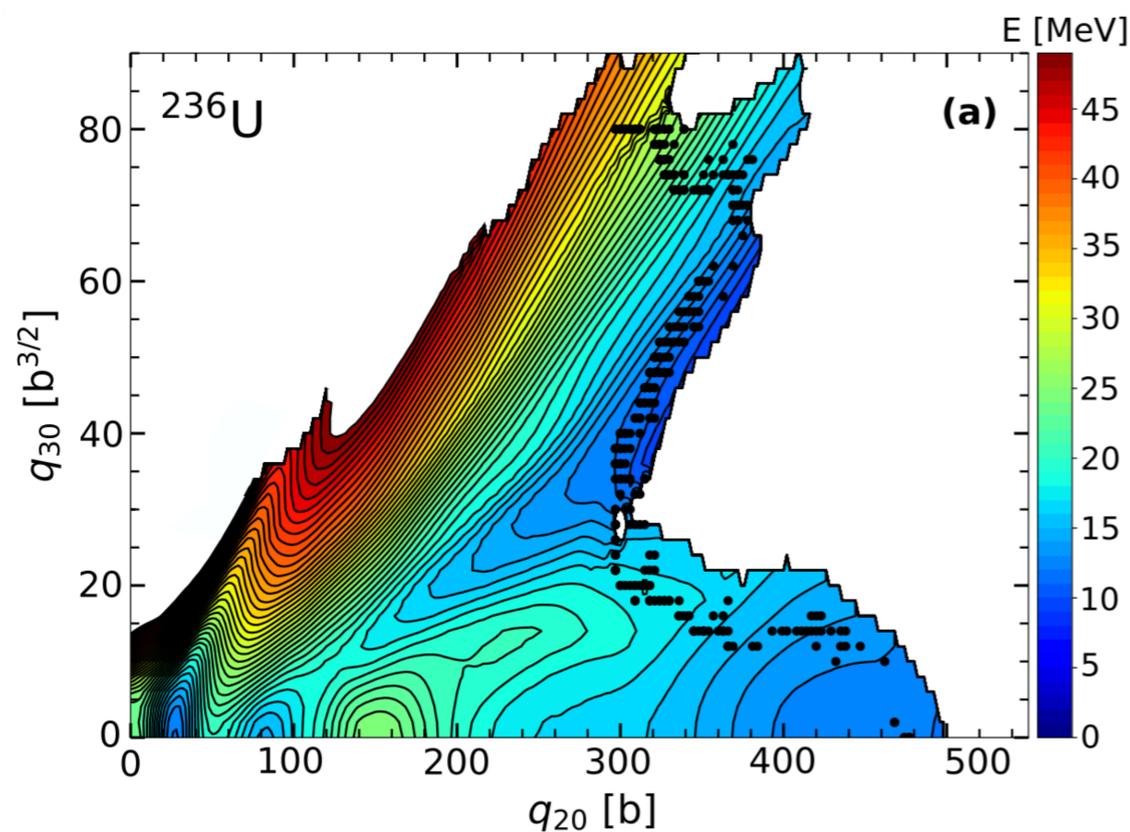
## Potential Energy Surface and Scission Configurations

- **Neutron-induced fission**: even- $Z$  and odd- $N$  nucleus absorbs a neutron
- HFB model determines the **potential energy surface** of a fissioning system that contains **scission configurations**
  - SkM\* EDF and a volume-surface pairing
  - Wfs expanded in the HO basis
  - Axial and time-reversal symmetry assumed
  - Constraints imposed on  $q_{20}$ ,  $q_{30}$ , and  $q_N$  values
  - Neck position is the isoscalar density minimum



HFBTHO program

P. Marević *et al.*, CPC 276 (2022) 108367



# Theoretical Framework

## Quantum Number Distributions in Scission Configurations

- Distribution in  $J_F$ ,  $N_F$ ,  $Z_F$  for both FFs in each scission configuration is extracted through **projection techniques**

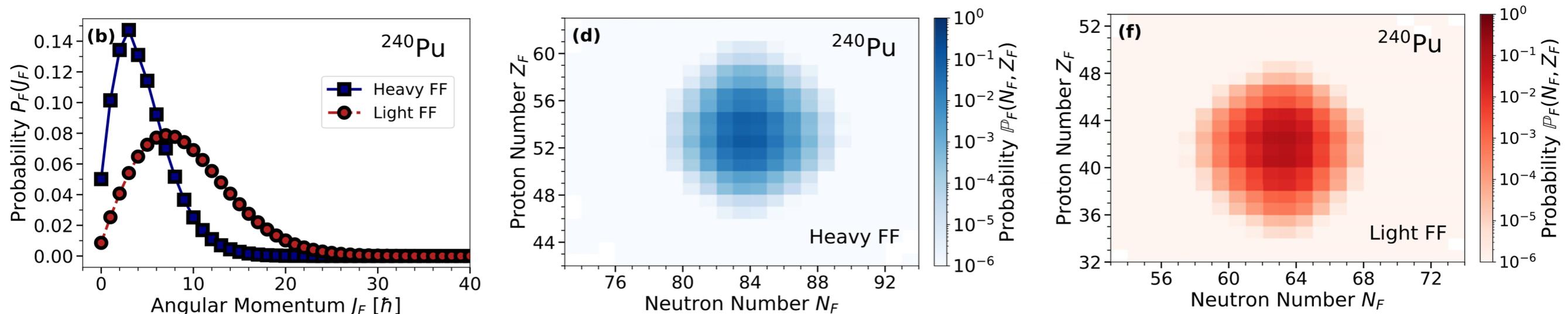
$$\mathbb{P}_F(J_F, N_F, Z_F | N_0, Z_0, q) = \langle \Phi_q^S | \hat{P}^{J_F} \hat{P}_{N_F, Z_F}^{N_0, Z_0} | \Phi_q^S \rangle / \langle \Phi_q^S | \hat{P}^{N_0} \hat{P}^{Z_0} | \Phi_q^S \rangle$$

- Projection operators are defined in FFs

$$\hat{P}^{J_F} = \frac{2J+1}{2} \int_0^\pi d\beta \sin \beta d_{00}^J(\beta) e^{-i\beta \hat{J}_y^F} \quad J_y^F(\mathbf{r}, \sigma) = \Theta^{F*}(z - z_N) J_y(\mathbf{r}, \sigma) \Theta^F(z - z_N)$$

- The procedure is repeated for all configurations (hundreds of them)
- Each scission configuration is characterized by a **full distribution**

### Distributions near the most likely fragmentation in $^{240}\text{Pu}^*$



# Theoretical Framework

## Probability of Populating Scission Configurations

- **Population probability** for each conf. is estimated with **TDGCM+GOA**
- Time-dependent wave function is a superposition of HFB states

$$|\Psi(t)\rangle = \int dq f_q(t) |\Phi_q\rangle \quad (\text{Adiabatic GCM})$$

- Variational principle and GOA lead to a Schrödinger-like equation

$$i\hbar \frac{\partial}{\partial t} g_q(t) = [\mathcal{H}_q^{coll} + i\mathcal{A}_q^{coll}] g_q(t)$$

- Collective wave function contains all the information on nuclear dynamics
  - Collective Hamiltonian can be calculated from EDF and HFB states
- Probability that the wave packet exits through any particular point is proportional to the time-integrated flux density

$$F(q) = \lim_{t \rightarrow \infty} \int_{\tau=0}^{\tau=t} d\tau \phi(q, \tau)$$



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FELIX Finite Element Solver  
D. Regnier *et al.*, CPC 225 (2018) 180-191

# Theoretical Framework

## Final Distributions

- Final distributions are obtained by folding the two results

$$\mathbb{P}_F(J_F, N_F, Z_F | N_0, Z_0) = \int dq F(q) \mathbb{P}_F(J_F, N_F, Z_F | N_0, Z_0, q)$$

$$\mathbb{P}(J_F, N_F, Z_F | N_0, Z_0) = \mathbb{P}_L(J_F, N_F, Z_F | N_0, Z_0) + \mathbb{P}_R(J_F, N_F, Z_F | N_0, Z_0)$$

- Distribution is normalized to 2 and covers the full range of  $N_F$  and  $Z_F$
- Fixing  $(N_F, Z_F)$  and renormalizing gives the  $J_F$  distribution in particular FF
- Marginalization over  $J_F$  gives pre-neutron mass and charge yields
- Initial conditions partially simulate different incident neutron energies

$$\mathbb{P}(J_F, N_F, Z_F | N_0, Z_0) \rightarrow \mathbb{P}(J_F, N_F, Z_F | N_0, Z_0, E_n)$$

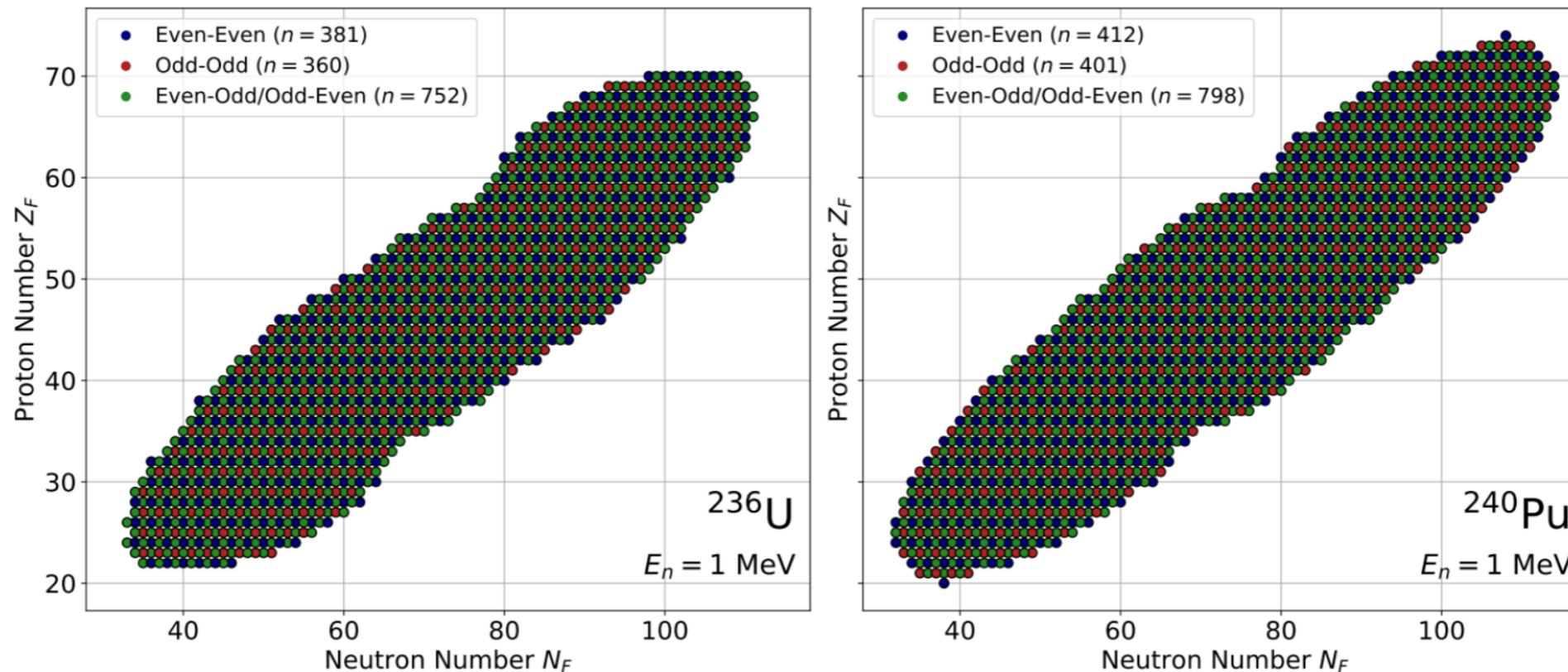
- Some current limitations of the model:

- Only  $K = 0$  components in AMP, influence of relative motion disregarded
- FFs are cold; eventually the effect of internal excitations should be included

$$\mathbb{P}(J_F, N_F, Z_F | N_0, Z_0, E_n) \rightarrow \mathbb{P}(J_F, N_F, Z_F | N_0, Z_0, E_n, E_F^*)$$

# n-Induced Fission of $^{235}\text{U}$ and $^{239}\text{Pu}$

- First microscopic prediction of  $J_F$  distributions for the **full range of FFs**



PHYSICAL REVIEW C **113**, 014612 (2026)

Editors' Suggestion

## Microscopic theory of angular momentum distributions across the full range of fission fragments

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and CEA, DAM, DIF, 91297 Arpajon, France

Microscopic Angular Momentum Distributions in Fragments for Neutron-Induced Fission of U-235 and Pu-239

<https://zenodo.org/records/17303186>

This dataset provides microscopic angular momentum distributions in even-even fission fragments for neutron-induced fission of  $^{235}\text{U}$  and  $^{239}\text{Pu}$ .

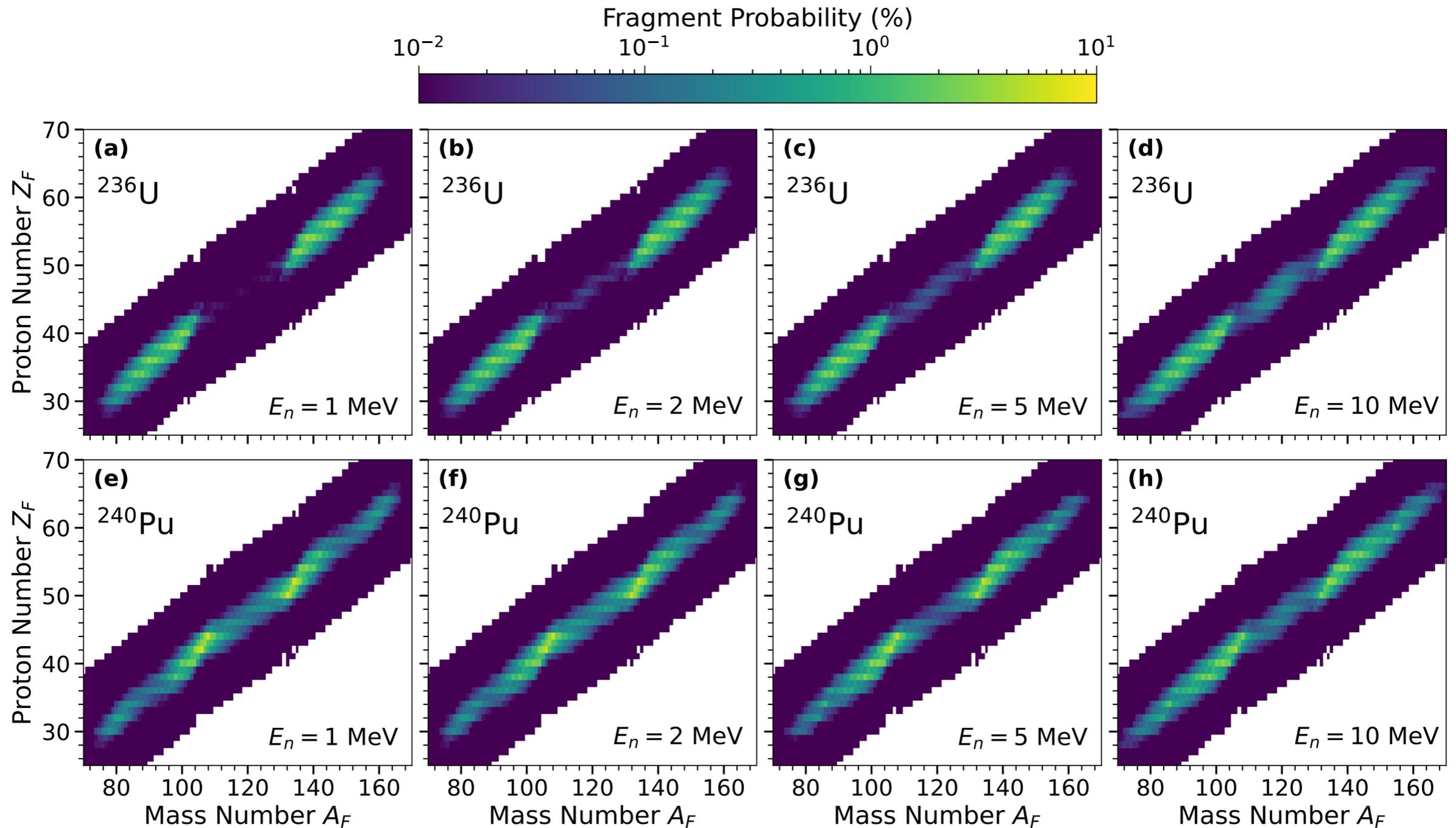
It was produced within the "Angular momentum predictions for low-energy induced fission" (AMPLIFI) project, funded by the European Union's Horizon Europe research and innovation programme under the Marie Skłodowska-Curie Actions Grant Agreement No. 101149053.

Reference: P. Marević, N. Schunck, M. Verriere, "Microscopic theory of angular momentum distributions across the full range of fission fragments", *Phys. Rev. C* **113**, 014612 (2026).

For a full description of the framework, see the [publication](#) or the [arXiv preprint](#).

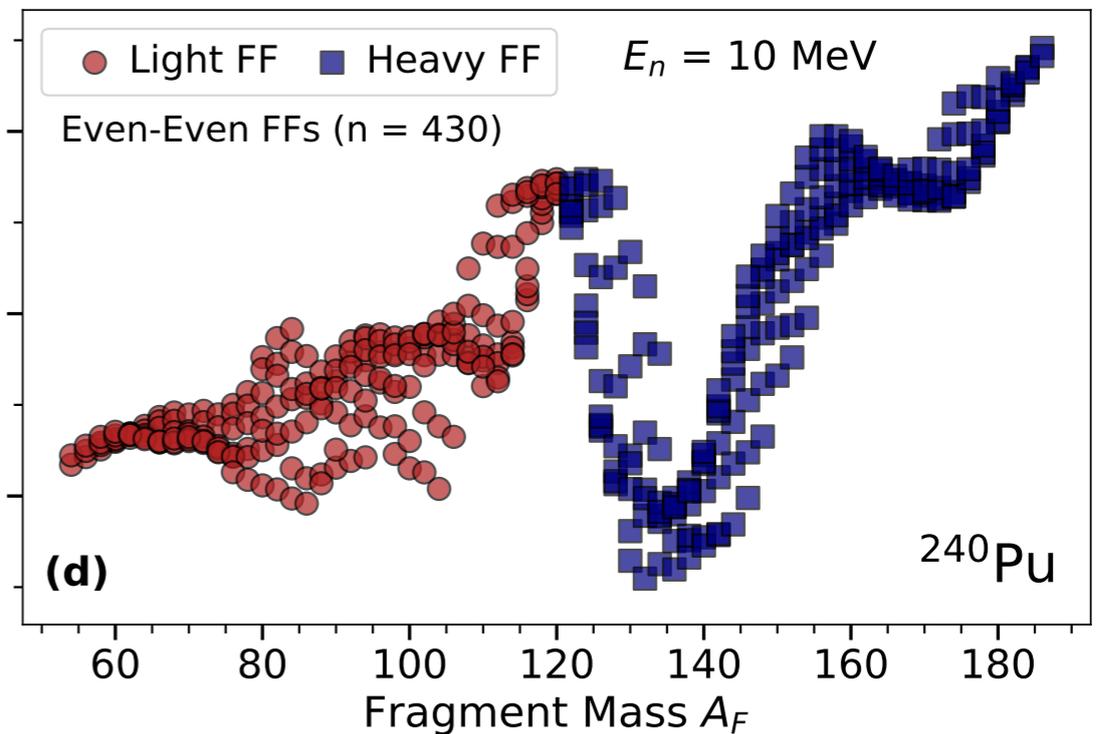
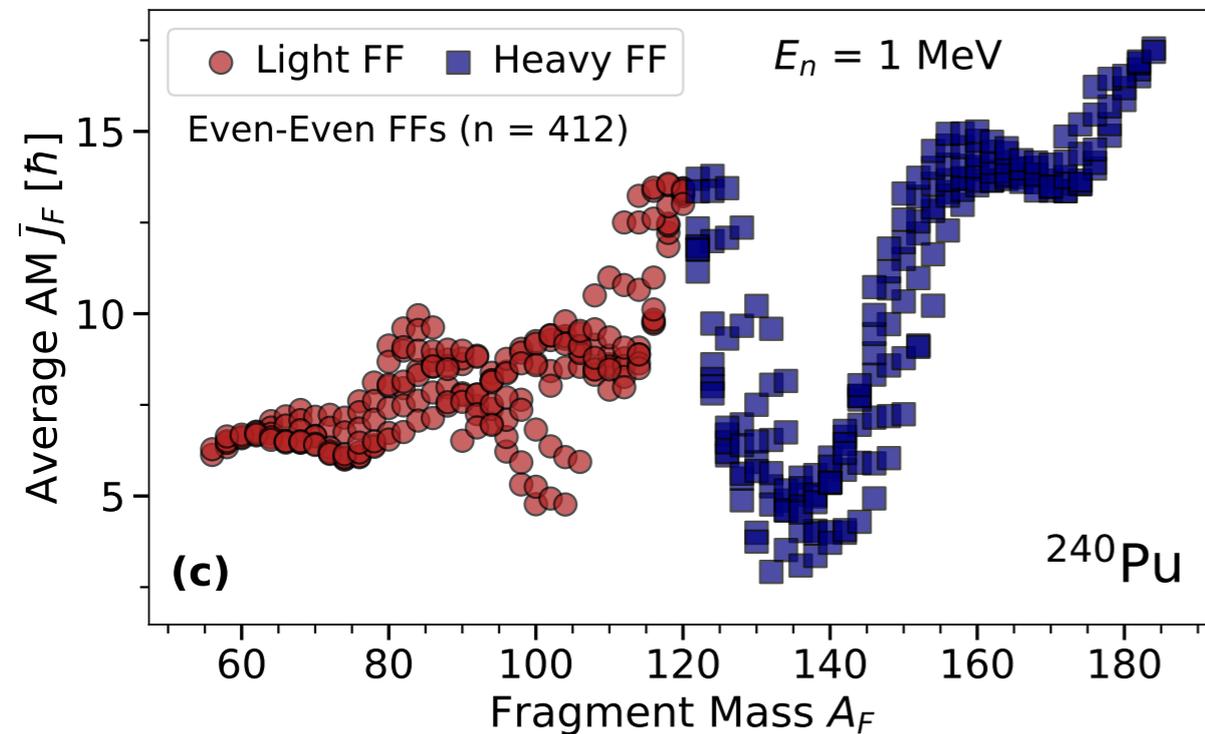
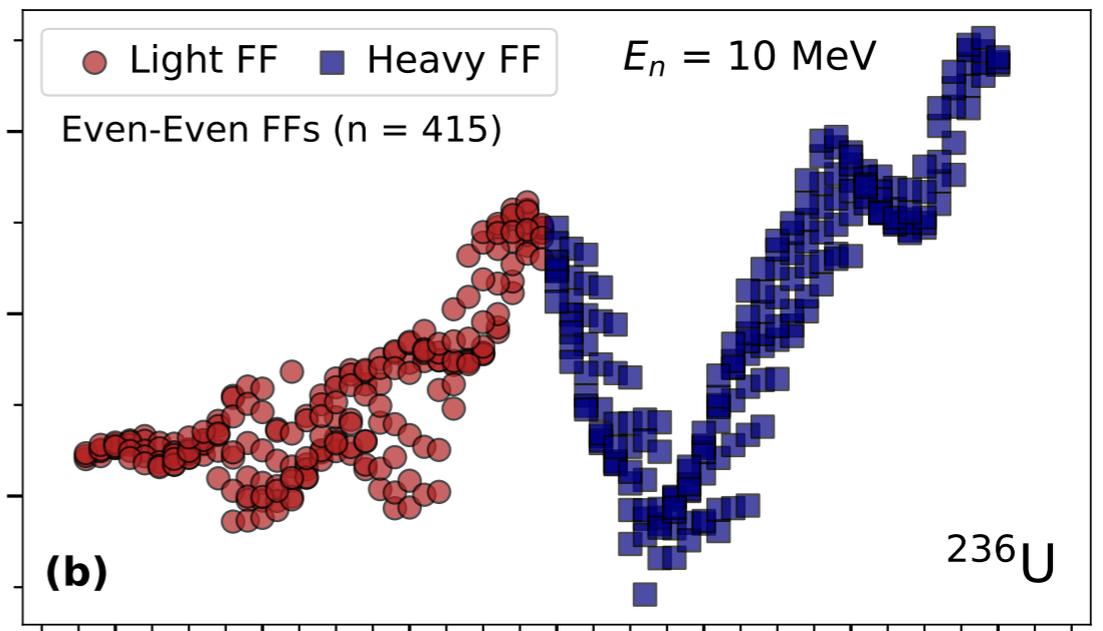
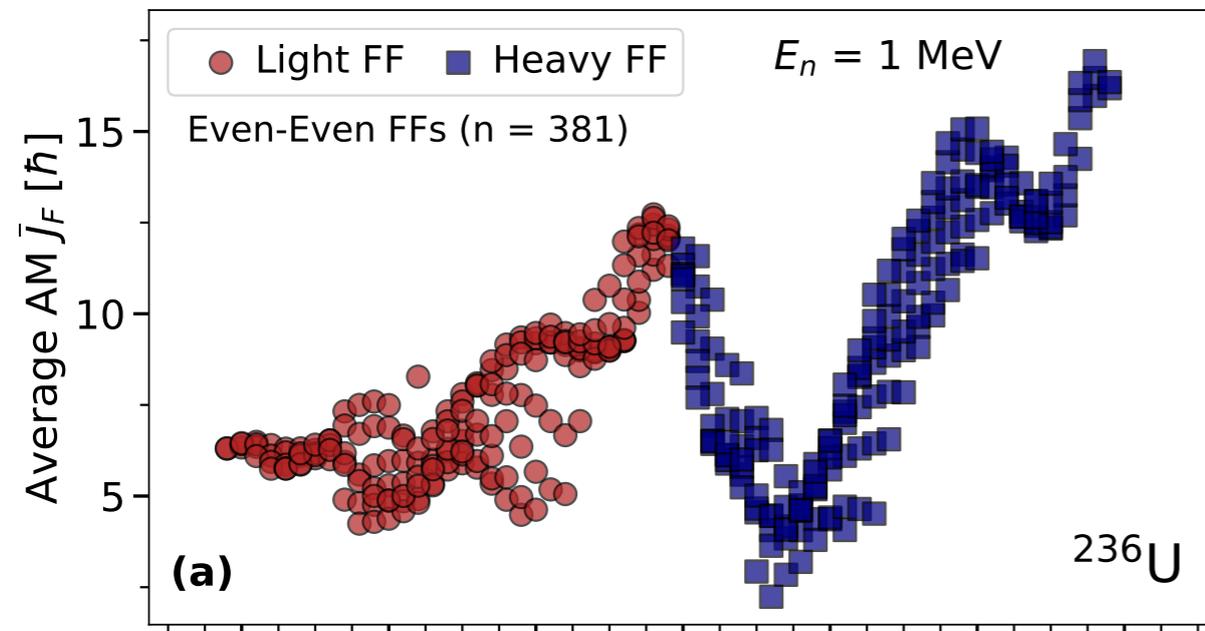
# n-Induced Fission of $^{235}\text{U}$ and $^{239}\text{Pu}$

- Reasonable isotopic yields can be predicted within the same framework



# n-Induced Fission of $^{235}\text{U}$ and $^{239}\text{Pu}$

- Unequivocal microscopic evidence of a universal **sawtooth pattern**



# n-Induced Fission of $^{235}\text{U}$ and $^{239}\text{Pu}$

Phenomenological formula:  $p(J_F) \propto (2J_F + 1) \exp\left(-\frac{1}{2} \frac{J_F(J_F + 1)}{B^2(Z_F, A_F, T_F)}\right)$

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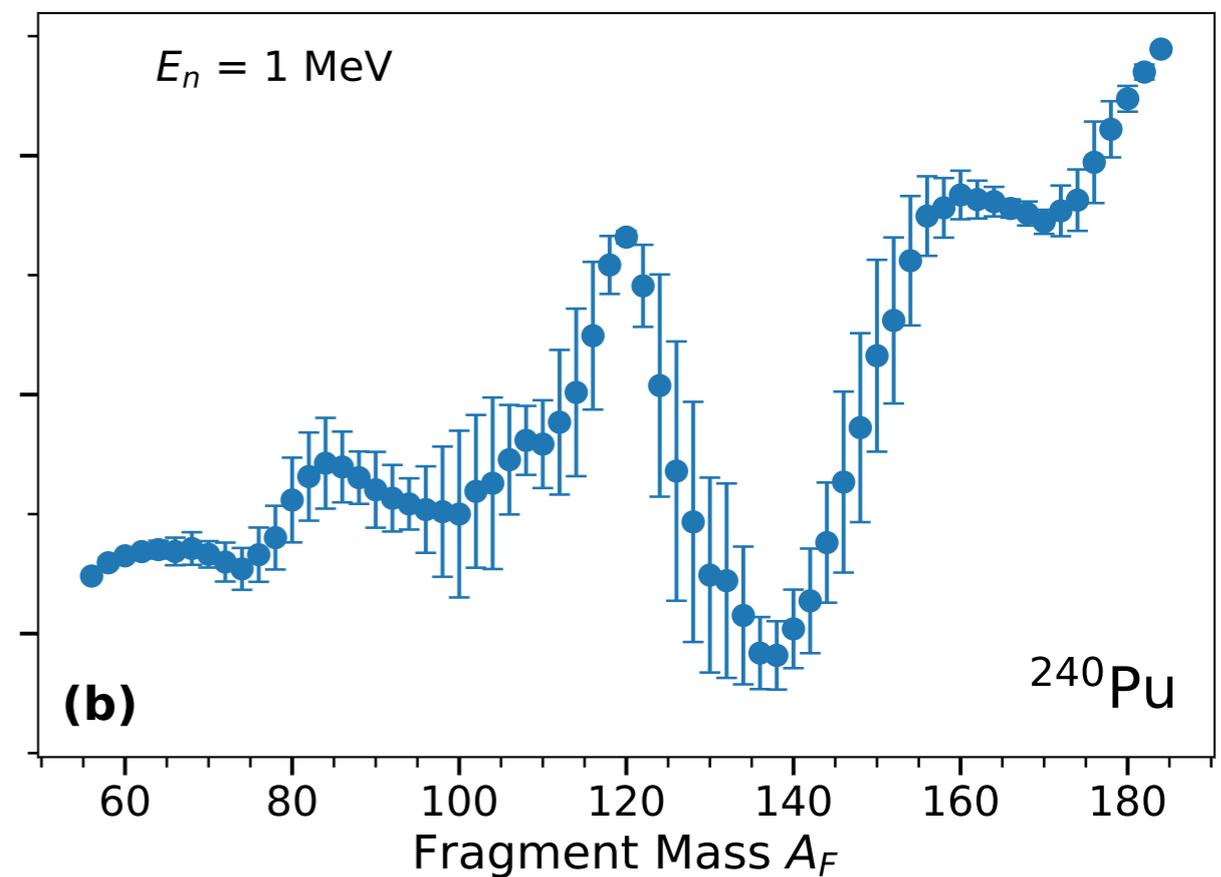
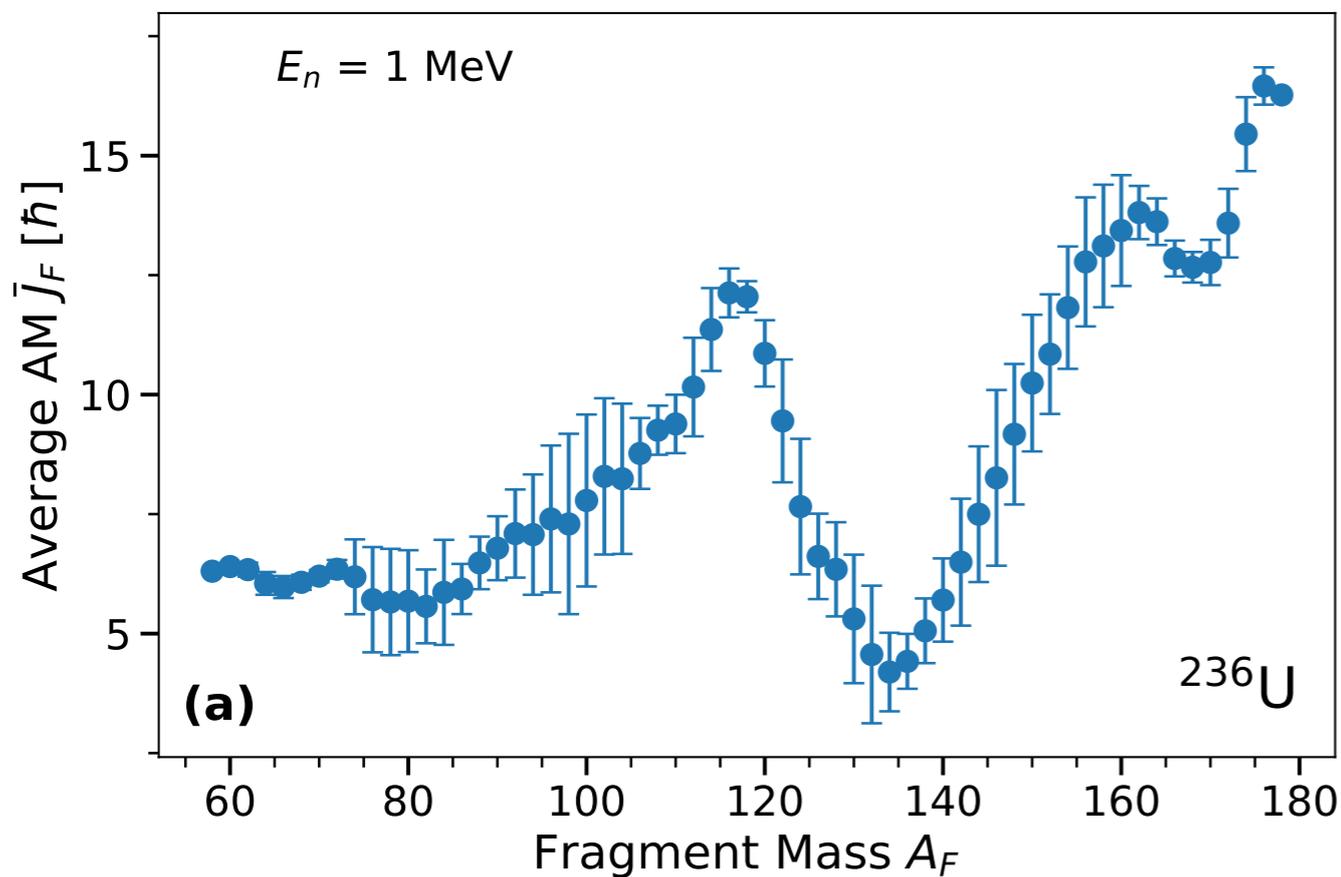
Phenomenological formula:  $p(J_F) \propto (2J_F + 1) \exp \left( - \frac{1}{2} \frac{J_F(J_F + 1)}{B^2(\cancel{Z}_F, A_F, T_F)} \right)$   
**usually neglected**

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- There is a strong **isobaric dependence** of AM distributions

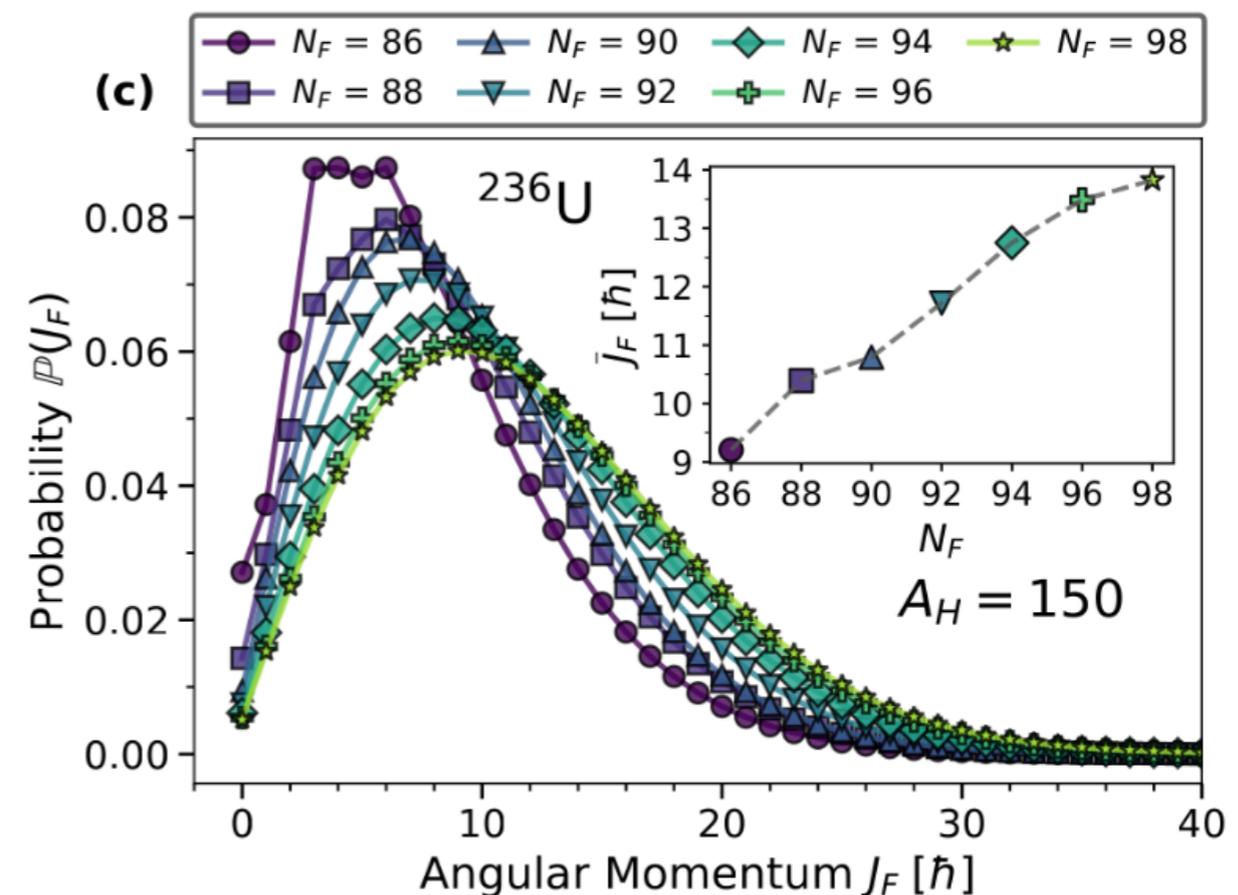
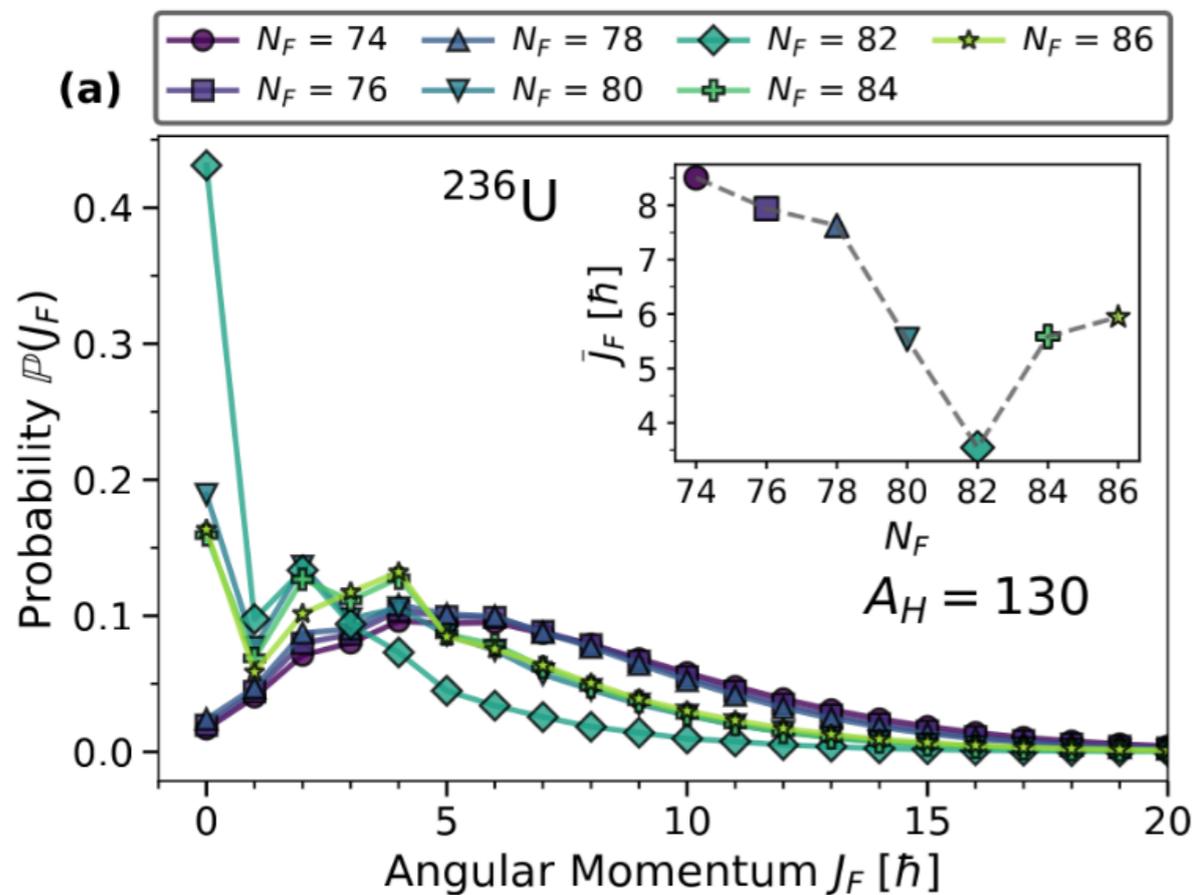


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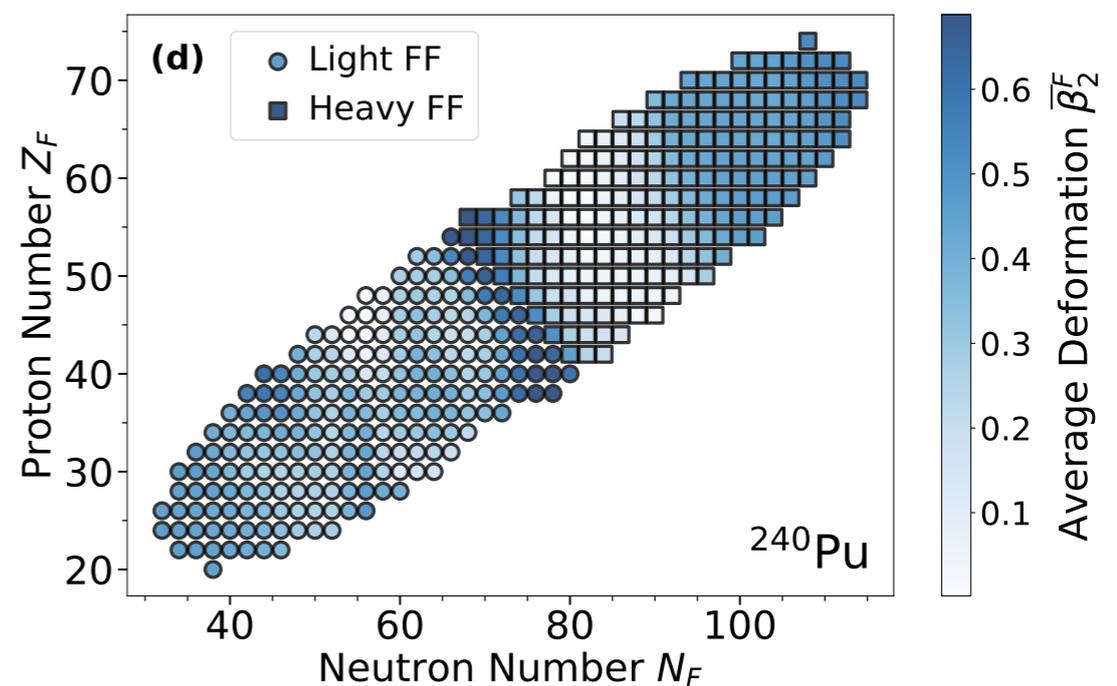
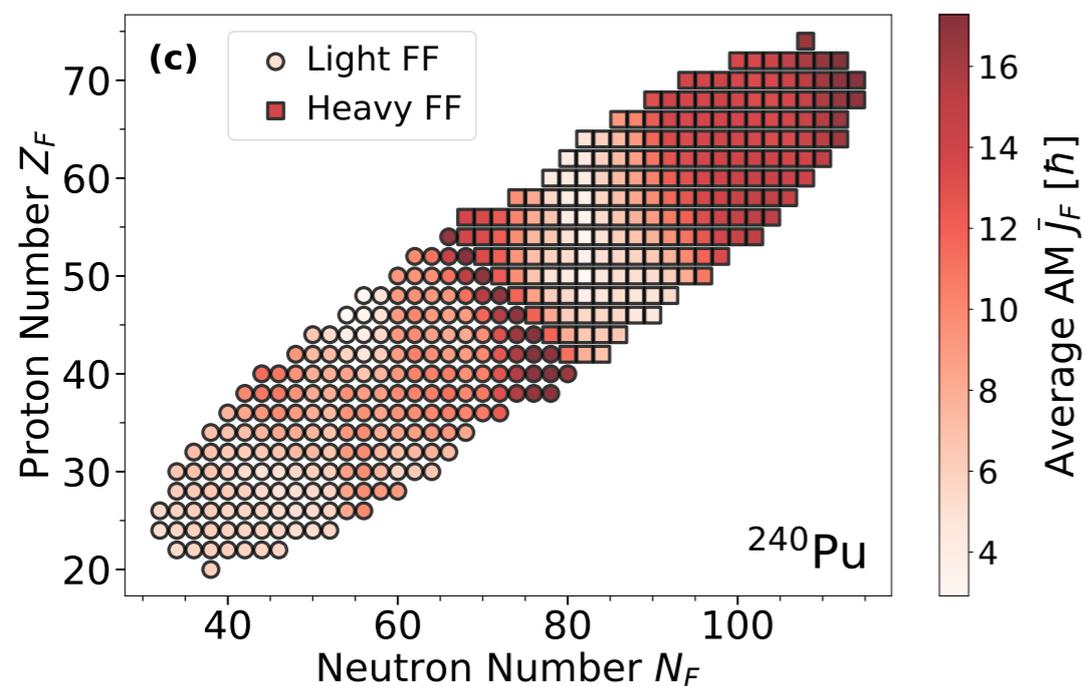
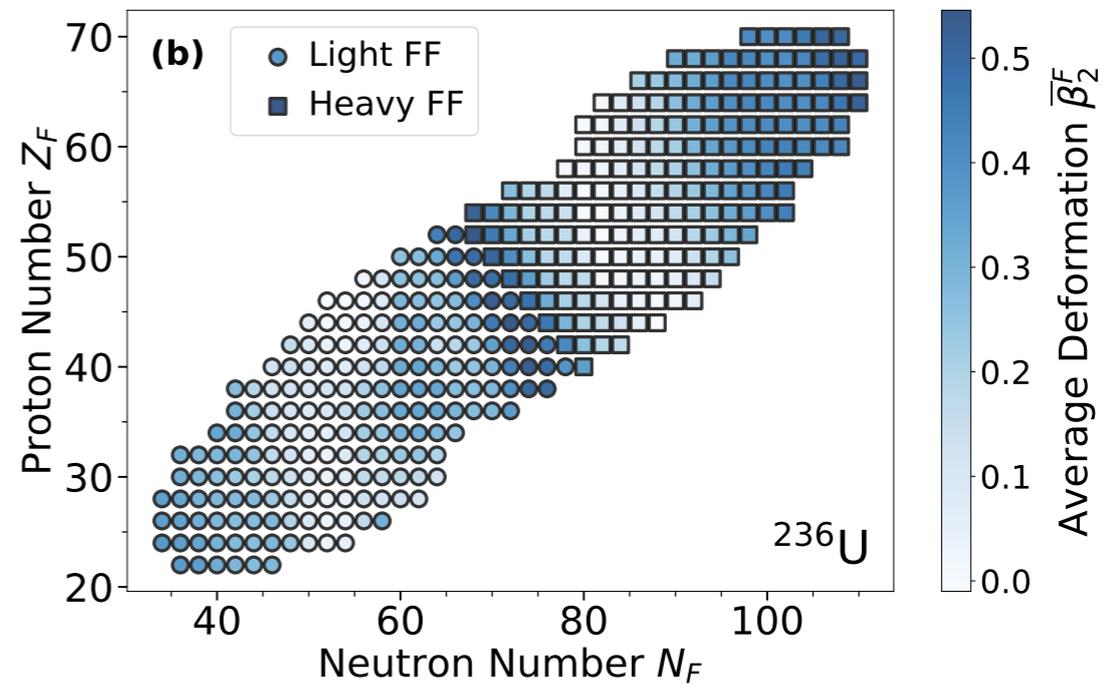
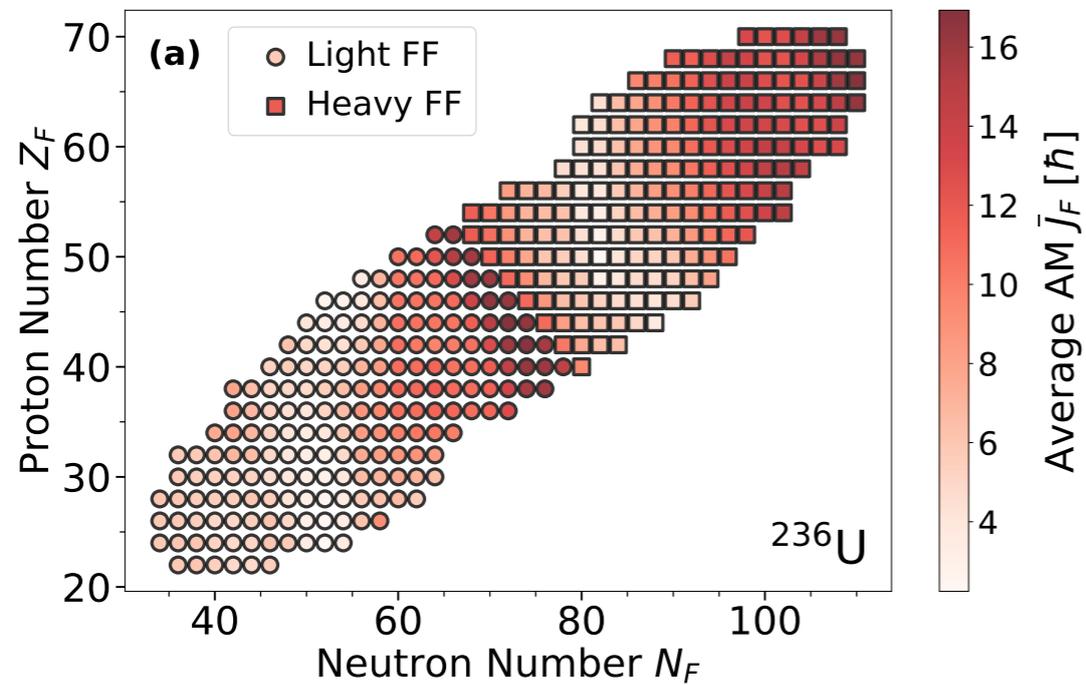
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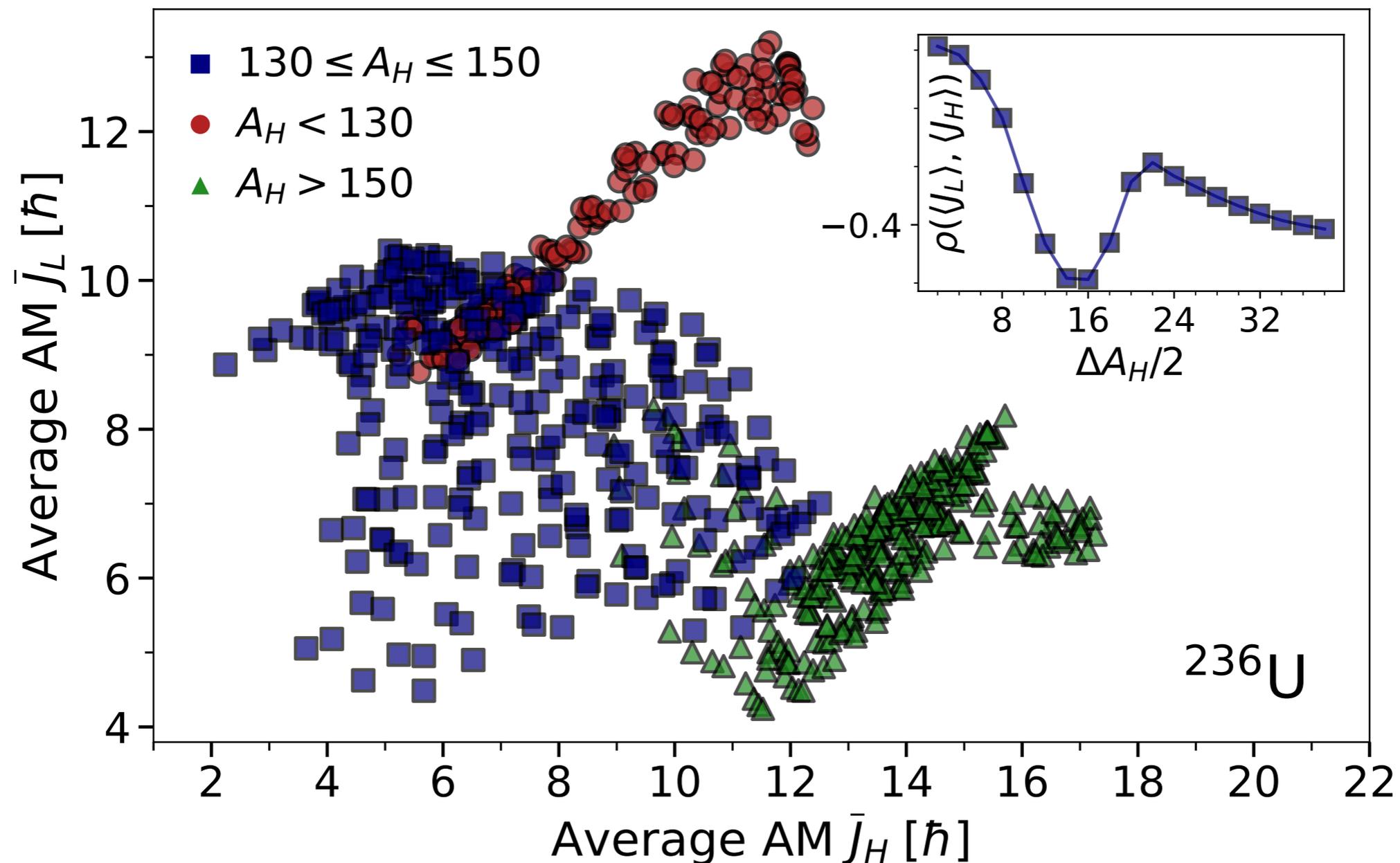
# n-Induced Fission of $^{235}\text{U}$ and $^{239}\text{Pu}$

- FF deformations and AM are strongly correlated ( $\rho_{\text{Pear}} = 0.67/0.64$ )



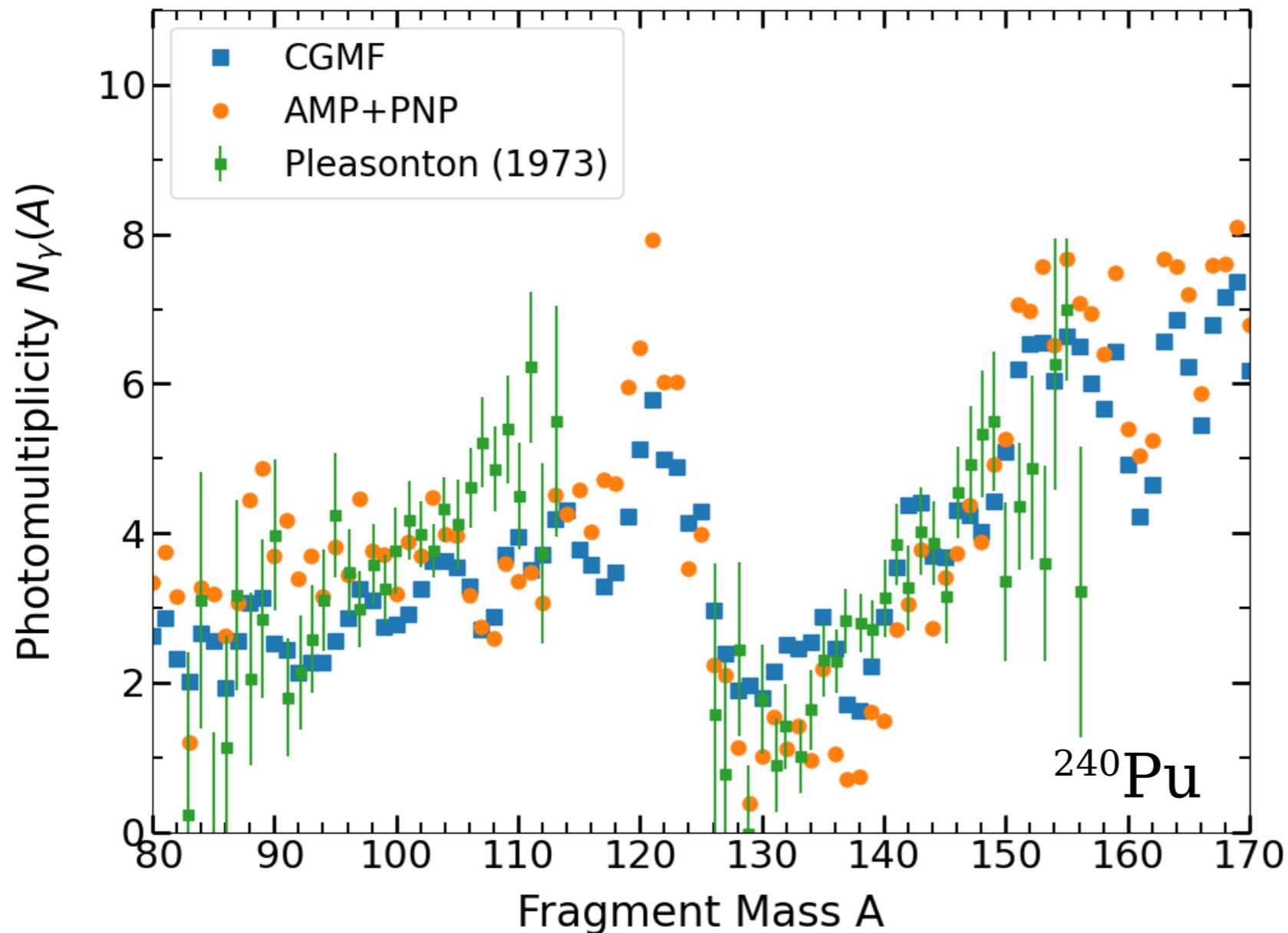
# n-Induced Fission of $^{235}\text{U}$ and $^{239}\text{Pu}$

- Weak negative correlation ( $\rho_{\text{Pear}} = -0.33$ ) in AM magnitudes for most strongly populated FFs



# n-Induced Fission of $^{235}\text{U}$ and $^{239}\text{Pu}$

- Photon multiplicities are reproduced **without adjustable parameters** in AM distributions



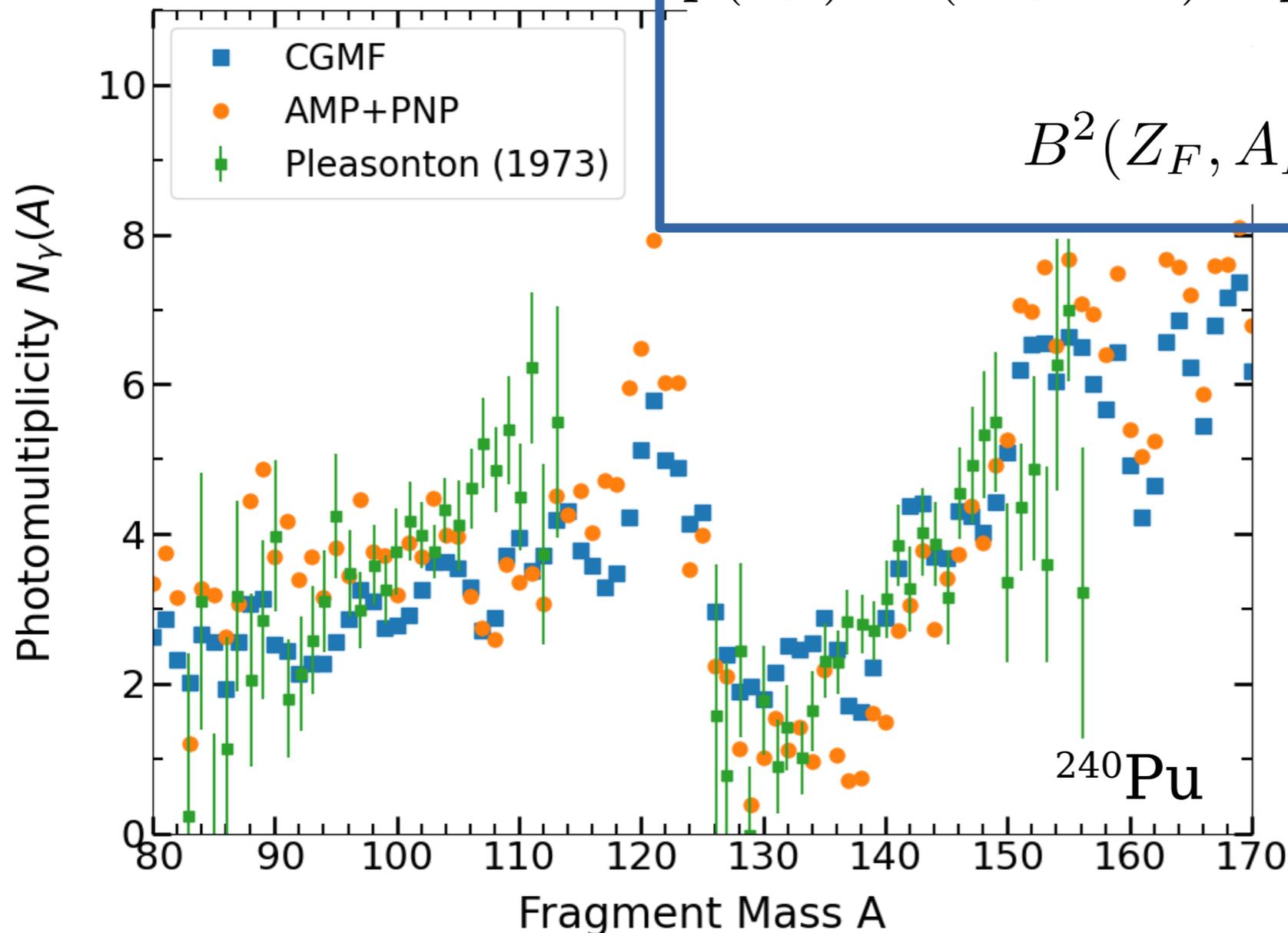
Photon multiplicity

$N_\gamma: 6.24 \rightarrow 6.08$

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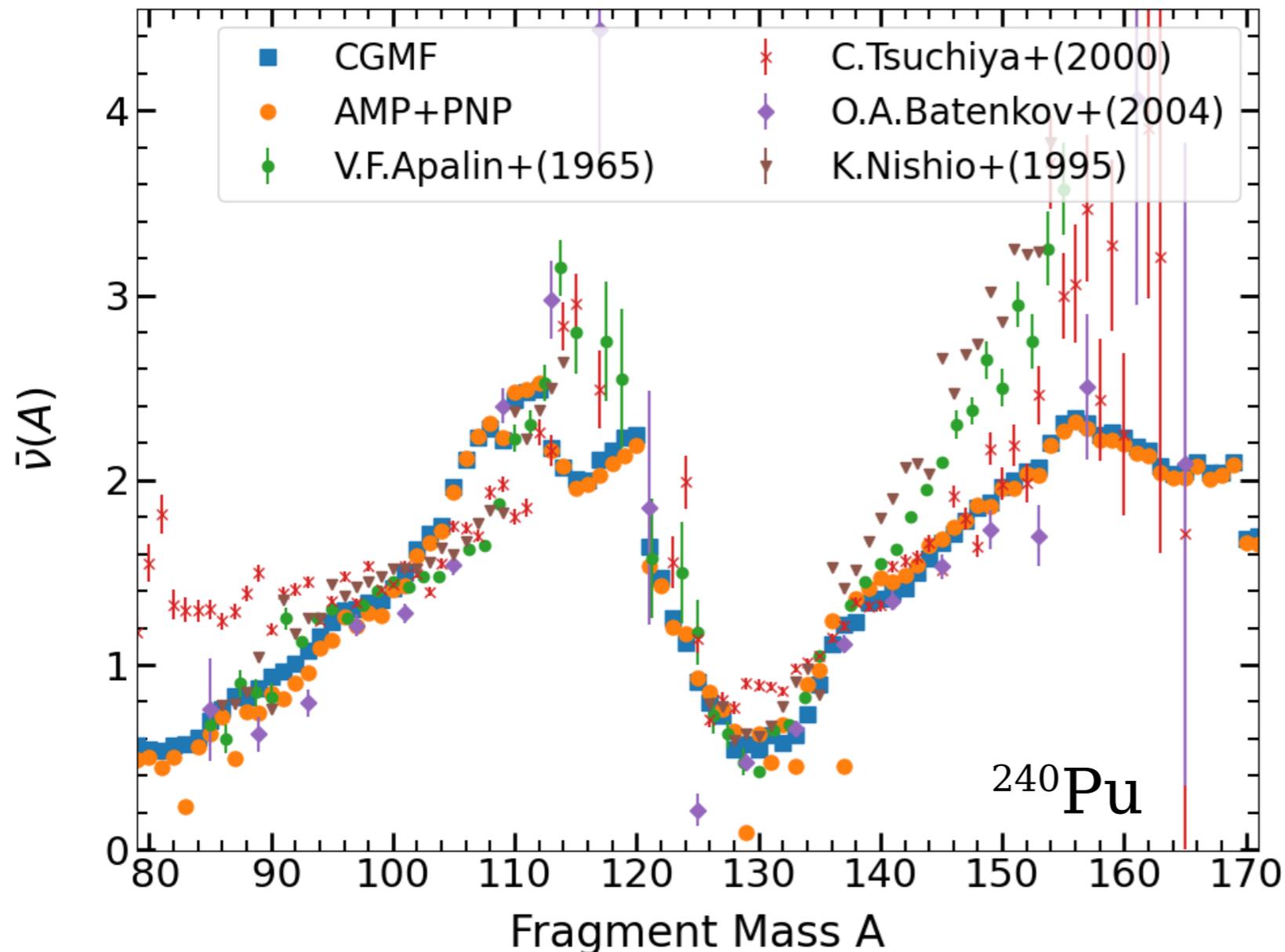
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Neutron multiplicity  
 $N_\nu: 2.86 \rightarrow 2.80$

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Microscopic Insights for Improved Nuclear Data

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**Database:** “*Microscopic Angular Momentum Distributions in Fragments for Neutron-Induced Fission of U-235 and Pu-239*”, <https://zenodo.org/records/17303186>



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