

Pairing as an observable for many-body nuclear dynamics: The case of fission and quasifission with VAMOS++

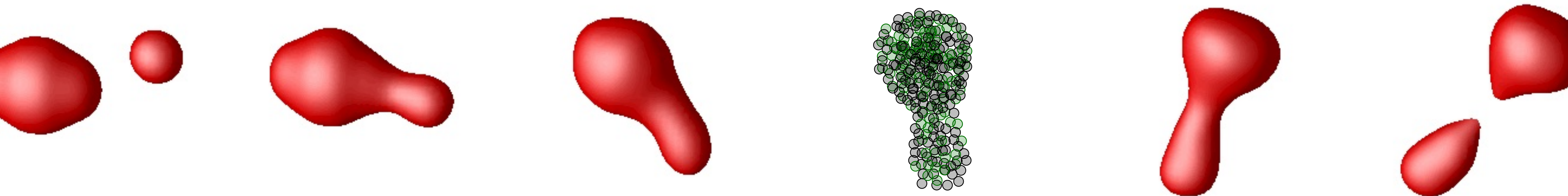
Manuel Caamaño

IGFAE – U. Santiago de Compostela (Spain)



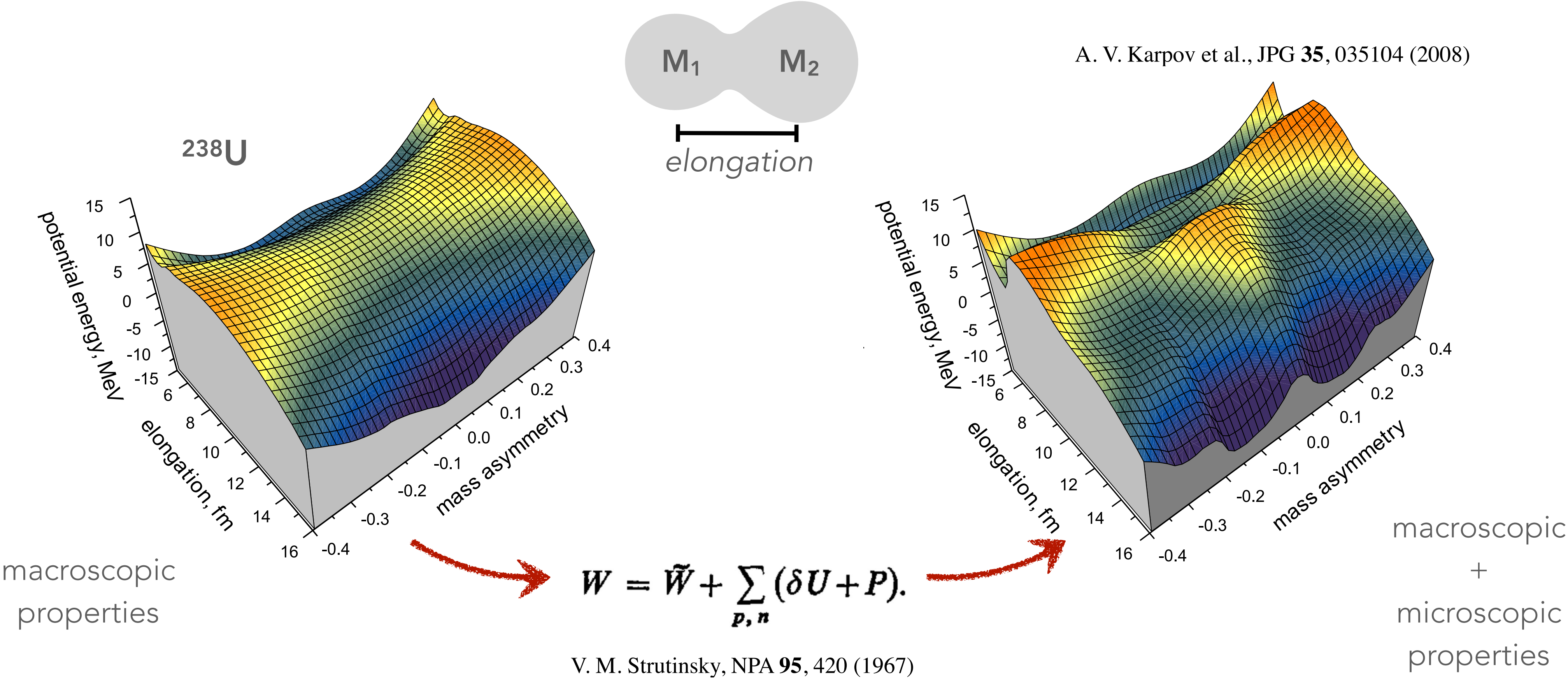
24^{ème} COLLOQUE GANIL

Nuclear Physics is a tough many-body quantum problem



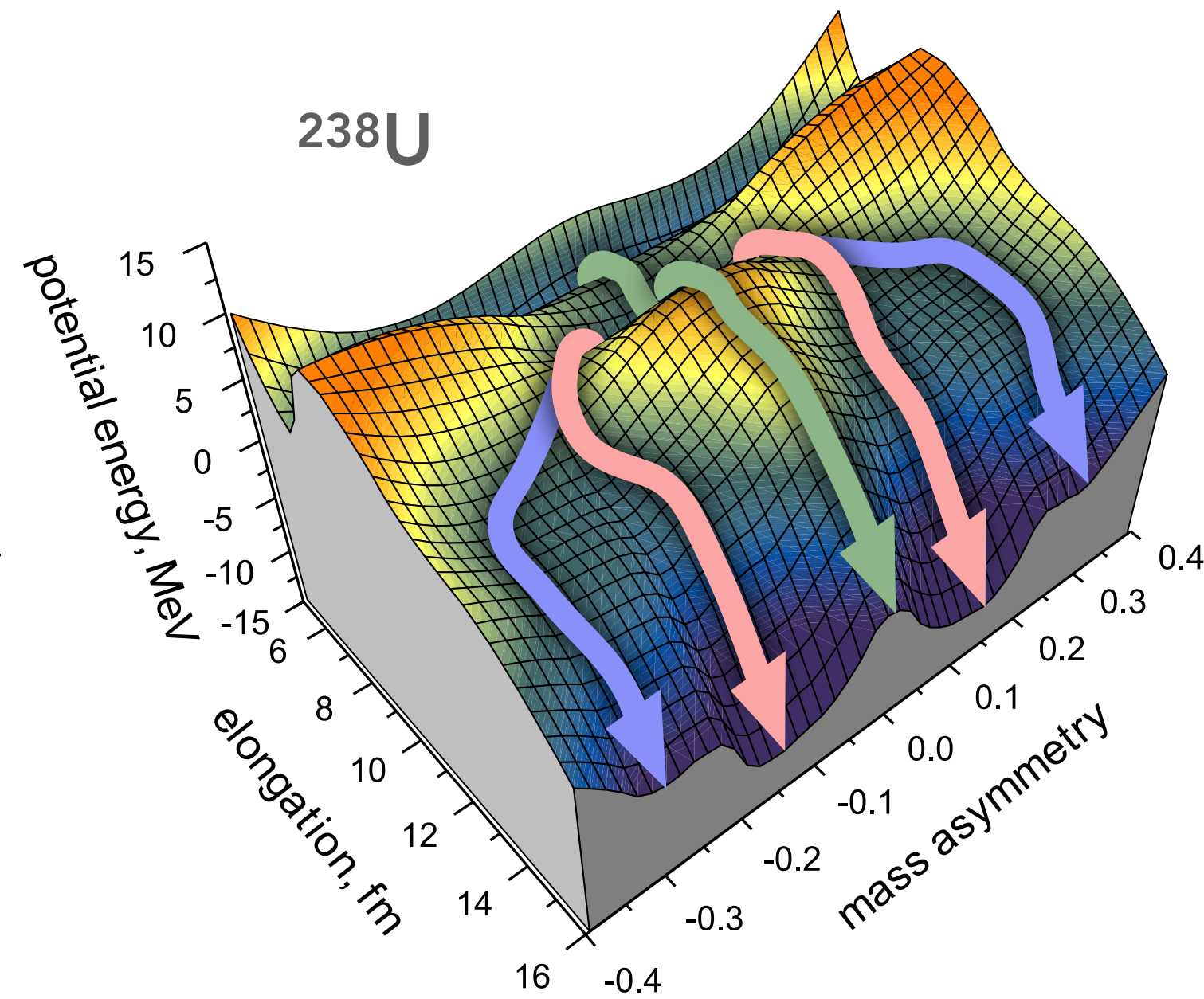
A. Wakhle et al., PRL **113**, 182502 (2014)

The case of Fission

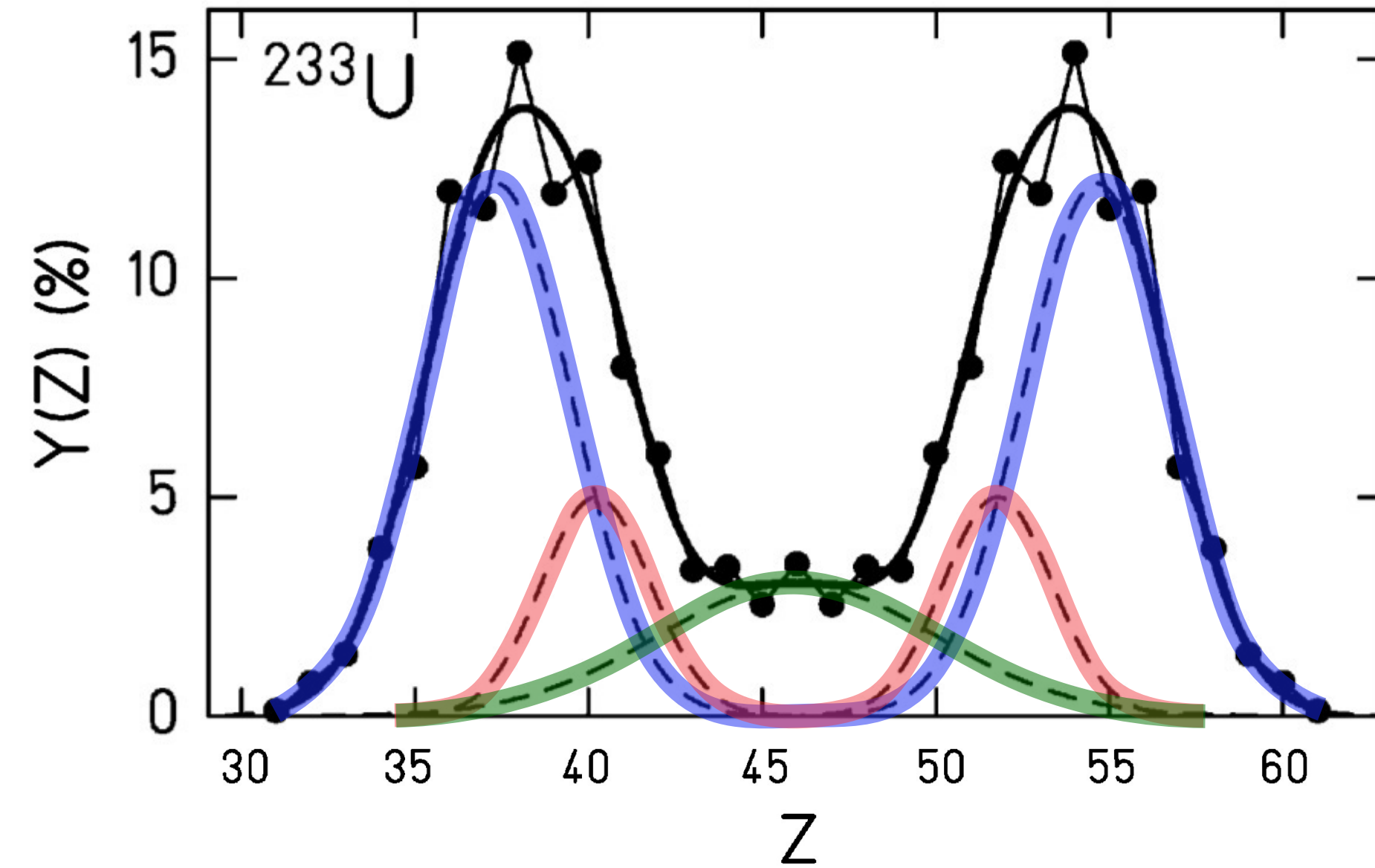


The case of Fission

A. V. Karpov et al., JPG **35**, 035104 (2008)



C. Böckstiegel et al., NPA **802**, 12 (2008)



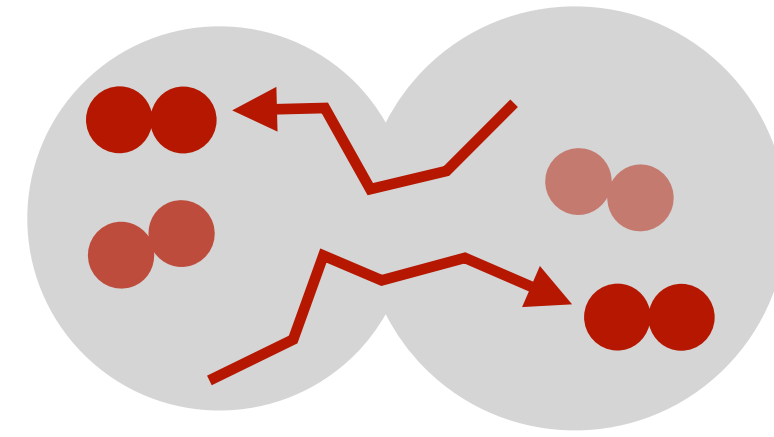
$$W = \tilde{W} + \sum_{p, n} (\delta U + P).$$

V. M. Strutinsky, NPA **95**, 420 (1967)

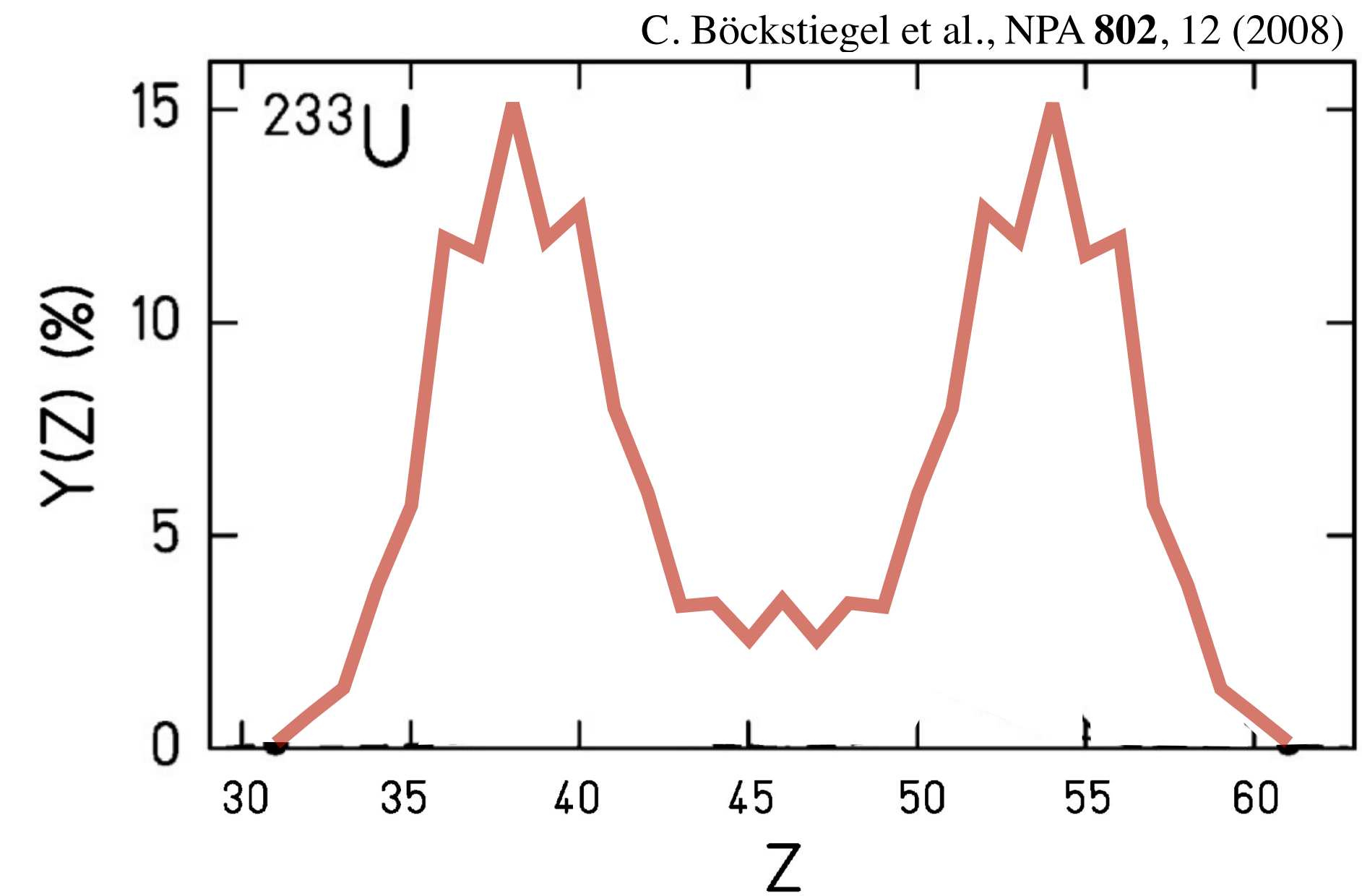
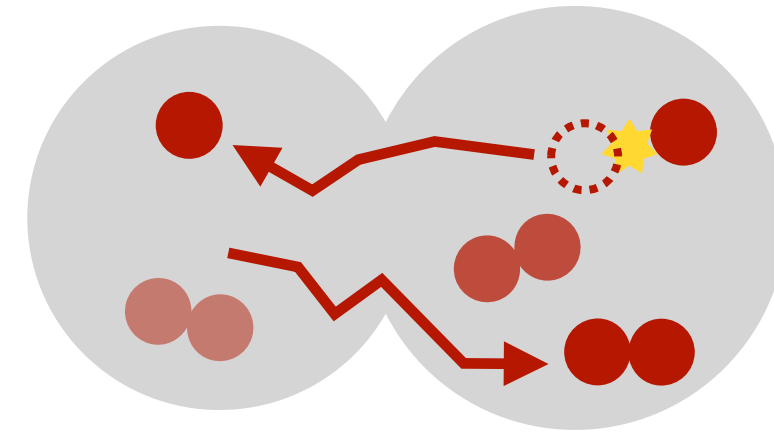
Modes: Paths carved in the *Potential Energy Surface* due to particular shells.

Pairing as an observable: the even-odd effect in fission

No broken proton pairs:
Only **even-Z**



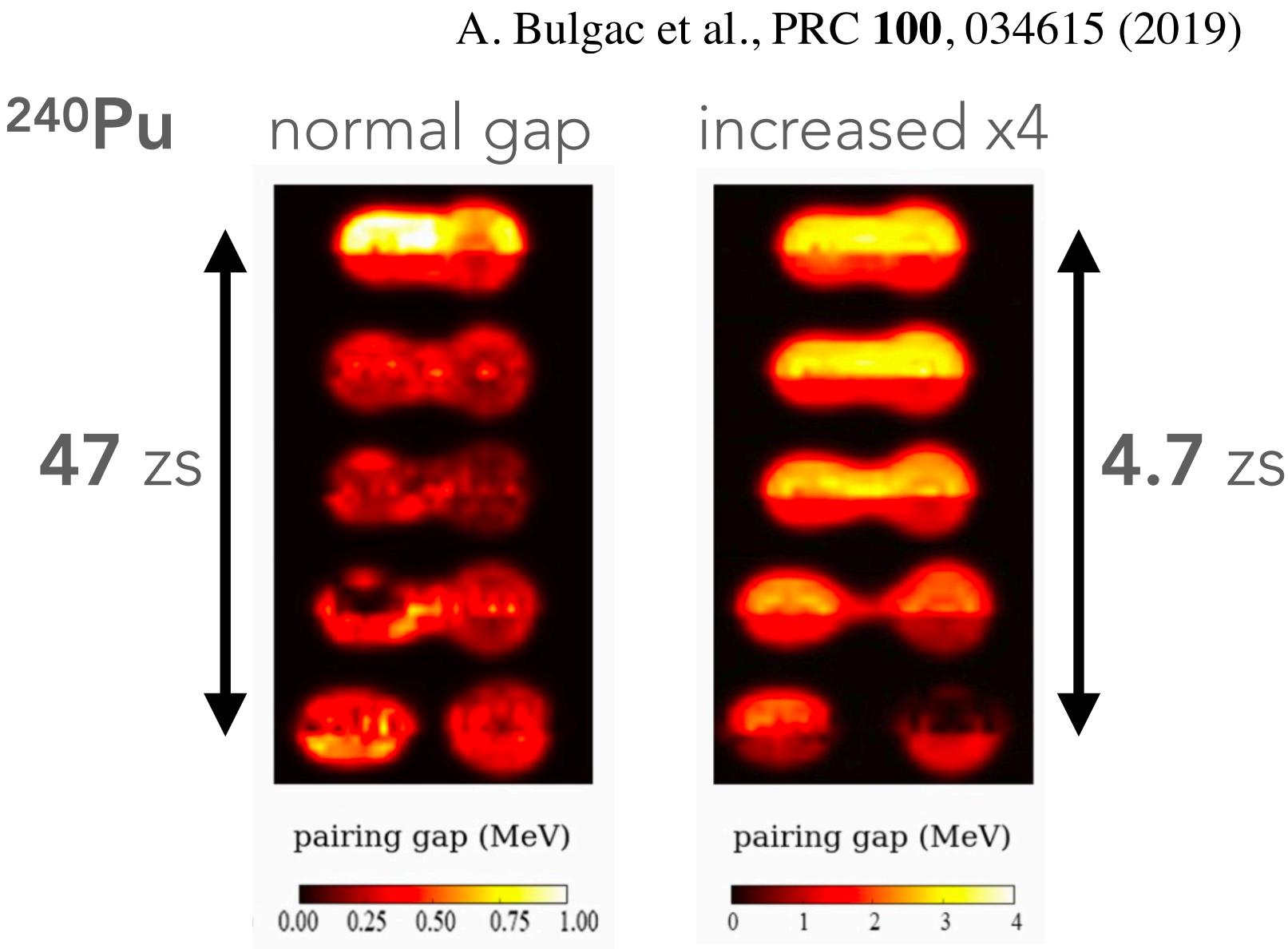
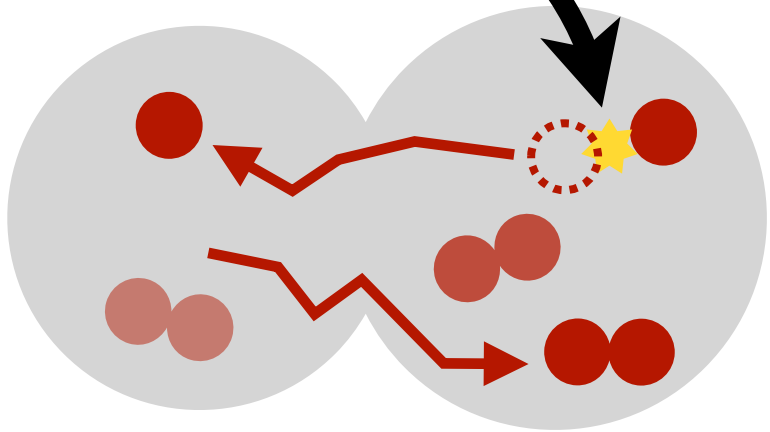
Broken proton pairs:
Possible **even-Z**
and **odd-Z**



Even-odd effect:
$$\delta = \frac{\sum_{\text{even}} Y(Z) - \sum_{\text{odd}} Y(Z)}{\sum Y(Z)}$$

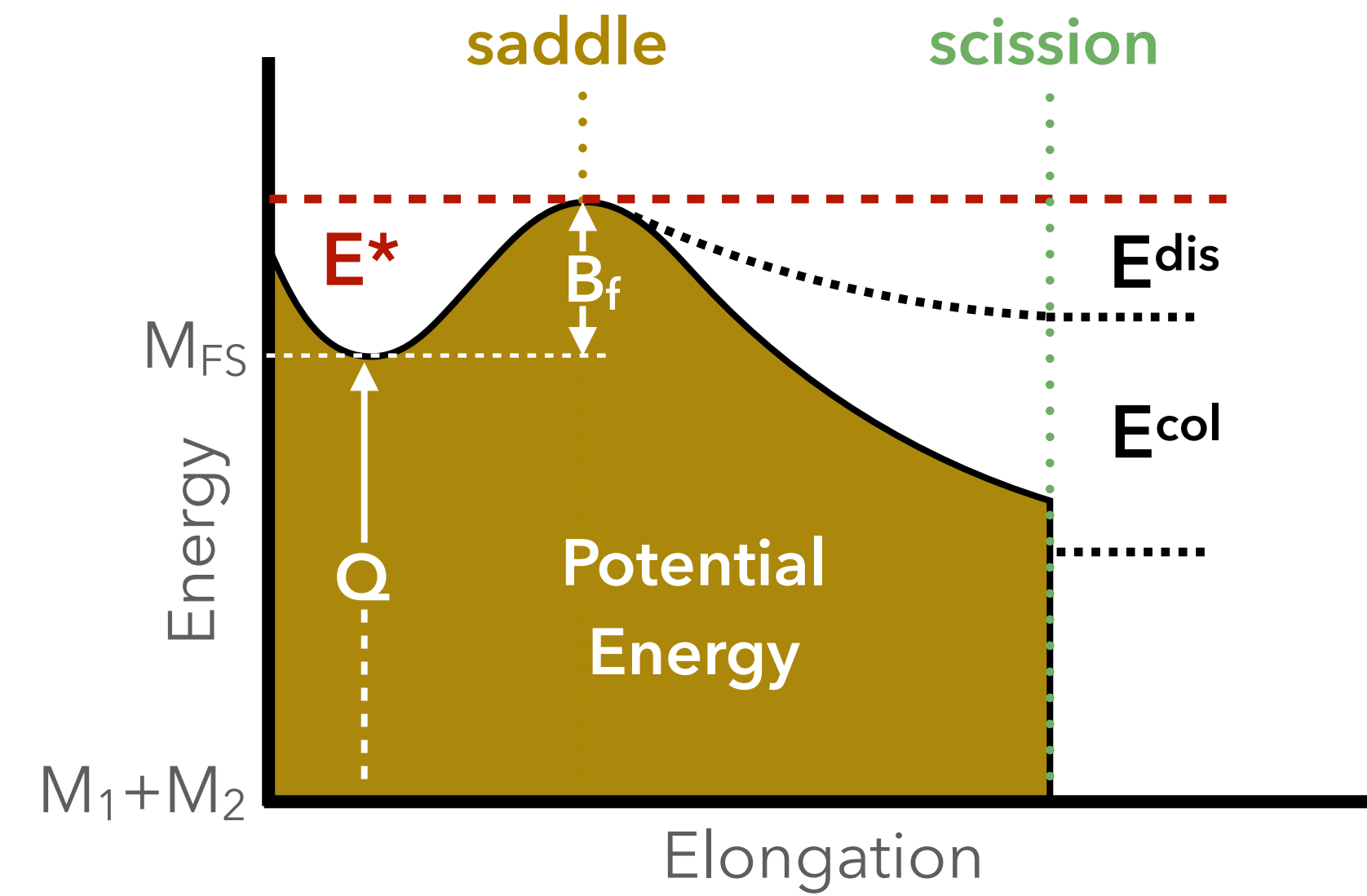
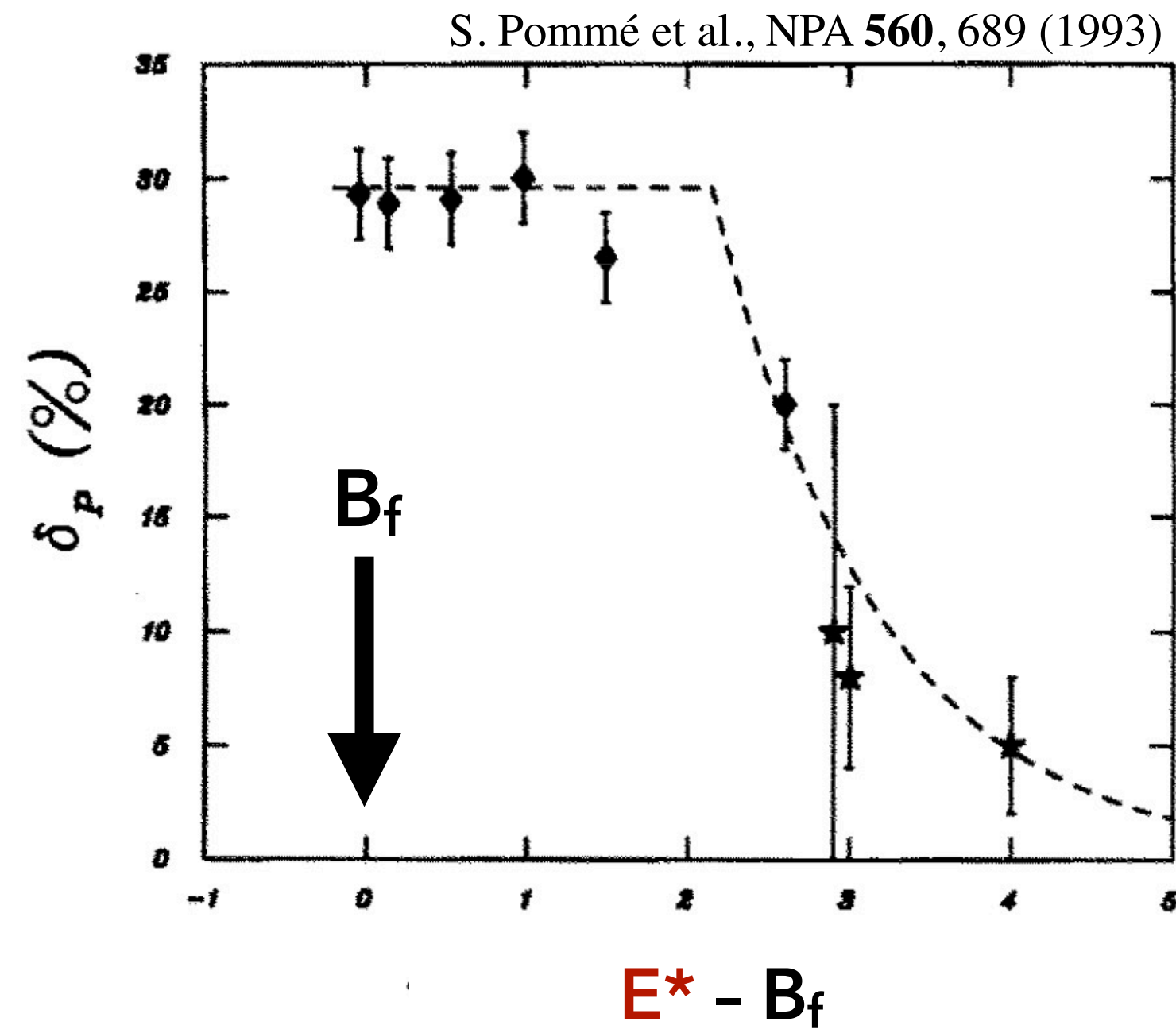
Pairing as an observable: the even-odd effect in fission

Braking a proton pair
increases dissipation in
 $E^{dis} + = 2\Delta_p$



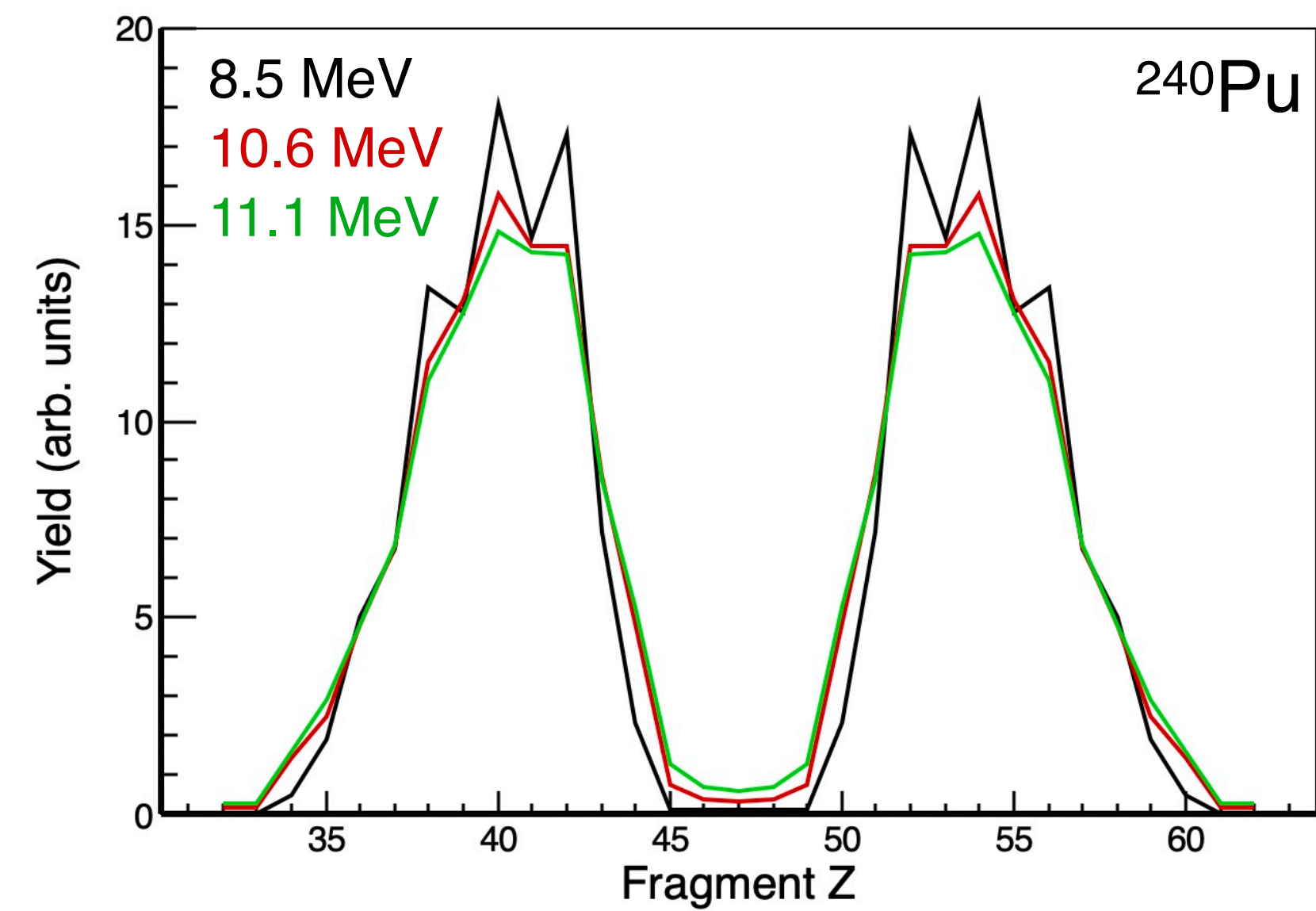
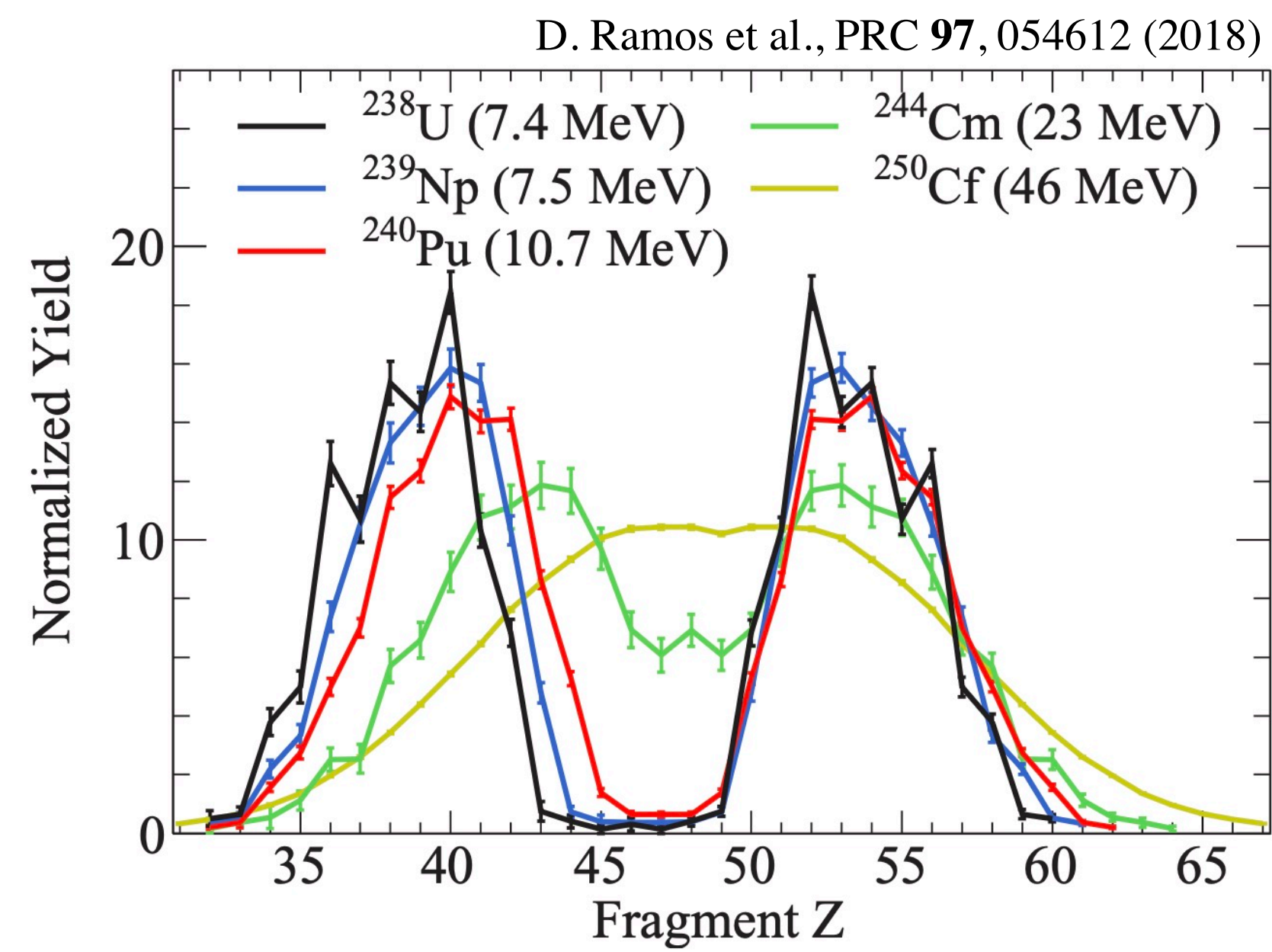
Pairing plays an important role in **nucleon transport, dynamics, and dissipation**.
Also on the **timescale** of the process.

Pairing as an observable: the even-odd effect in fission



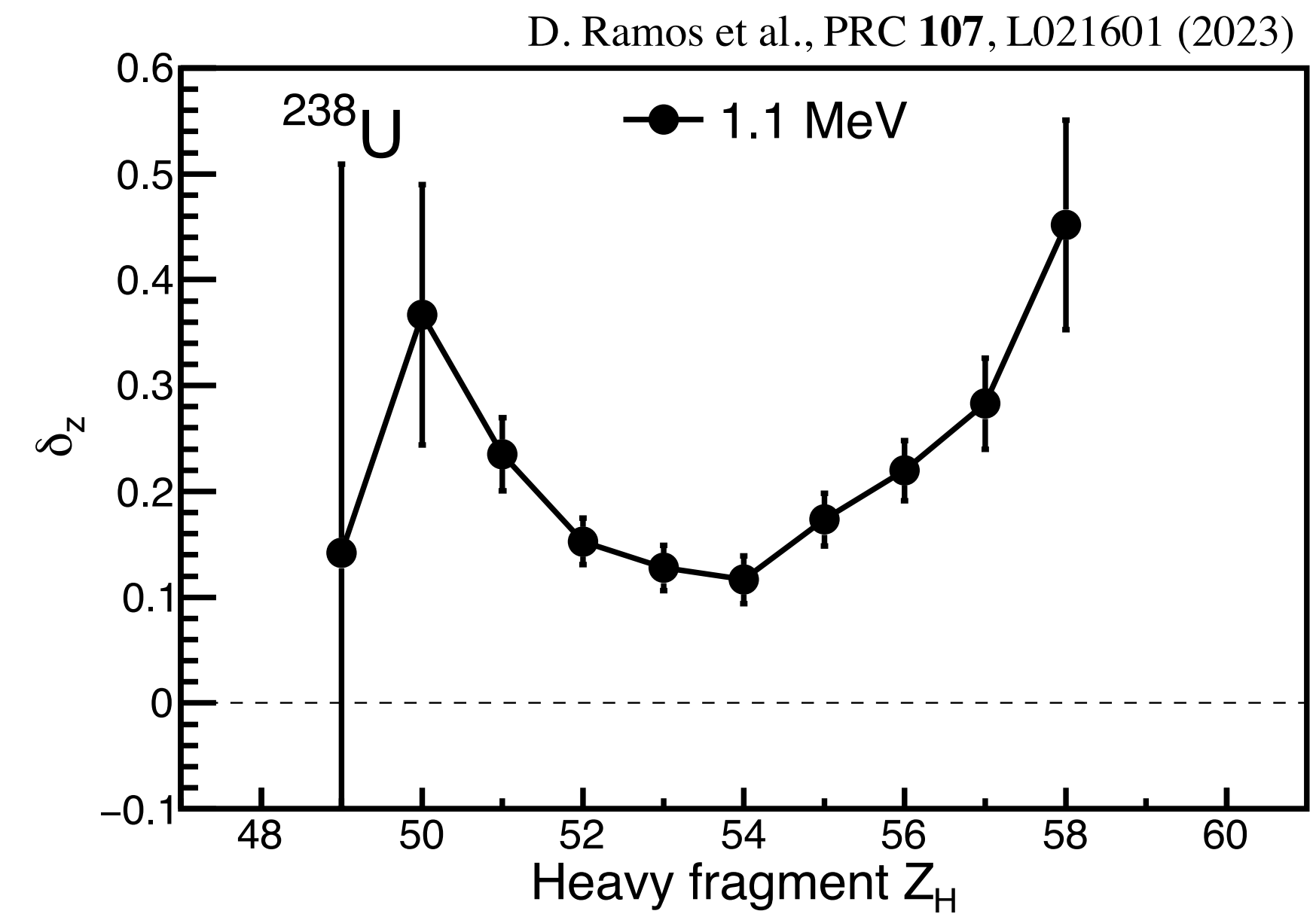
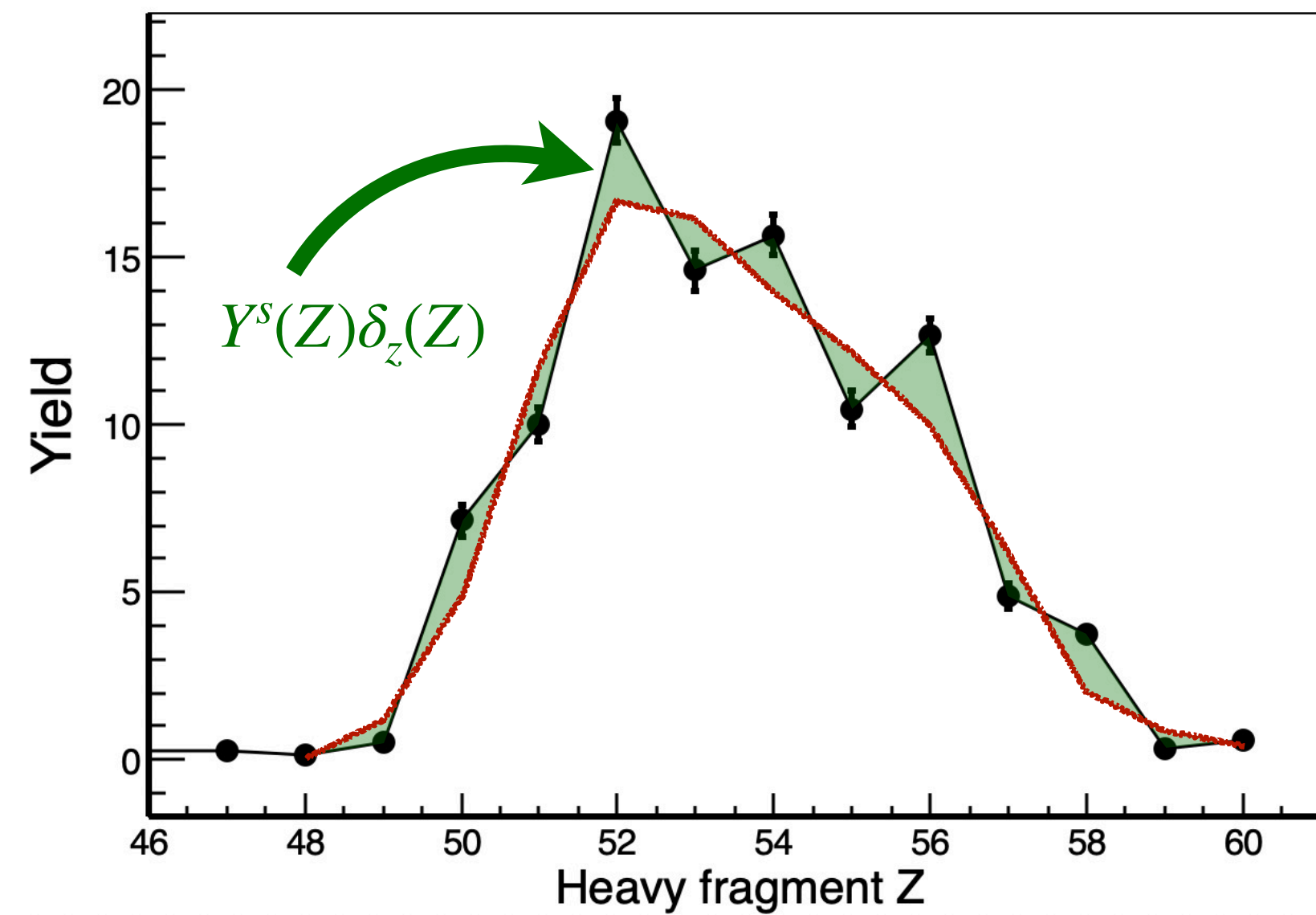
Correlation between the **even-odd effect** and the available **excitation energy**.

Even-odd effect in fission with VAMOS++



Measurement of **isotopic distributions** of several systems and **as a function of the excitation energy**

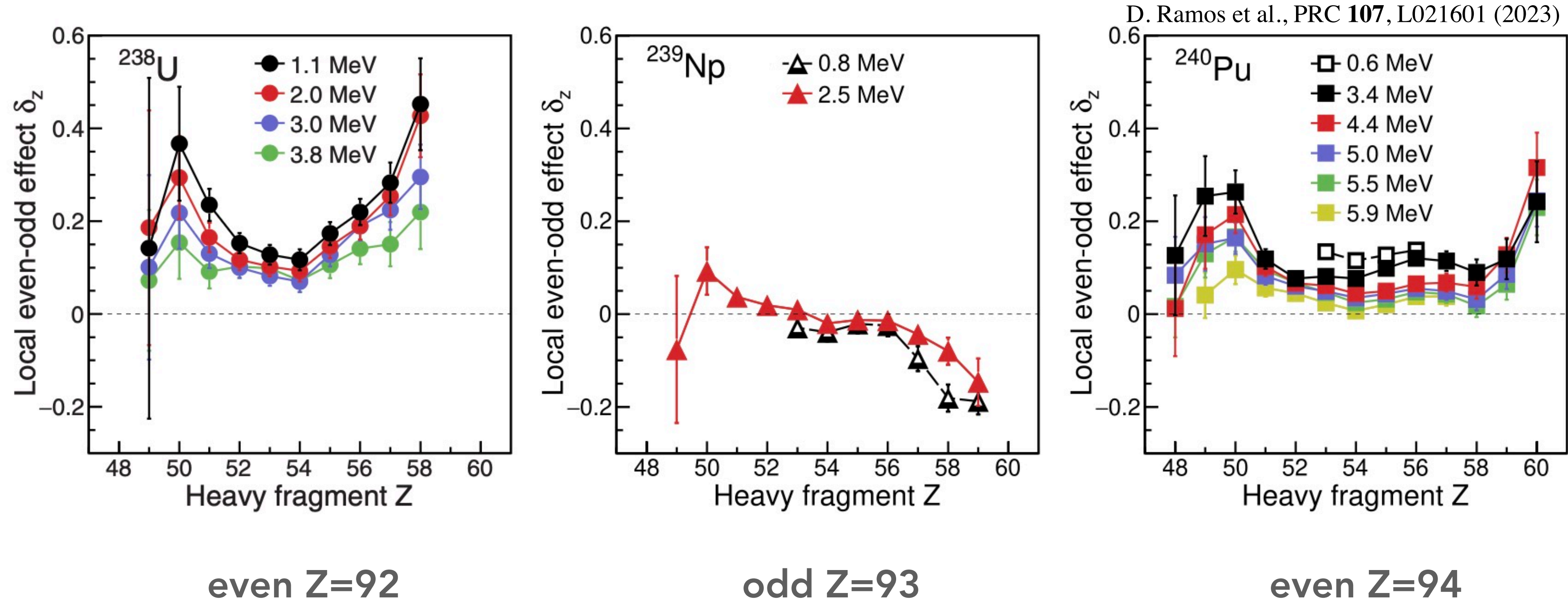
From global to local even-odd effect



$$Y(Z) = Y^s(Z) [1 + (-1)^Z \delta_z(Z)]$$

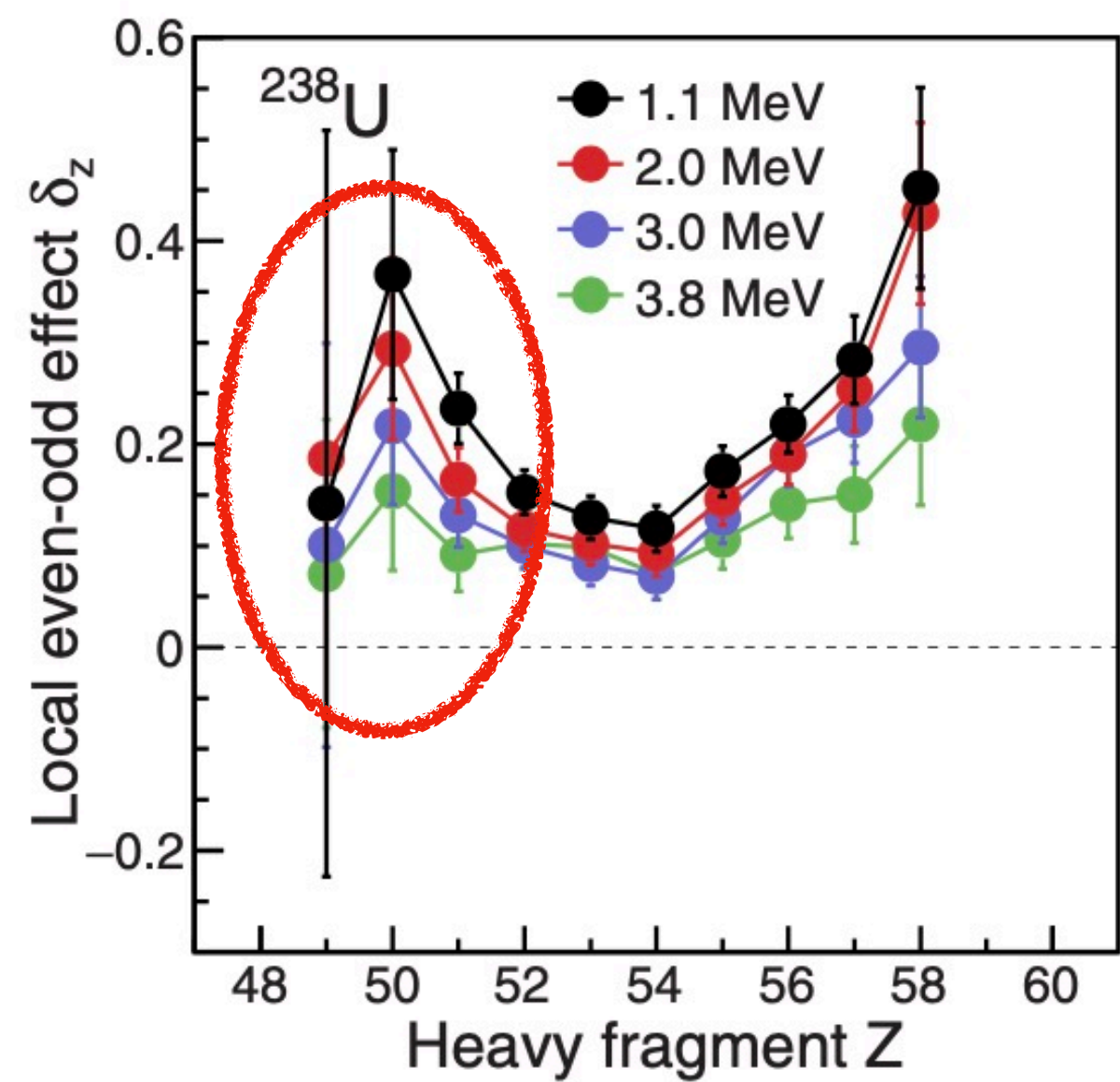
Local even-odd effect to focus on the **effect of shells**.

Systematics of local even-odd effect

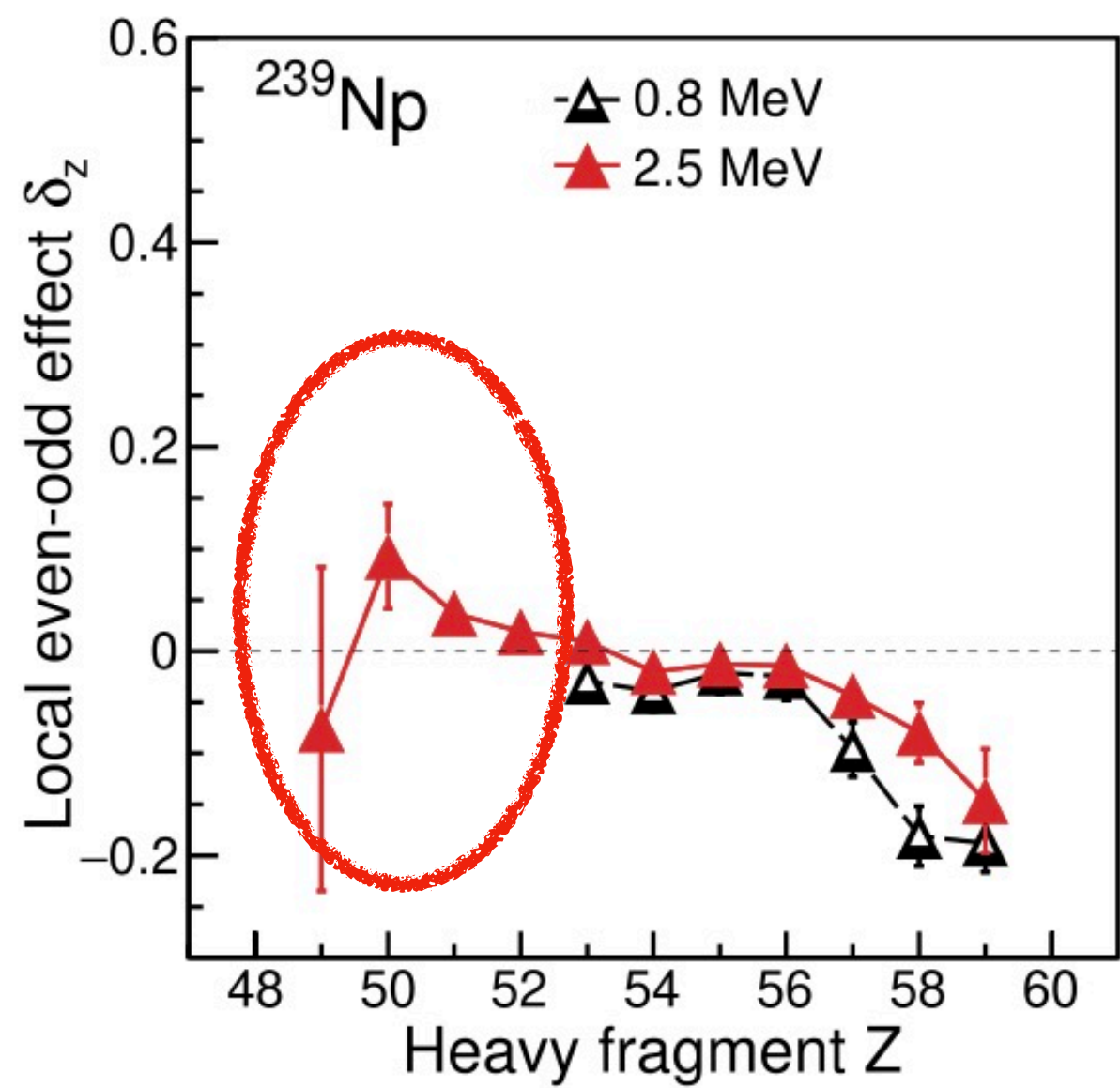


Measurement of **local even-odd effect as a function of excitation energy for three systems.**
Expected properties: the effect decreases with increasing excitation, increases with Z , is negative for odd- Z systems

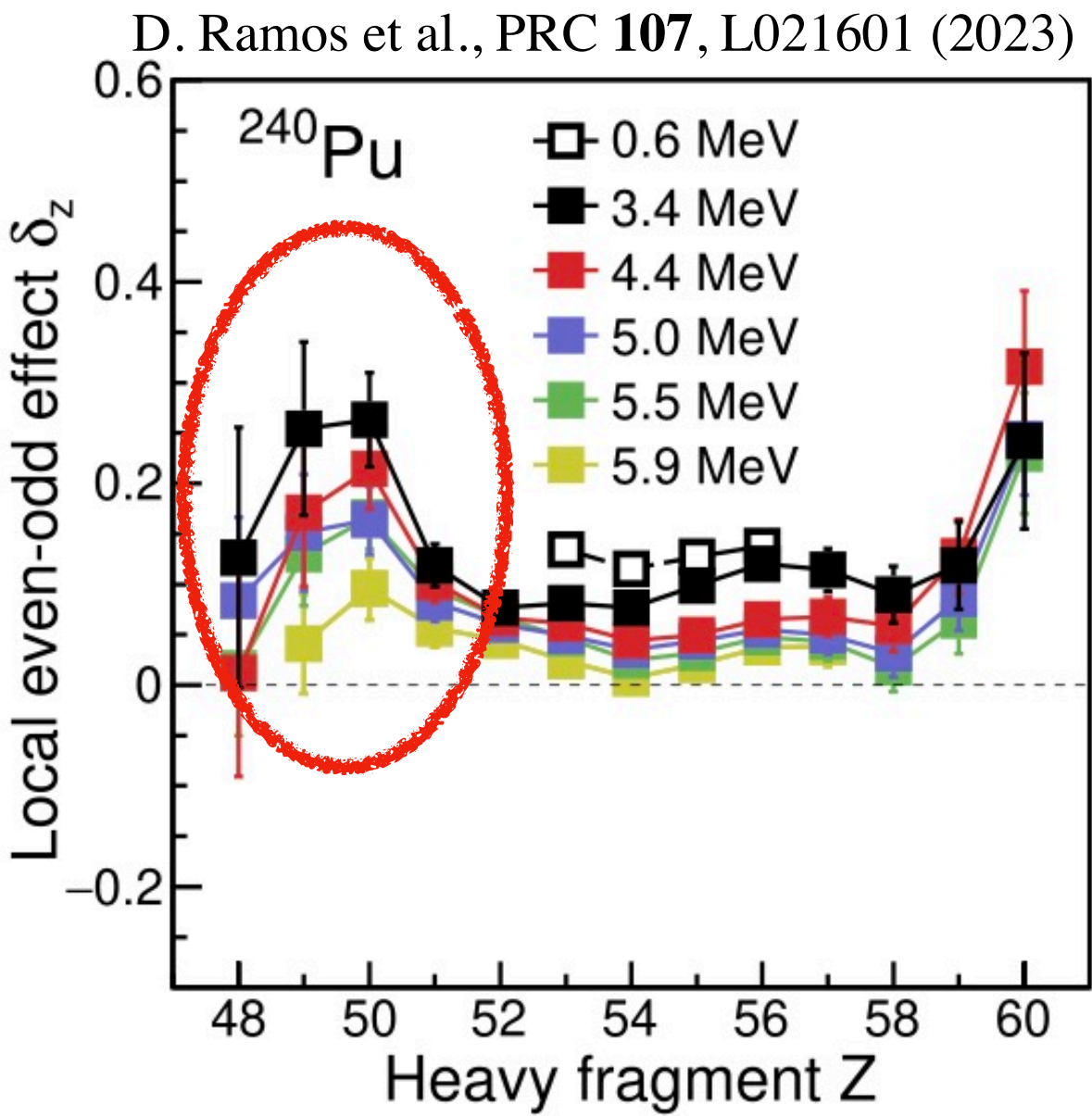
Local even-odd effect and **Z=50**



even Z=92

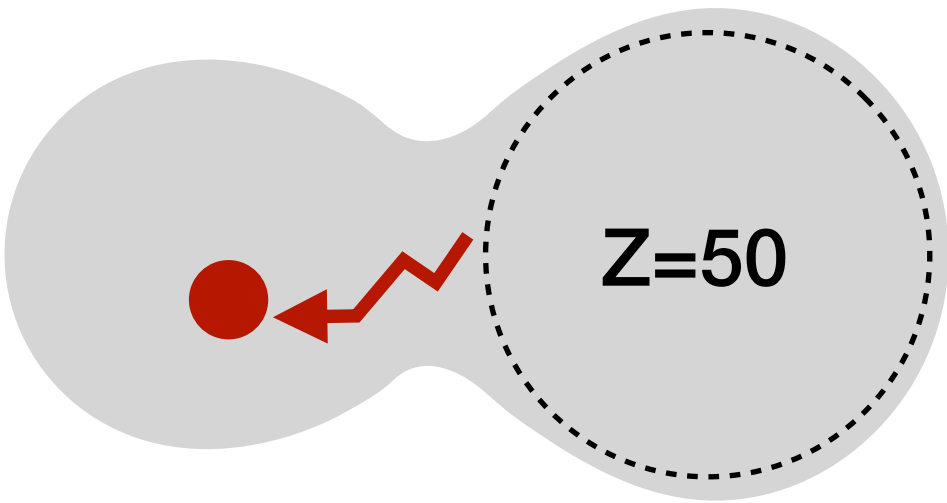


odd Z=93

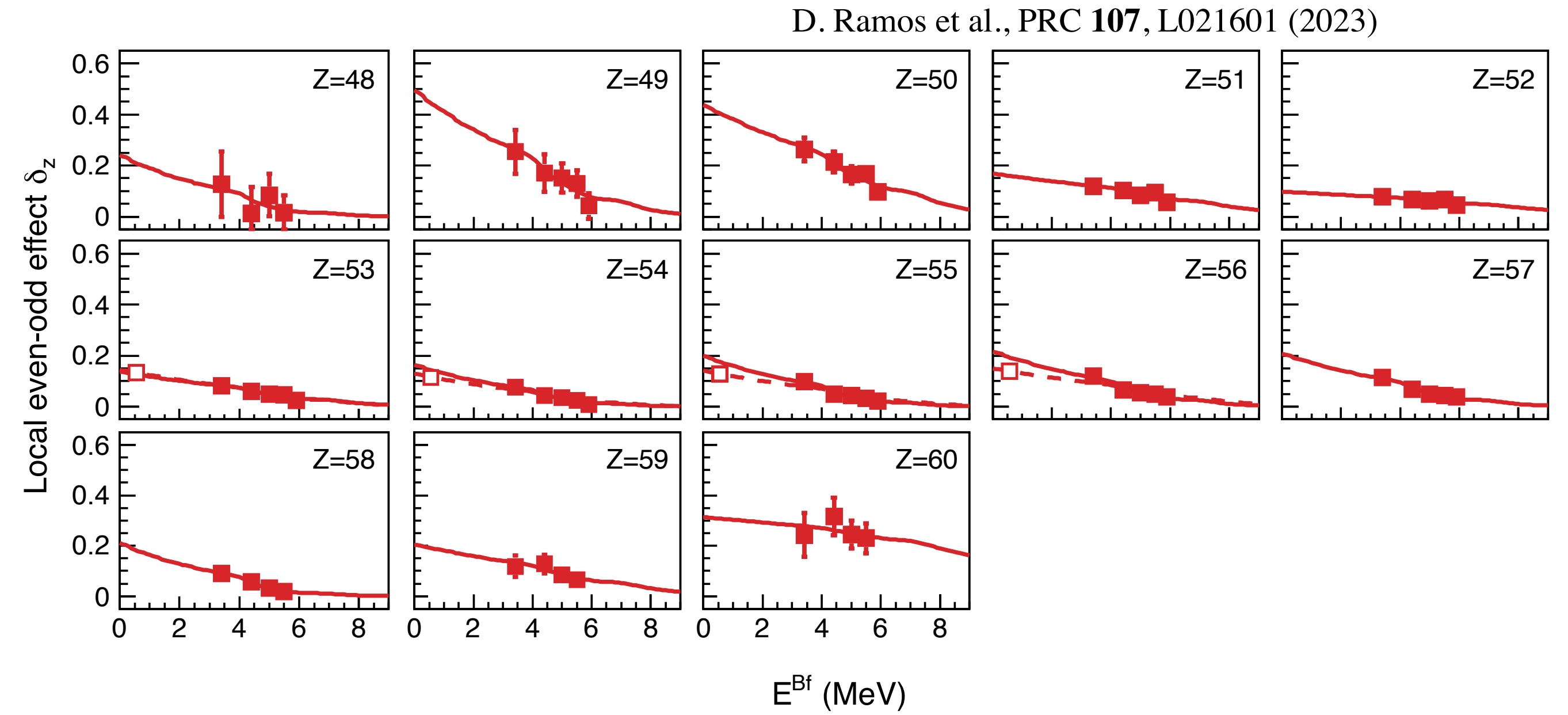
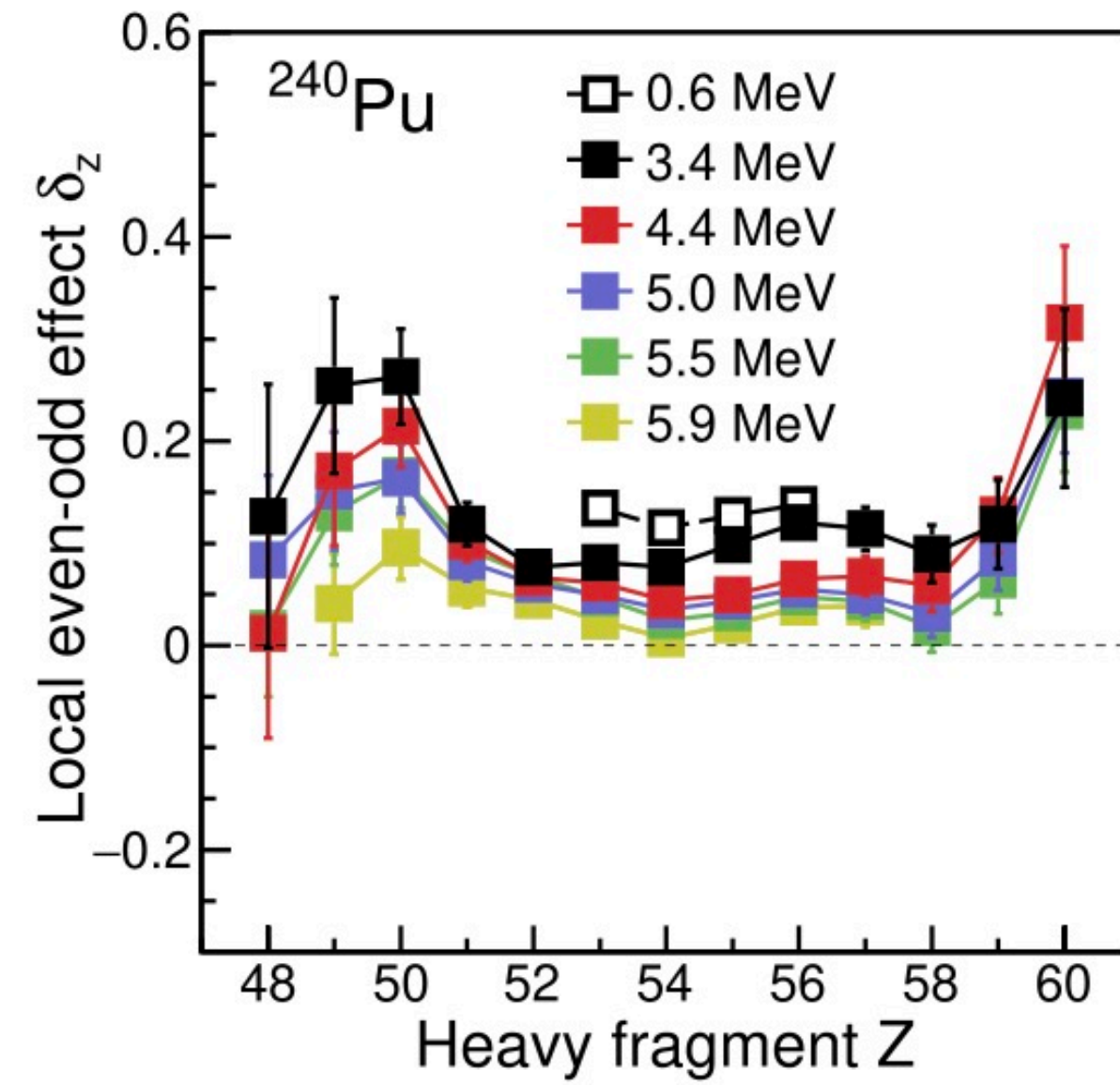


even Z=94

- A positive peak at Z=50, even in odd-Z system.
- **Z=50 is formed preferably paired close to the barrier.**



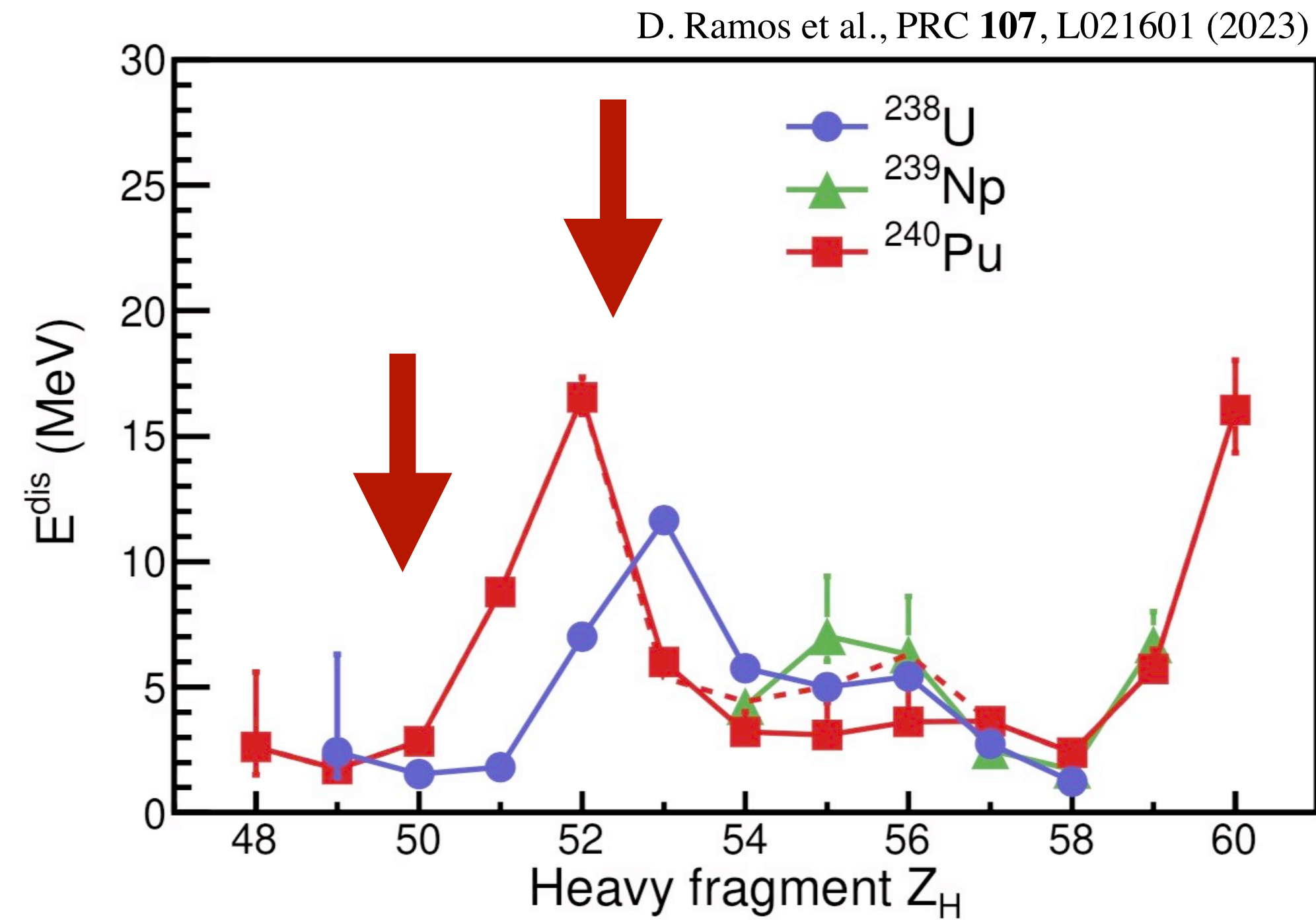
Local even-odd effect evolution for each Z



$$E^{\text{dis}}(Z) + [E^{Bf} - \Delta] = G(Z) \ln(|\delta_Z|) \quad E^{Bf} > \Delta,$$

$$E^{\text{dis}}(Z) = G(Z) \ln(|\delta_Z|) \quad E^{Bf} \leq \Delta.$$

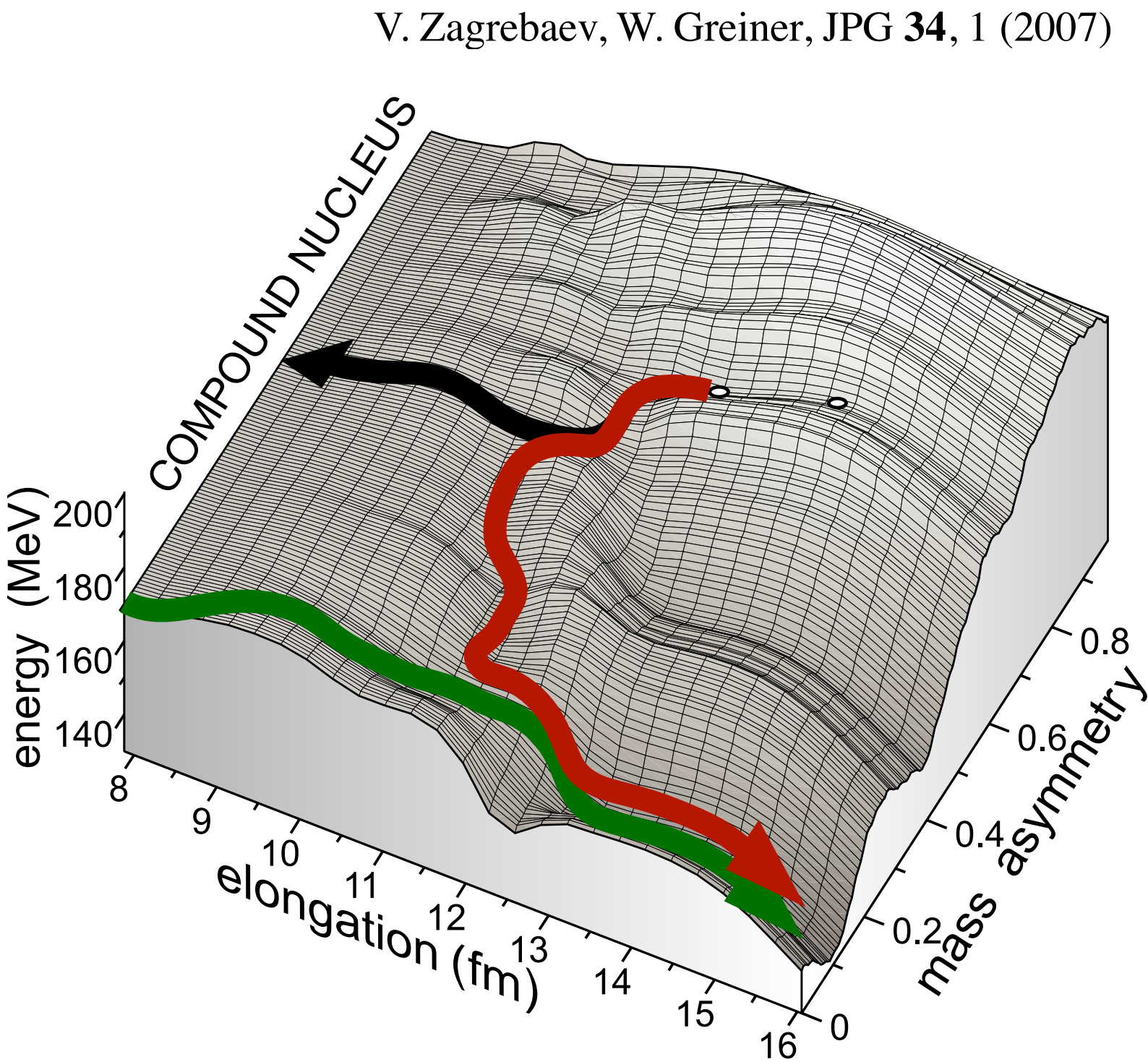
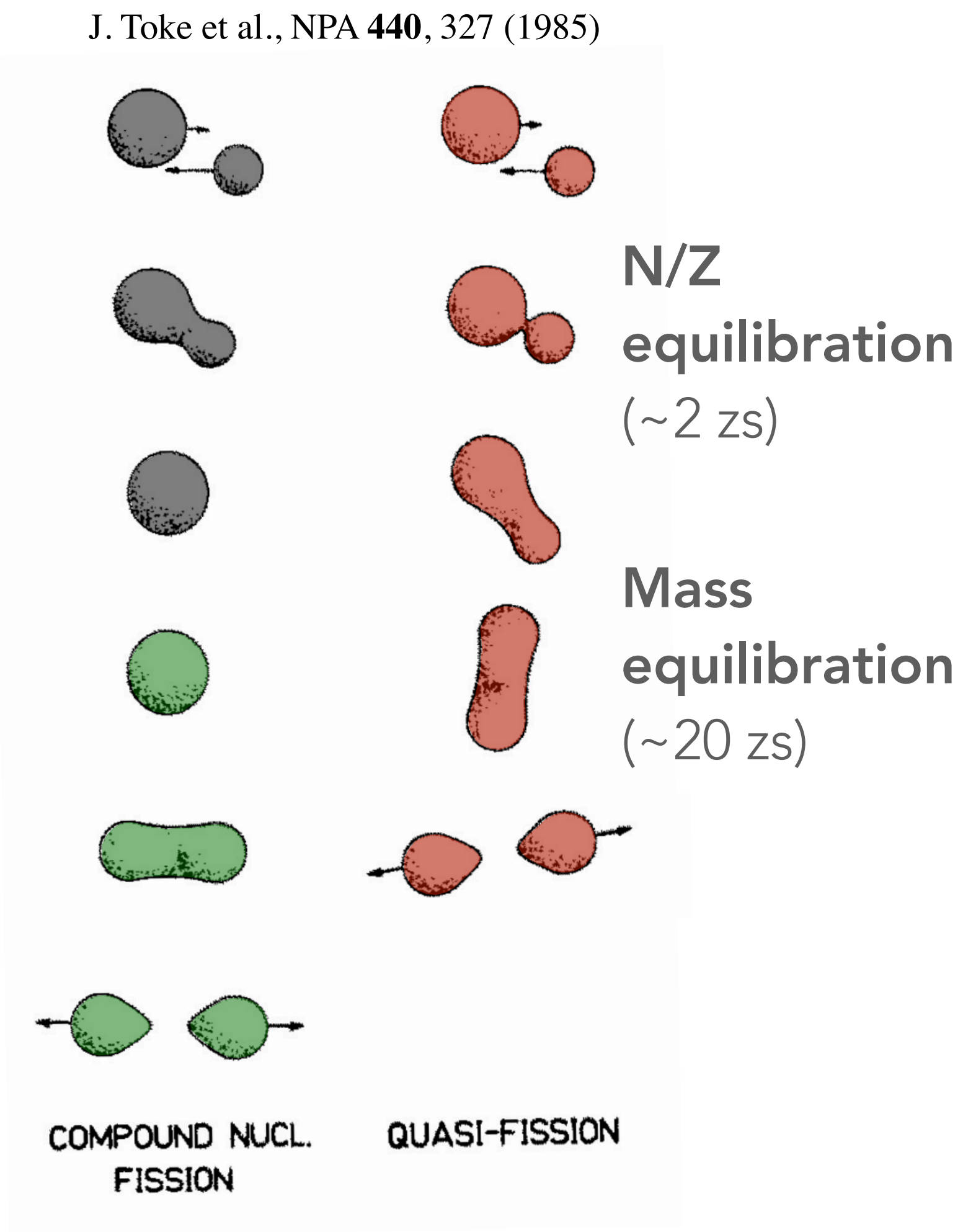
Dissipation energy



Similar **evolution of the dissipated energy as a function of Z** for the three systems:

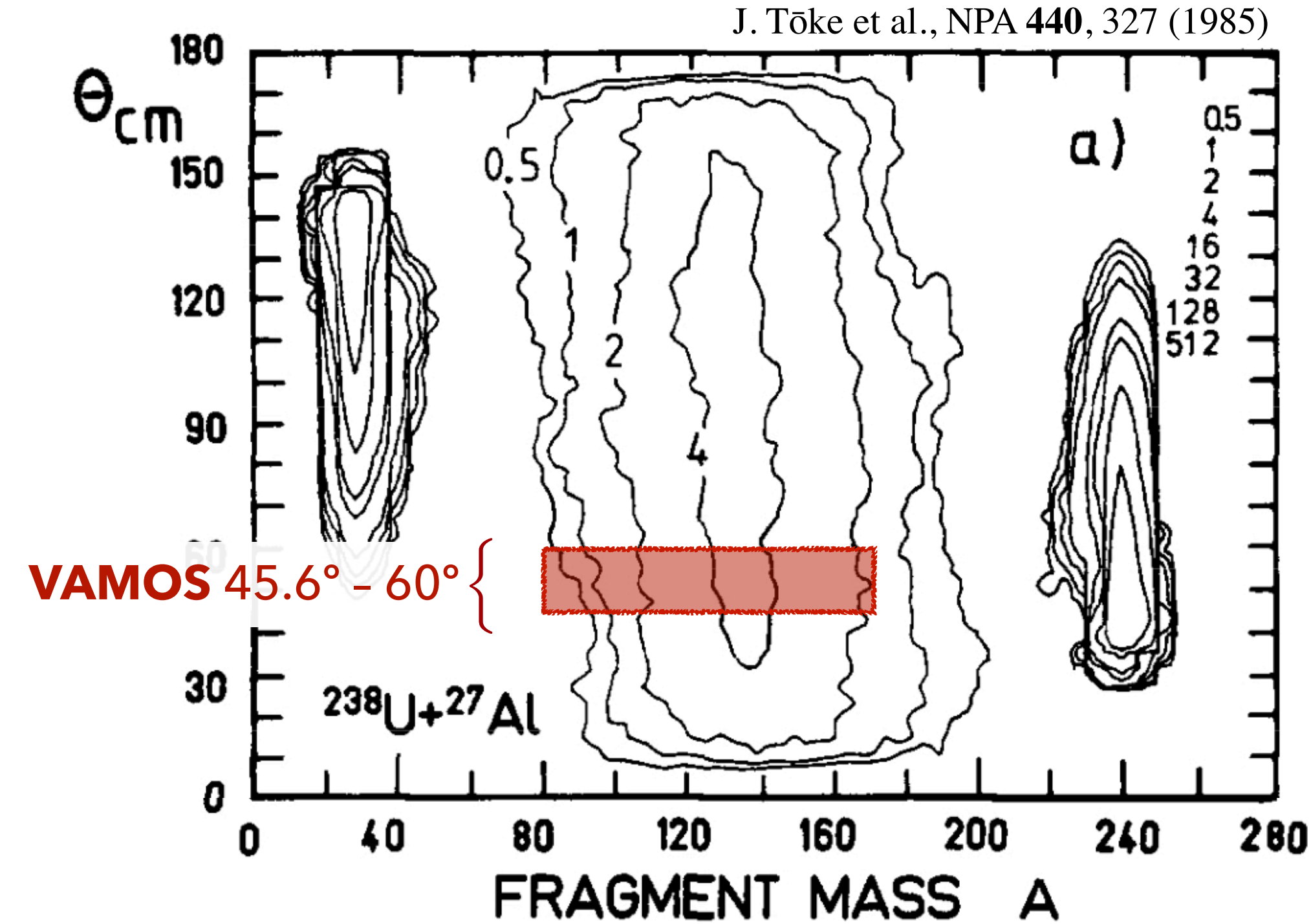
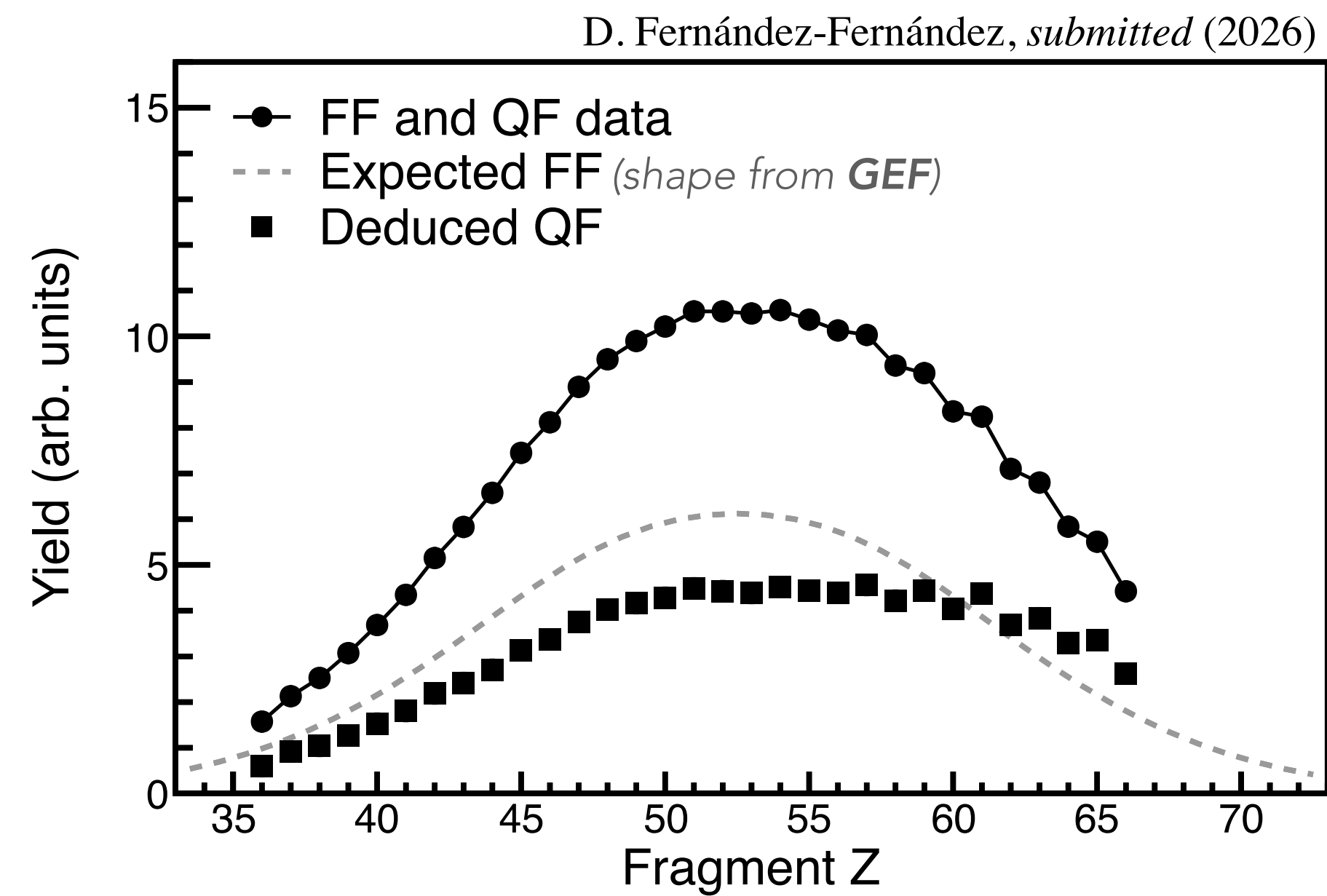
- Very low for **$Z \sim 50$**
- A maximum around **$Z \sim 52$**

Quasifission



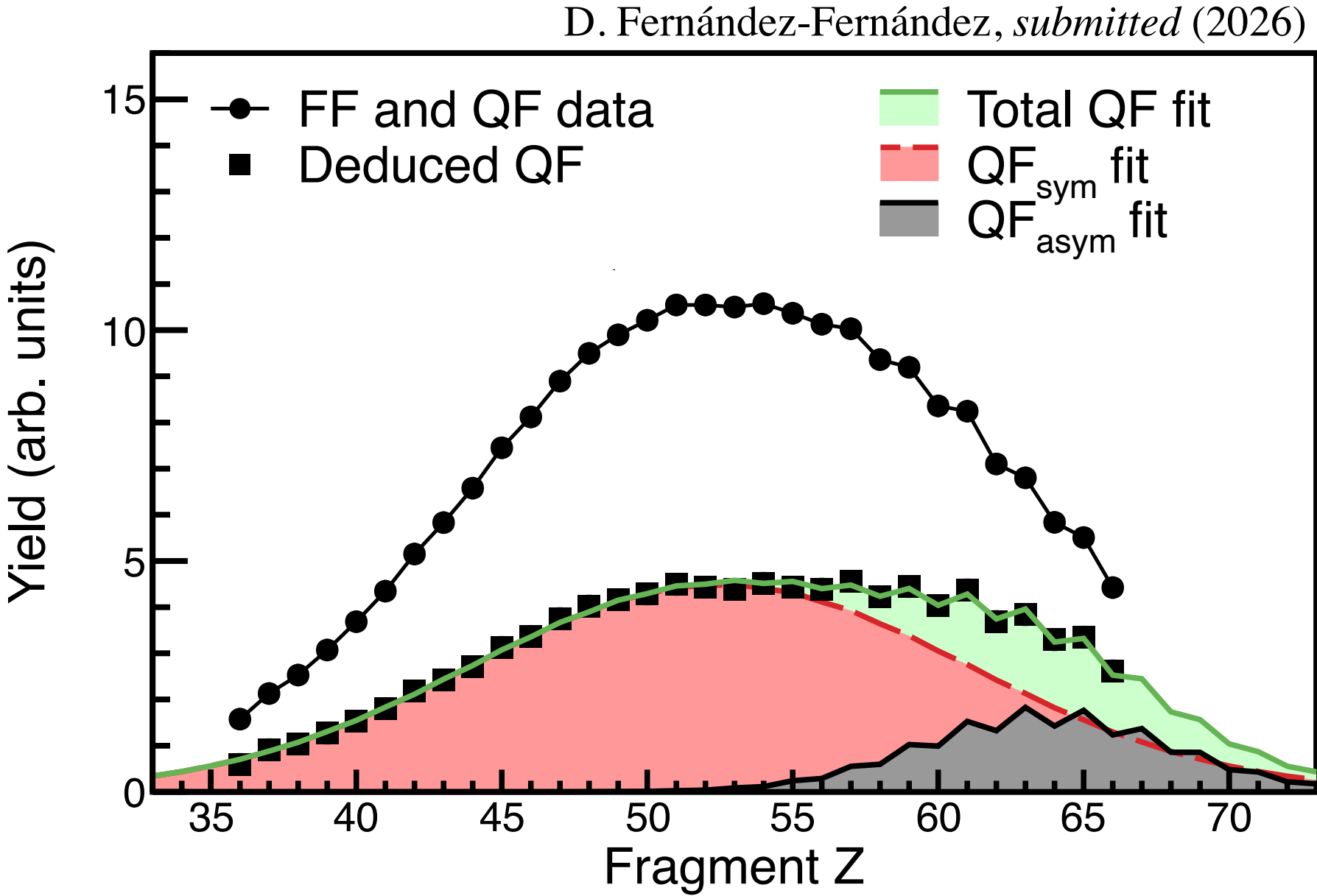
QF seems to explore **different regions of a Potential Energy Surface** similar to fission

Quasifission in VAMOS++: $^{238}\text{U} + ^{27}\text{Al}$ (@ 5.84 A MeV) $\rightarrow$ ^{265}Db ($E^*=61.2$ MeV)

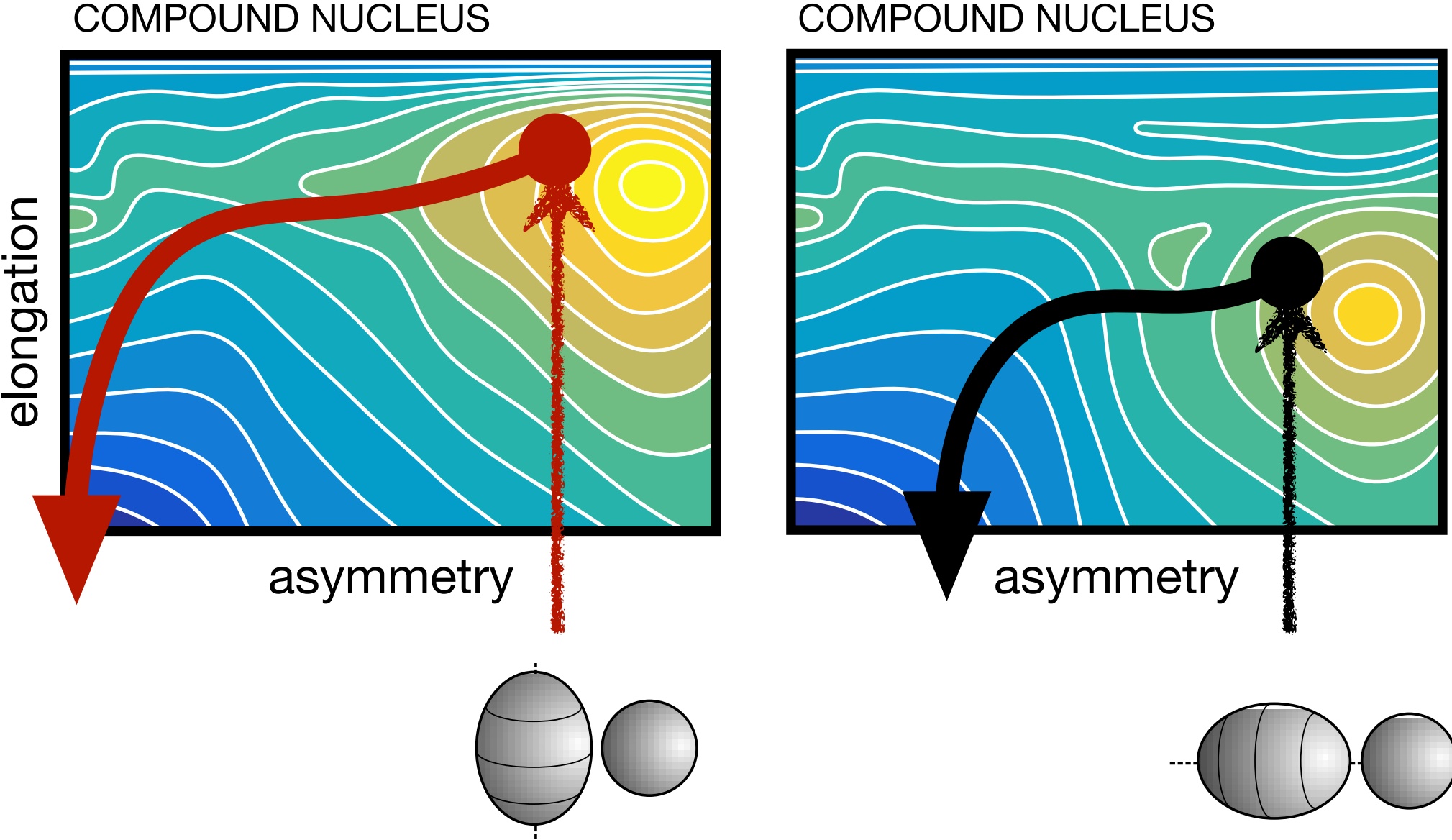


Isotopic identification but small angular coverage.

Modes in quasifission



$$Y_{sym,asym}(Z) = \text{Gauss}_{sym,asym}(Z) \left[1 + (-1)^Z \delta_{sym,asym} \right]$$

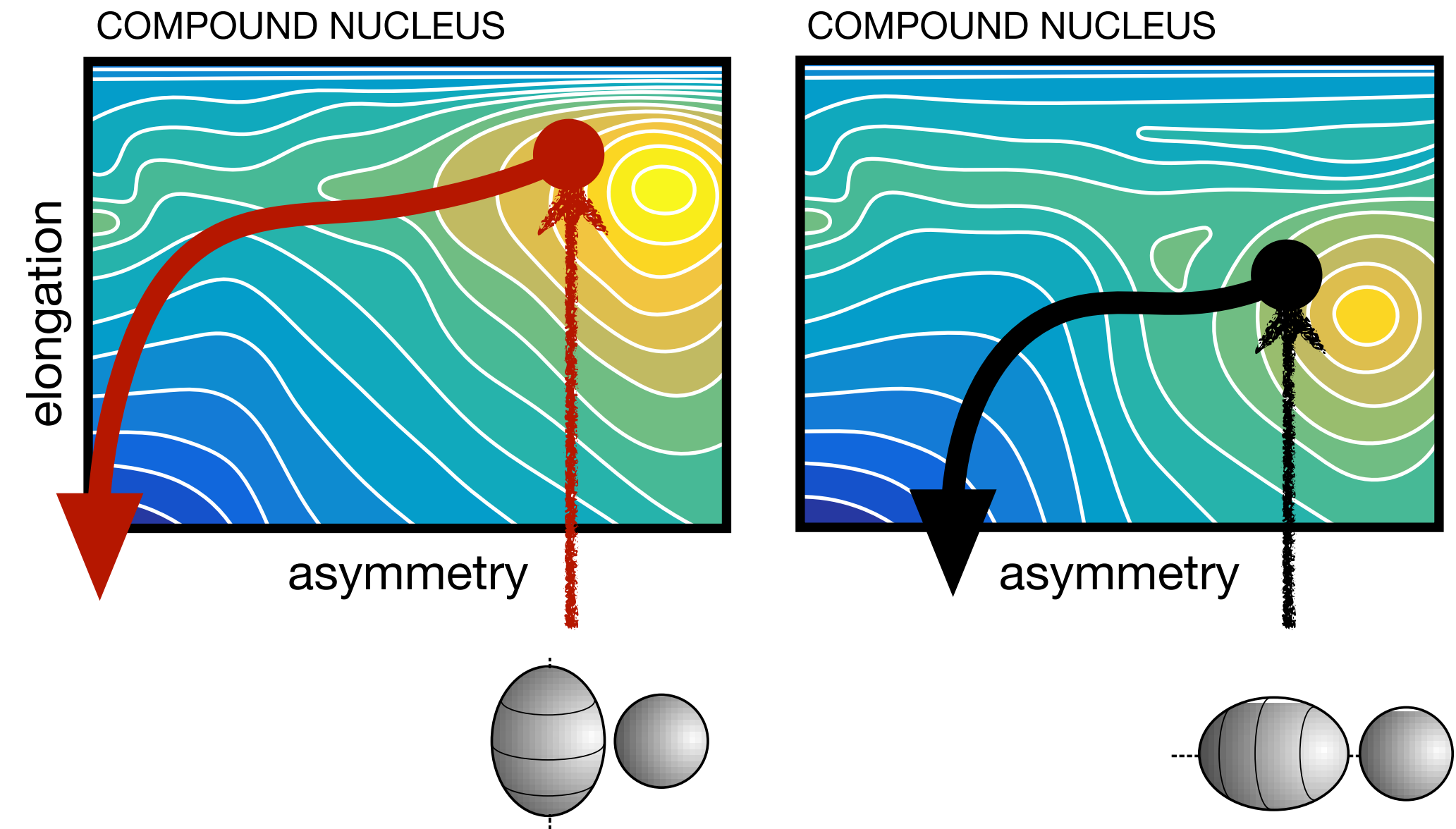
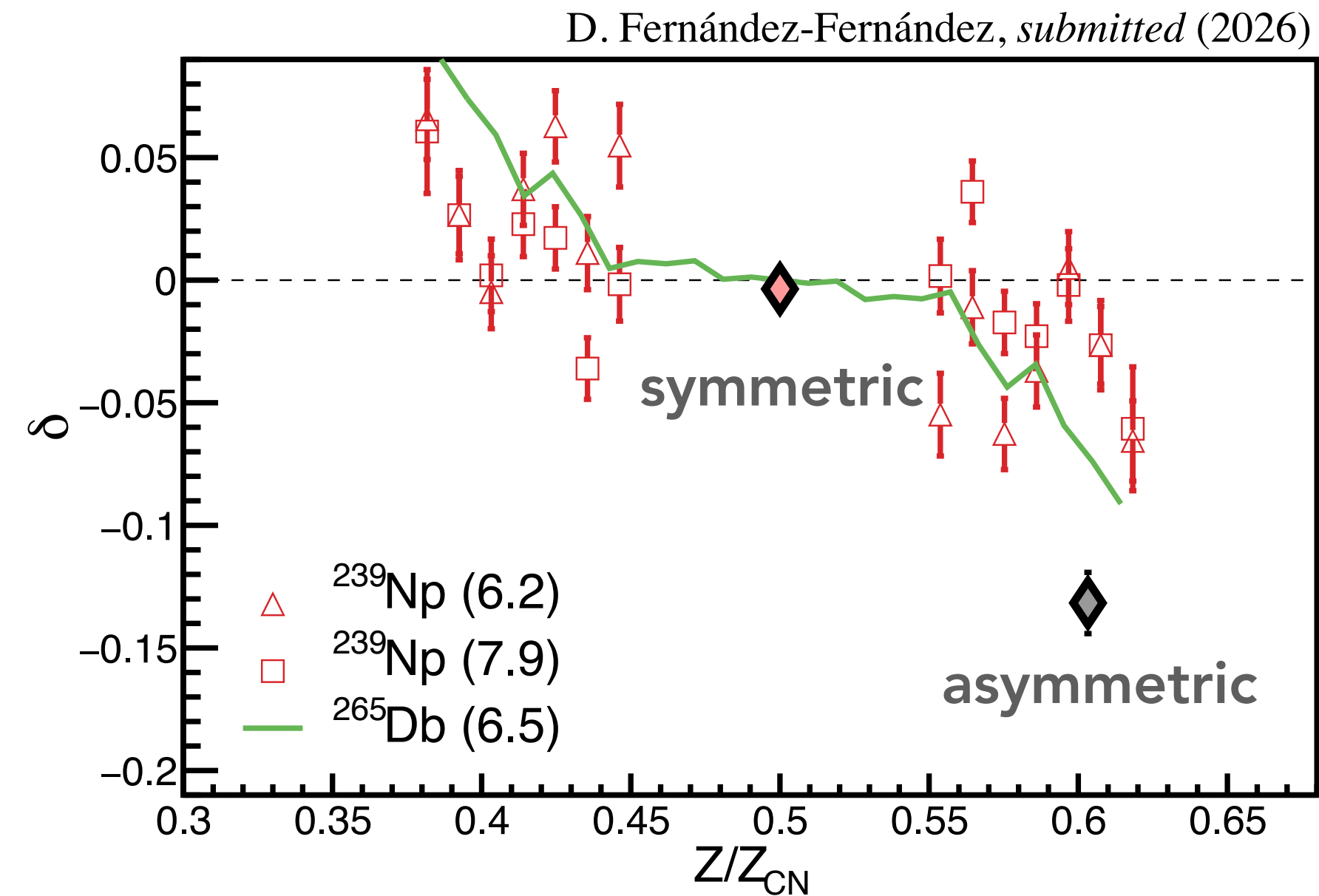


Symmetric QF

Asymmetric QF

Subtraction of fusion-fission and fit to **two different QF modes** modulated by **even-odd effects**.
Symmetric QF very similar to FF. Asymmetric QF, very different.

Modes in quasifission

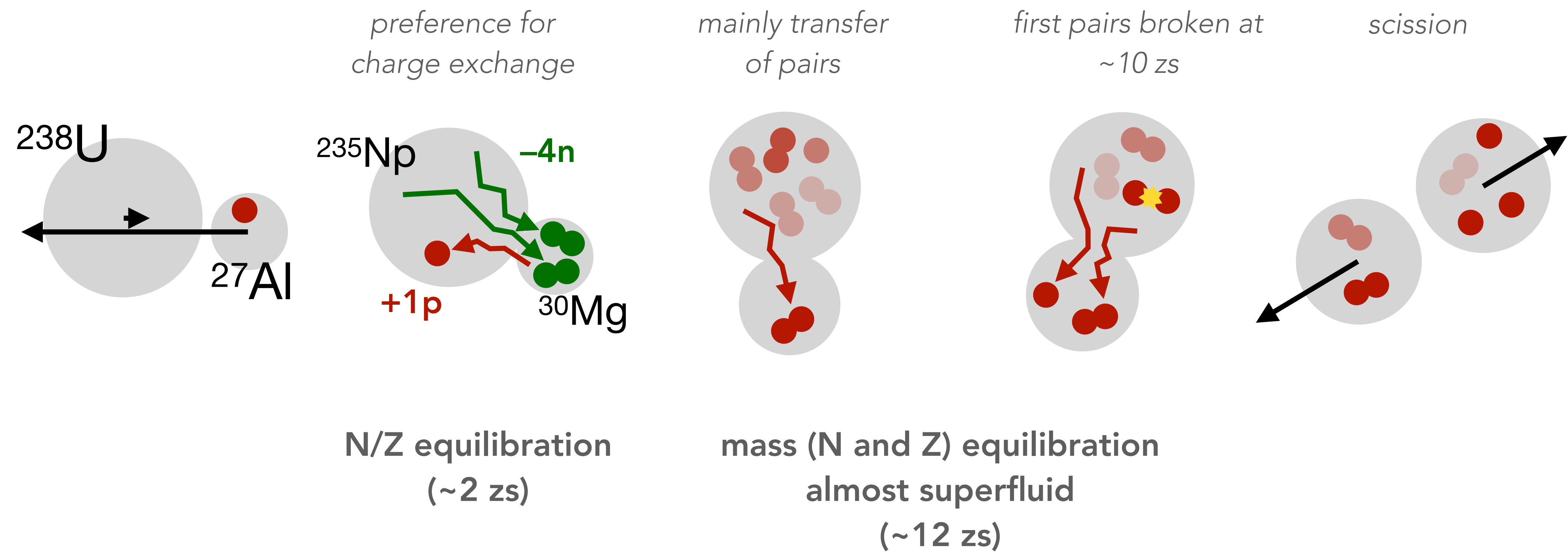


Symmetric QF

Asymmetric QF

The QF asymmetric mode shows **negative even-odd effect (!)**.
And much bigger than in low excitation fission. Very few broken pairs, **almost superfluid dynamics**.
The even-odd effect seems to be **sensitive to the path in the potential**.

Pairing as a marker for dynamics



Some conclusions

The even-odd effect is an experimental observable directly connected to nucleon and reaction dynamics

In fission,

- Allows an experimental access of the energy dissipated in fission.
- Reveals a dependence of this dissipation with the shell/mode.

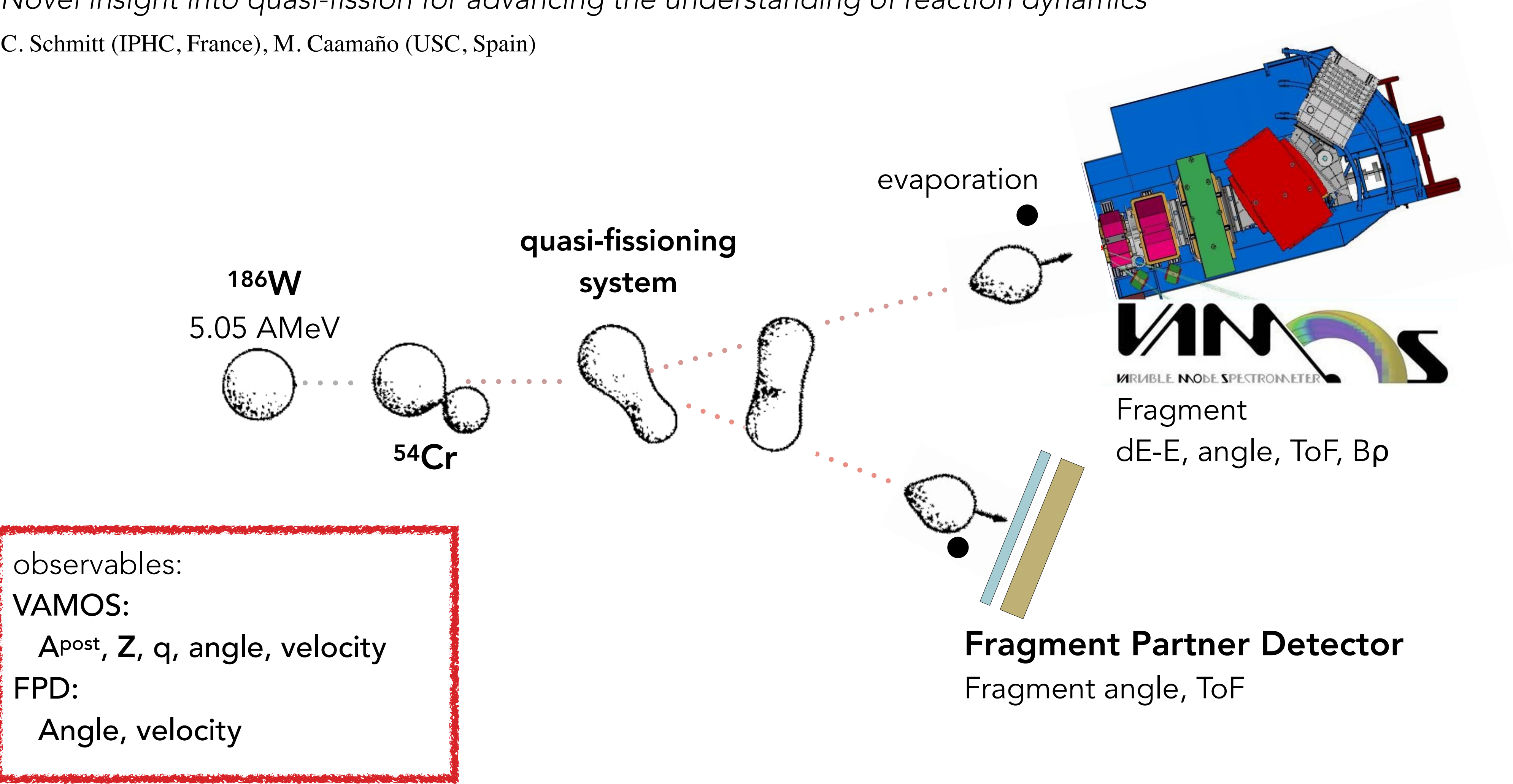
In quasifission,

- The even-odd effect is observed for the first time.
- Shows different dynamics depending on the QF mode.
- Pictures an almost superfluid equilibration in the asymmetric mode.

New experiment at VAMOS/GANIL

Novel insight into quasi-fission for advancing the understanding of reaction dynamics

C. Schmitt (IPHC, France), M. Caamaño (USC, Spain)



Cheers

D. Ramos, C. Schmitt, A. Lemasson, D. Fernández, G. Mantovani, M. Rejmund,
D. Ackermann, H. Álvarez-Pol, L. Audouin, L. Bégué-Guillou, S. Biswas, J. Buete,
M. Ciemala, E. Clement, A. Cobo Zarzuelo, K. Cook, O. Dorvaux, M. Dasgupta, J. Dudouet,
D. Durand, F. Farget, B. Fernández-Domínguez, D. François, J.D. Frankland, M.O. Fregeau,
D. Galaviz, E. Galiana-Baldó, B. Gall, D. Gilbert, D. Gruyer, A. Heinz, A. Henriques,
D. Hinde, B. Jacquot, I. Jangid, B. Jurado, Y.H. Kim, M. Kmiecik, N. Kumar, J. Ljungvall,
K. Mahata, A. Maj, K. Mazurek, M. Moukaddam, P. Morfouace, A. Navin, D. Ralet, T. Roger,
A. Shrivastava, P. Teubig, and I. Tsekhanovich

*USC (Spain), GANIL (France), IPHC (France), INFN-LNL (Italy), ANU (Australia),
IFJ PAN (Poland), U. Strasbourg (France), IP2I (France), LPC (France),
Chalmers UT (Sweden), LIP (Portugal), CENBG (France), CENS-IBS (South Korea),
Bhabha ARC (India)*

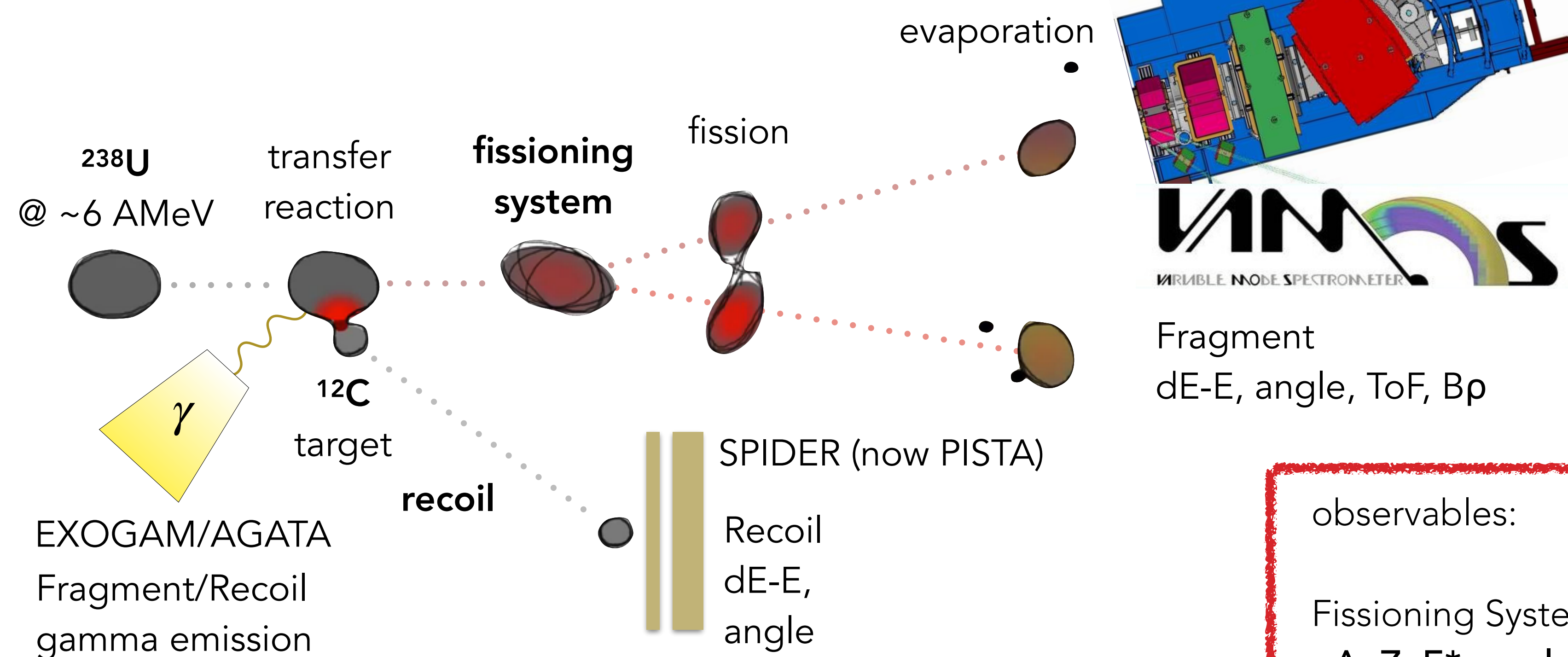
This work was supported by the Spanish Ministry of Research and Innovation under the budget items FPA2010-22174-C02-01 and RYC-2012-11585, by the Spanish Research State Agency No. PGC2018-096717-B-C22, PID2021-128487NB-I00, and PID2024-160773NB-C21, by the European Union ERDF, by the "María de Maeztu" Units of Excellence program No. MDM-2016-0692, by Xunta de Galicia as Centro singular de investigación de Galicia accreditation 2019–2022, from the "Consolidación e estruturación" No. ED431F 2016/002 and ED431C 2024/13. This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 654002.

Pairing as an observable for many-body nuclear dynamics

Even-odd effect in fission with VAMOS++

Production and fission from fusion and multi-nucleon transfer

F. Farget, M. Rejmund, A. Lemasson, D. Ramos et al.



observables:

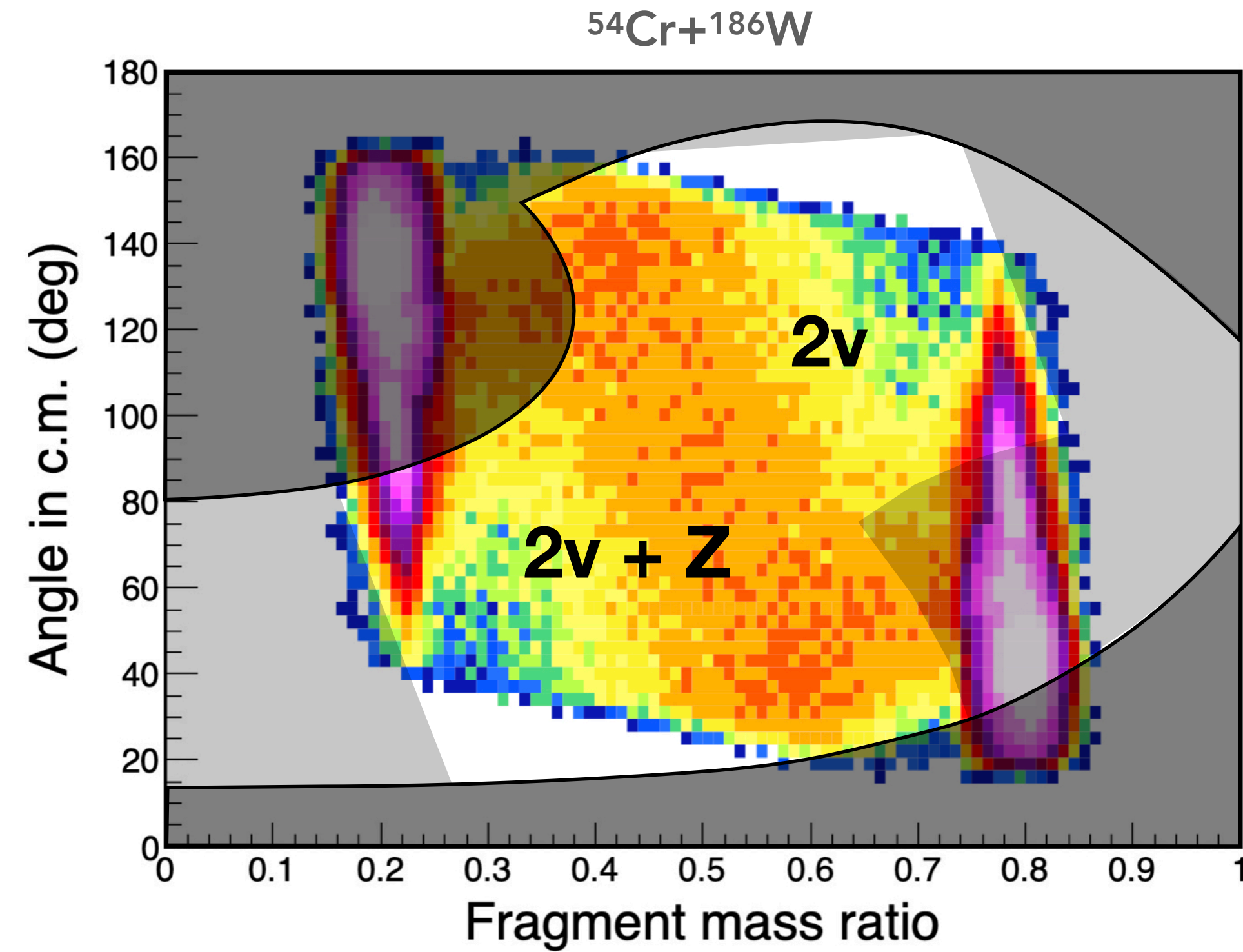
Fissioning System:

- A, Z, E*, angle, velocity

Fission Fragments:

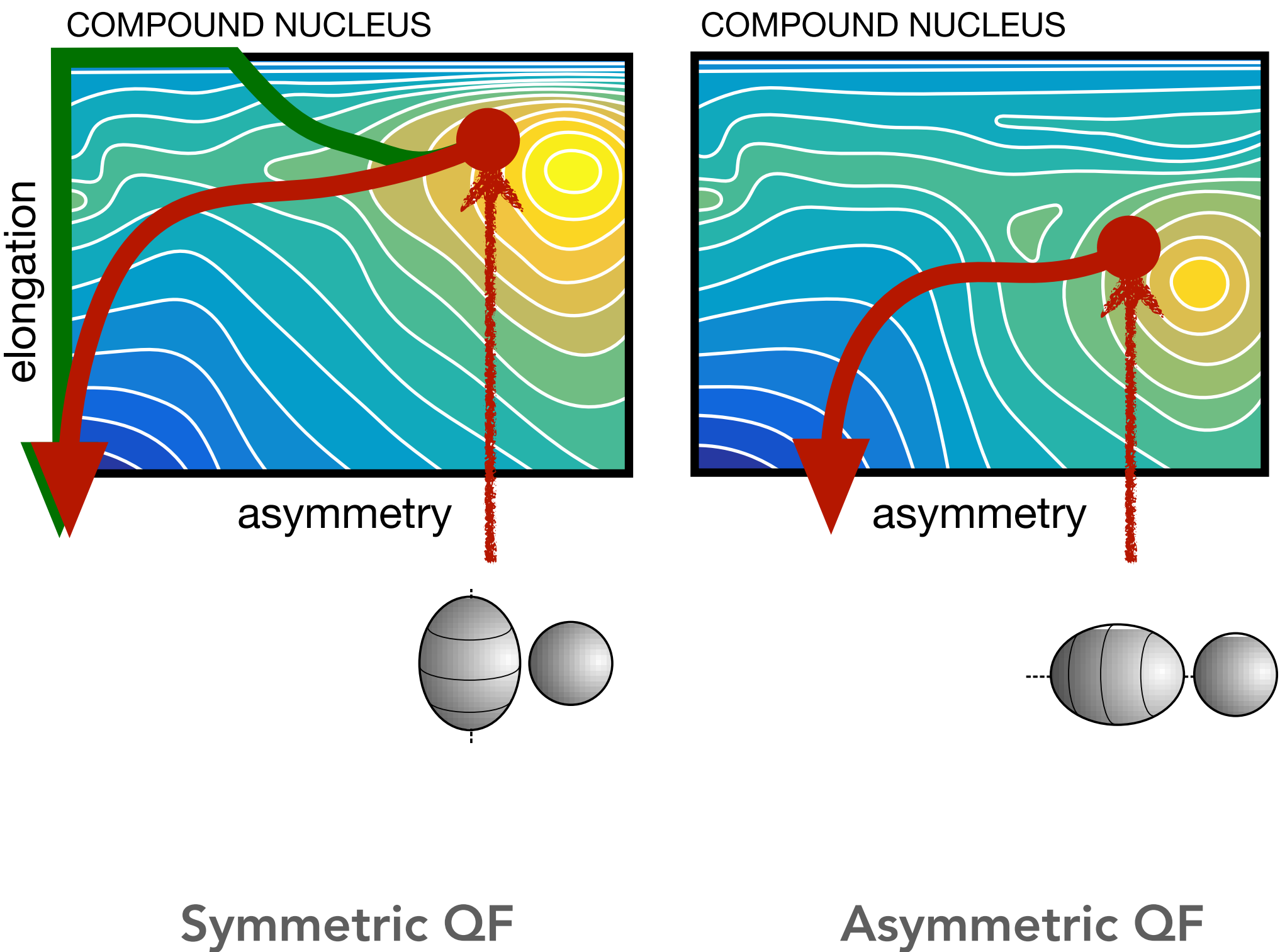
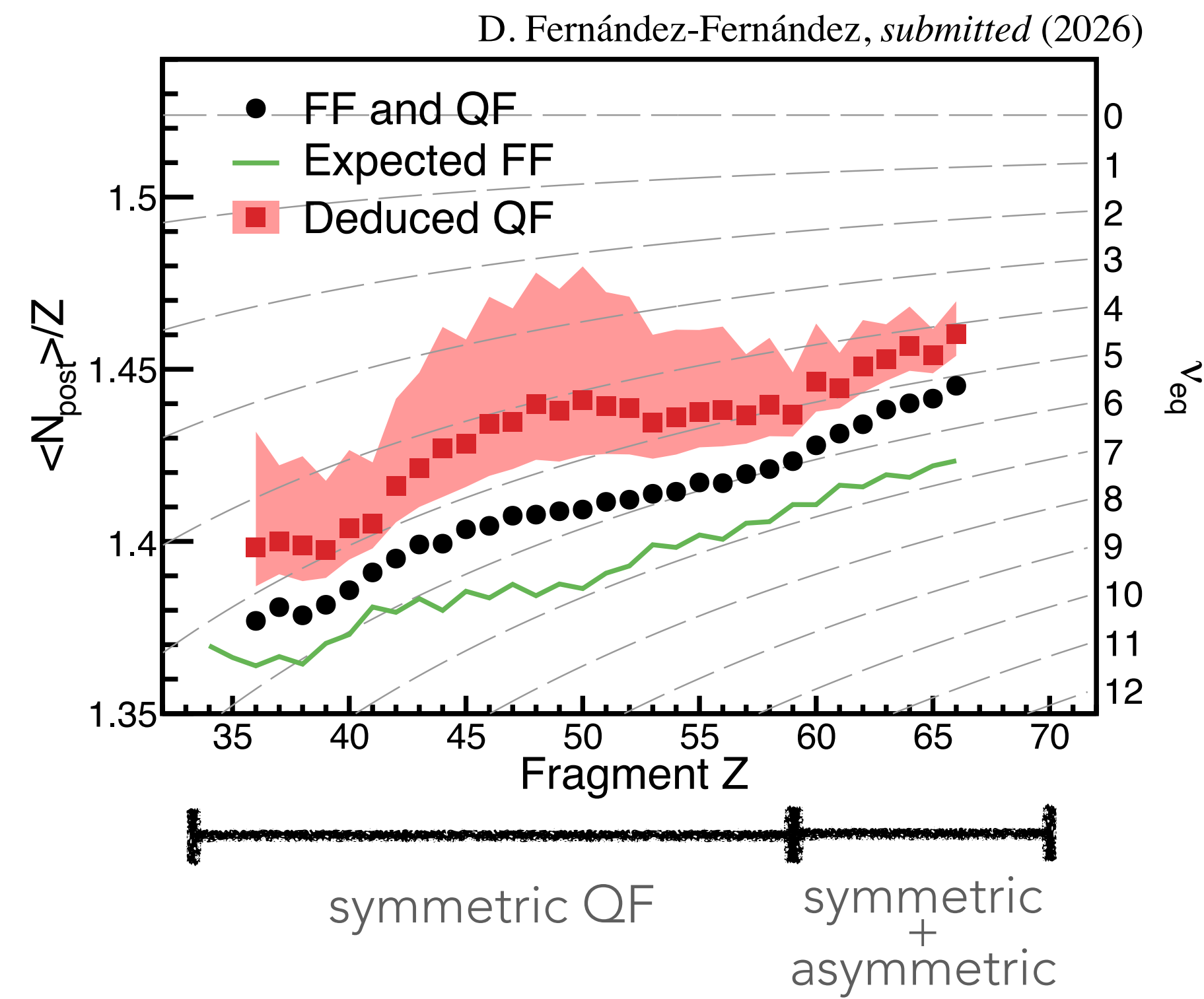
- A^{post}, Z, q, angle, velocity

New experiment at VAMOS/GANIL



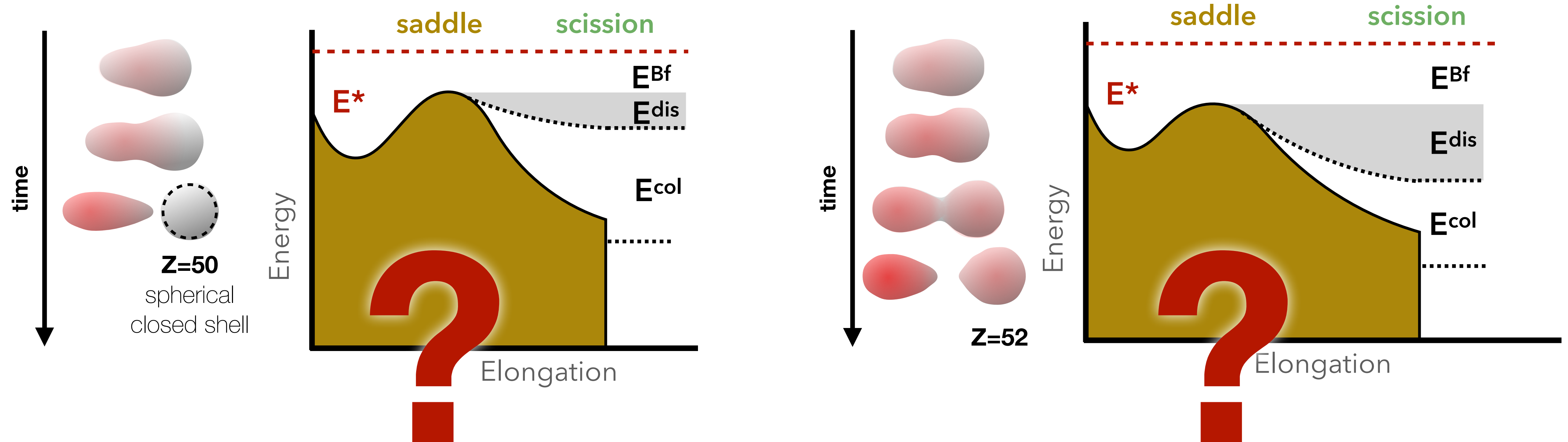
- The idea is to cover as much angle in c.m. as possible with both fragments in coincidence.
- We will use the classic 2ν **method** between VAMOS and the FPD to obtain TKE, and masses (before and after evaporation).
- In half of the coverage, we will also have **fragment Z identification**, which gives us **structure effects, TXE, eofx, etc.**

Modes in quasifission



N/Z shows less evaporation in QF than in fusion-fission.
Less excitation energy generated in QF.

Dissipation energy

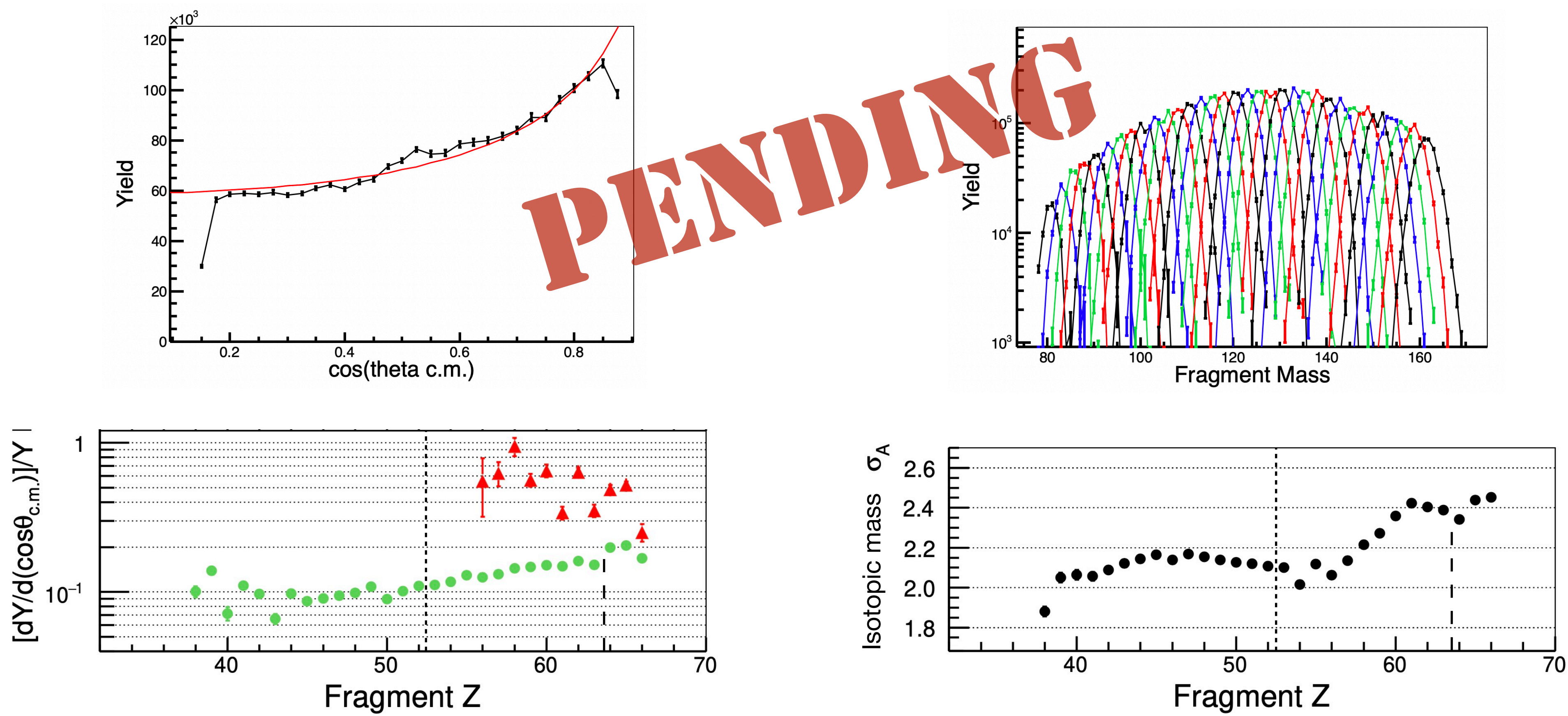


Questions pending:

Where is the dissipation generated? at the barrier, the descend, at scission?

What makes it different for each Z ? Is it the length of the path? the barrier height? the gradient?

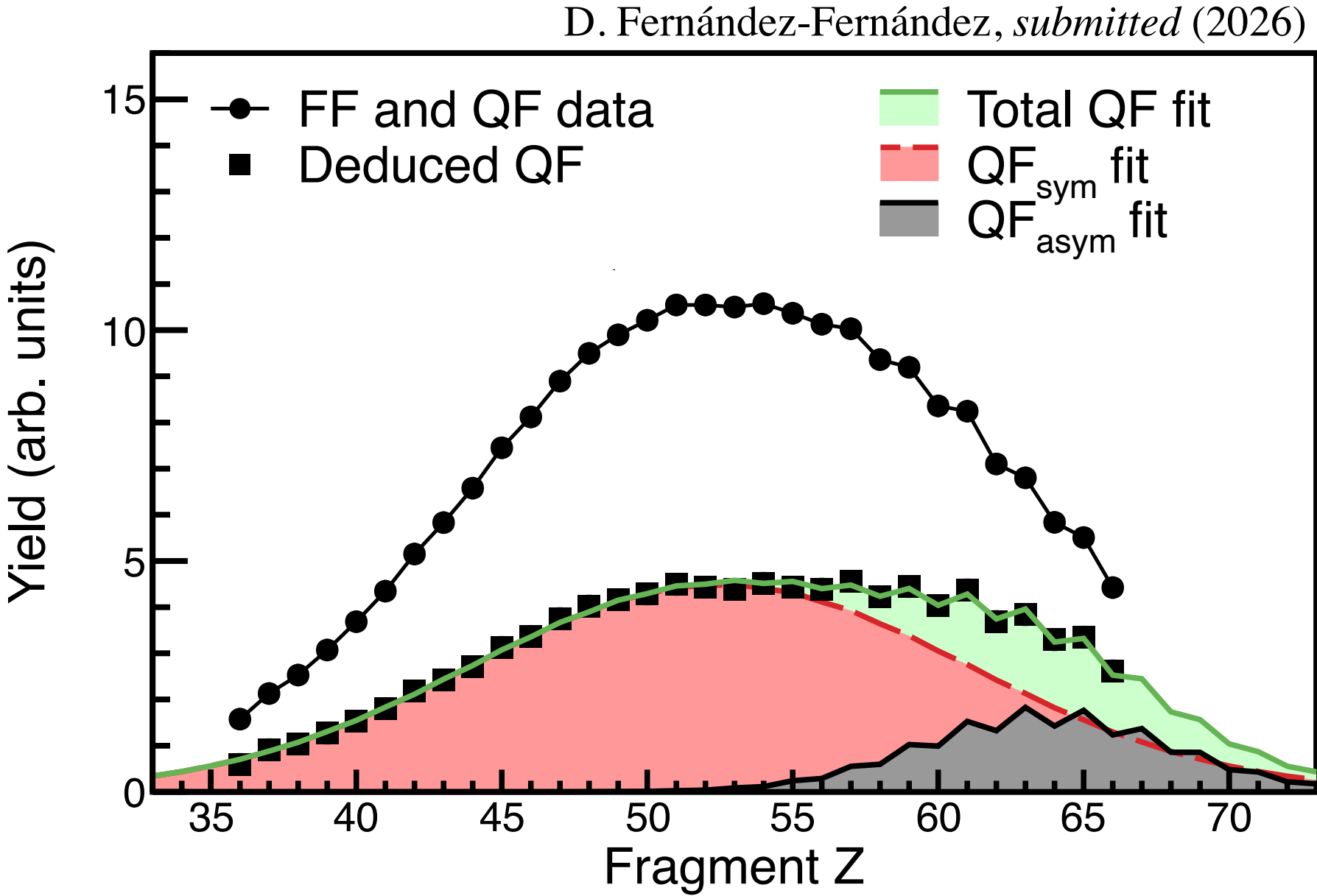
Characterisation of modes



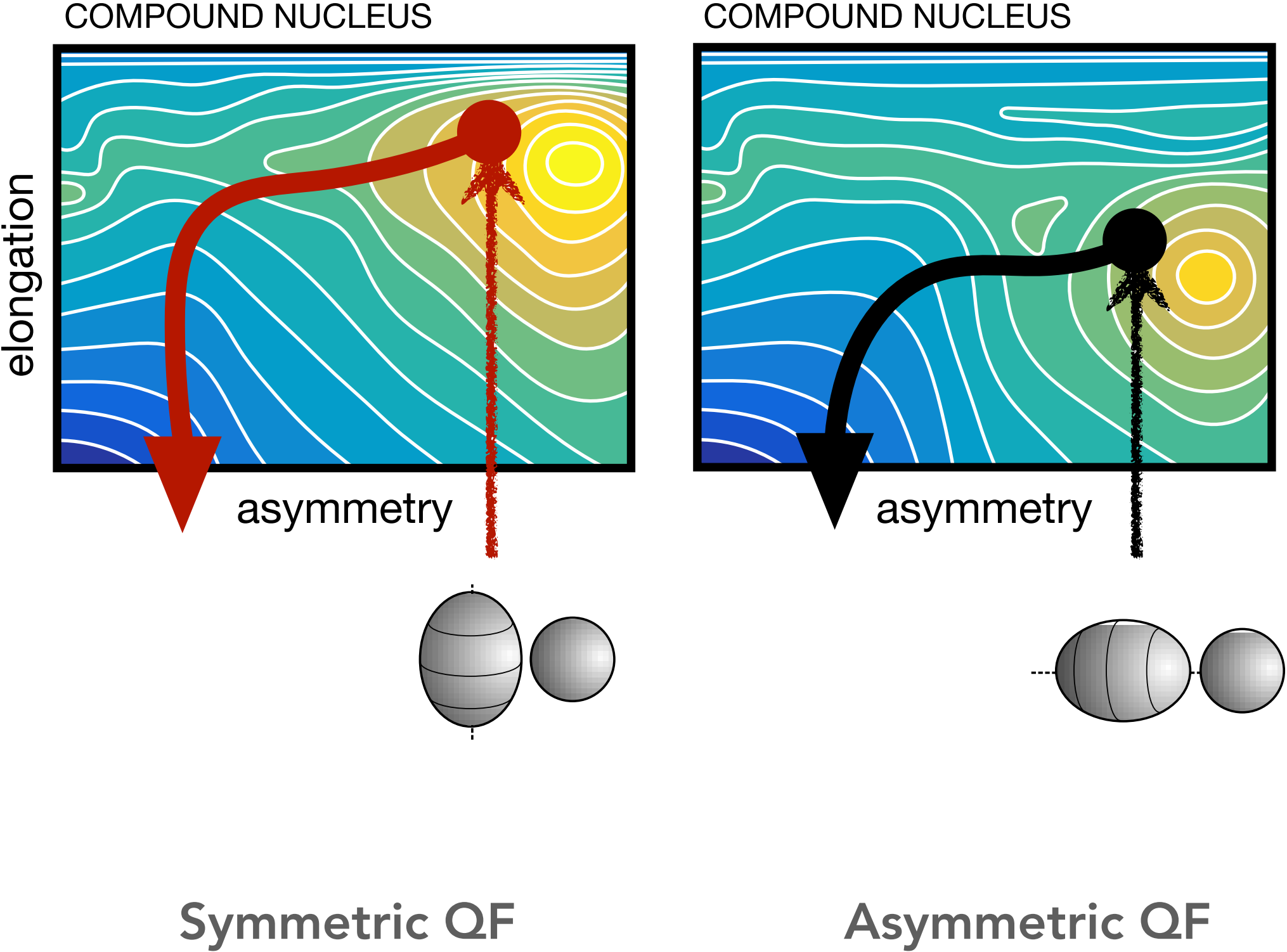
Angular distribution

Mass distribution width

Modes in quasifission



$$Y_{sym,asym}(Z) = \text{Gauss}_{sym,asym}(Z) \left[1 + (-1)^Z \delta_{sym,asym} \right]$$



Why is eofx sensitive to the PES close to the barrier?:

If we focus around a particular Z, for ex. Z=62, populated by both modes, the main difference between them is how close is to the fission barrier.

(Also the starting/touching point is smaller to Asymmetric QF -> Smaller drop from touching to scission)

Explore the possibility of changes in the barrier due to the shell instead of changes in E_diss

$$E^{\text{dis}}(Z) + [E^{Bf} - \Delta] = G(Z) \ln(|\delta_Z|) \quad E^{Bf} > \Delta,$$

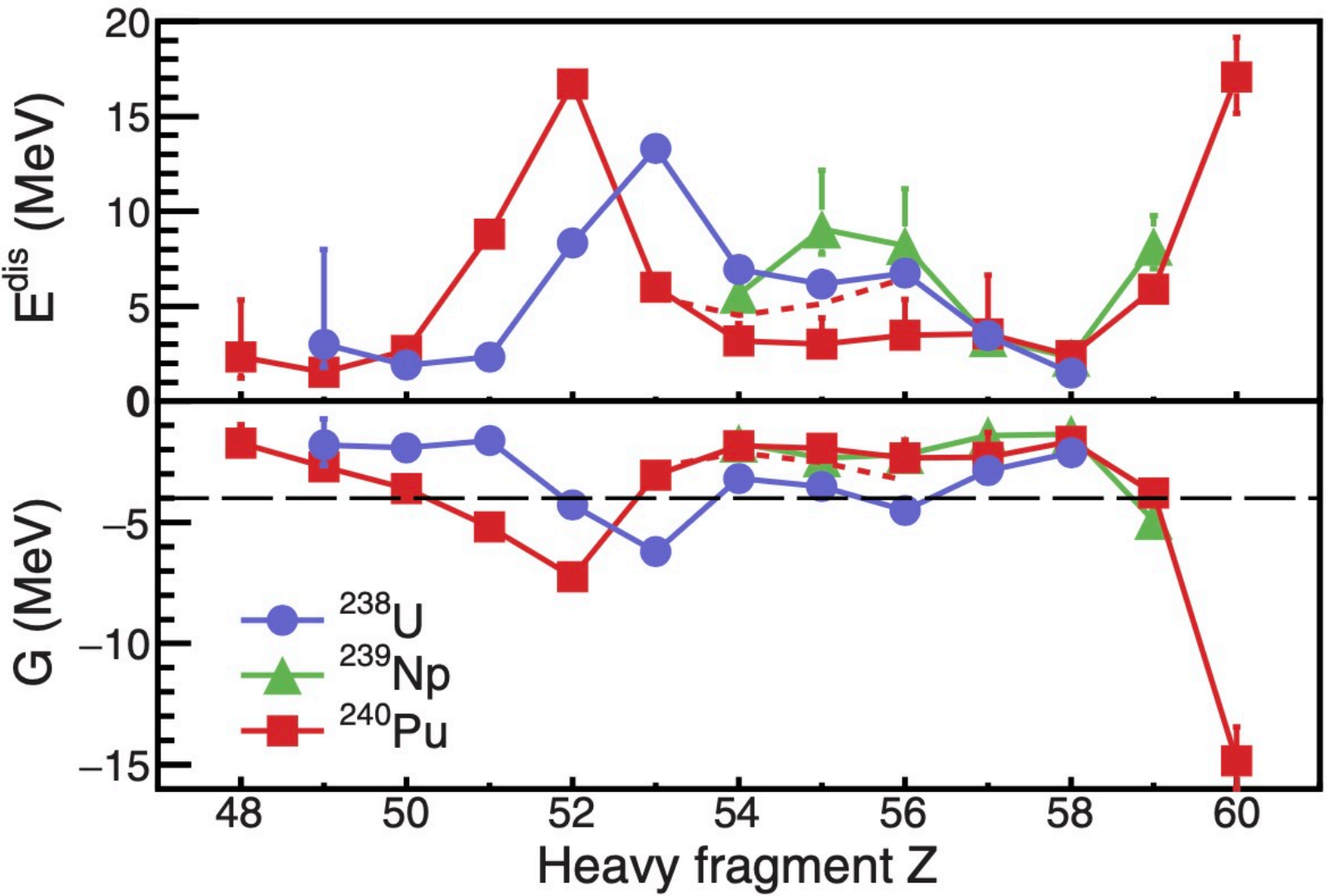
$$E^{\text{dis}}(Z) = G(Z) \ln(|\delta_Z|) \quad E^{Bf} \leq \Delta.$$

$$E^{\text{int}} = E^{Bf} + E^{\text{dis}}.$$

$$E^{Bf} = E^* - Bf$$

$$E^{\text{dis}} + E^* - Bf - \Delta = G \ln \delta$$

$$E^* + \textcolor{red}{E^{\text{dis}} - Bf} - \Delta = G \ln \delta$$



if Bf gets smaller, E^{dis} as well.

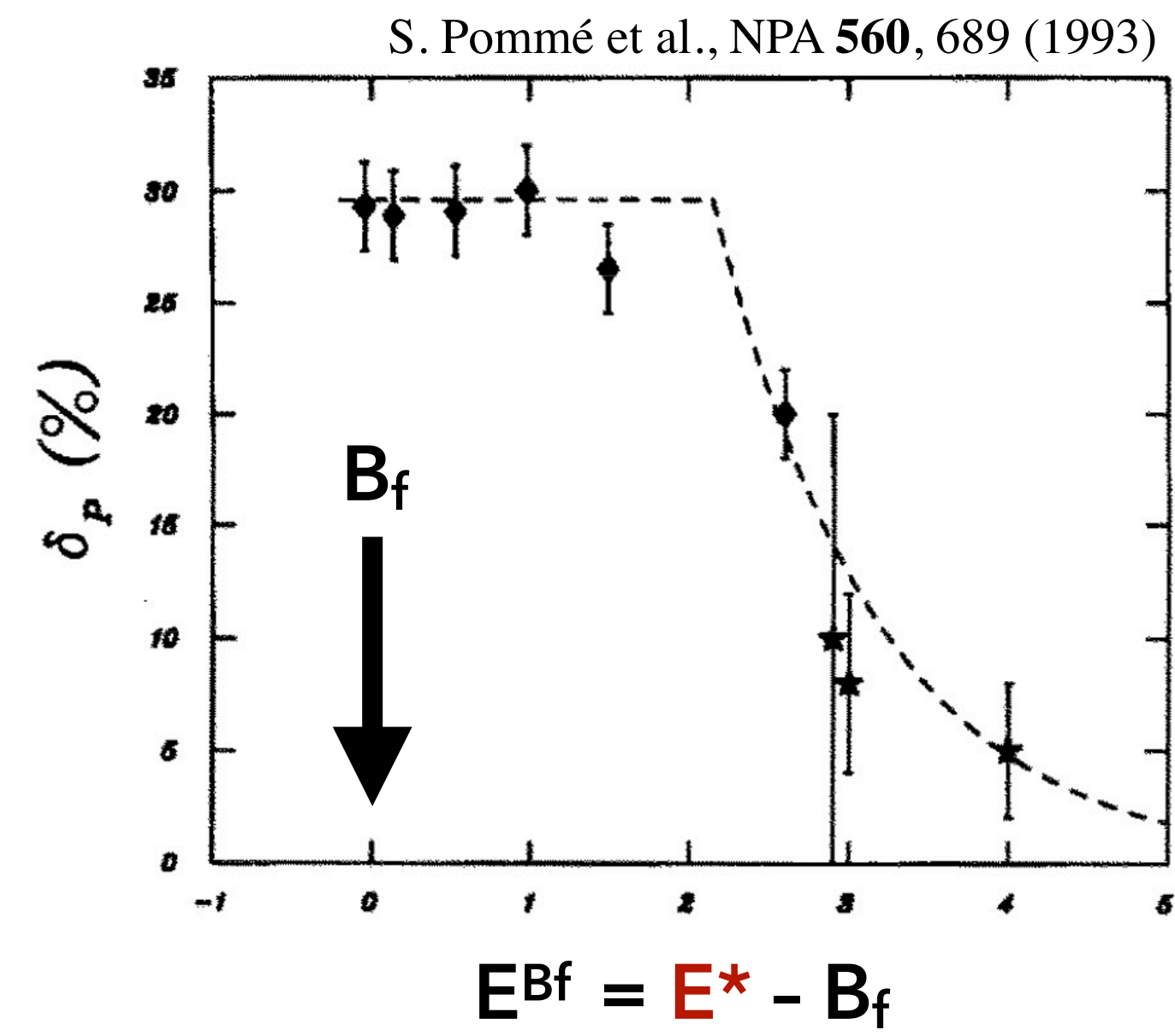
However, the effect is still there, because Bf is smaller than E^{dis}

And the typical differences between the saddle and minima in multi-humped barriers is ~3 MeV

240Pu: 5.99 2.94 4.91

238U: 5.08 2.75 5.64

Pairing as an observable: the even-odd effect in fission



$$E^{\text{dis}}(Z) + [E^{Bf} - \Delta] = G(Z) \ln(|\delta_Z|) \quad E^{Bf} > \Delta,$$
$$E^{\text{dis}}(Z) = G(Z) \ln(|\delta_Z|) \quad E^{Bf} \leq \Delta.$$

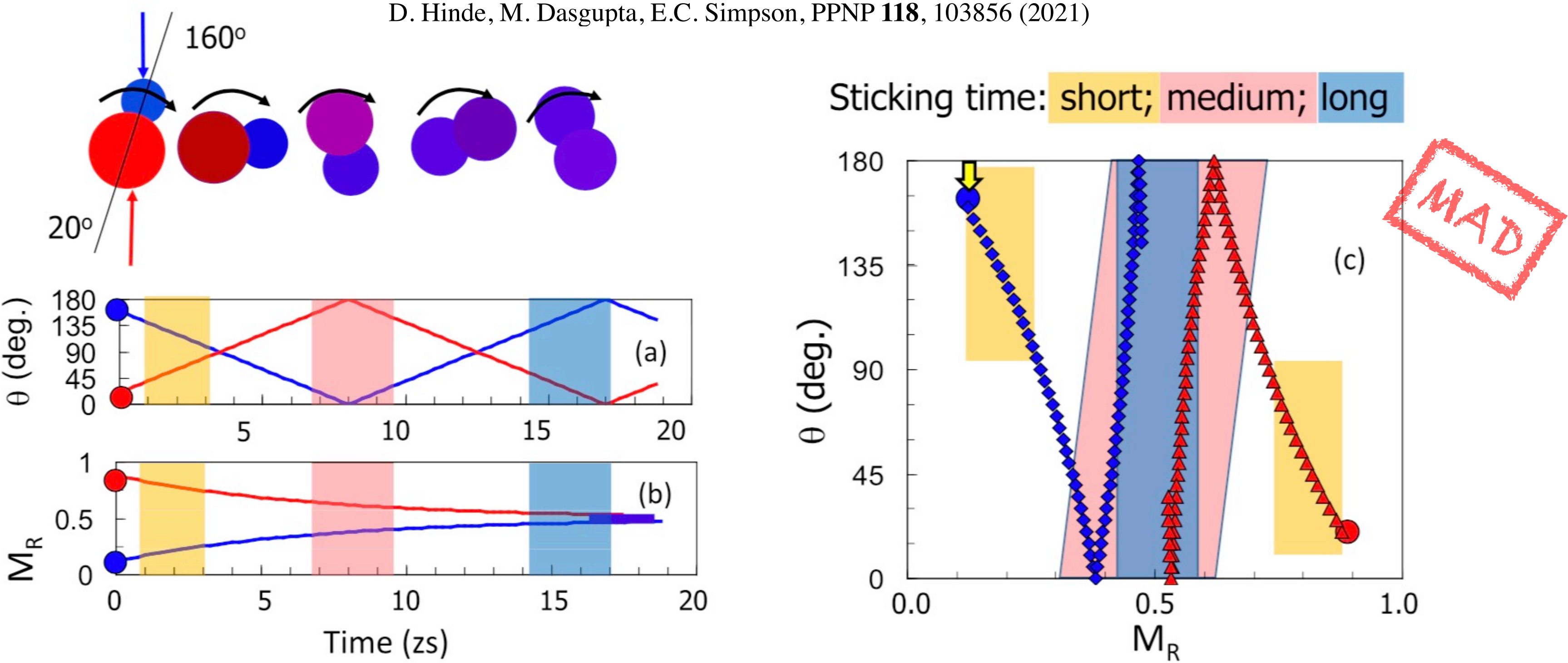
why the exponential descend after Δ ??
because of level densities:

$$N_{Z_1=e}^{ee}(Z_1) = \int_{-2\Delta_1}^{U_{tot}+2\Delta_2} \rho_1(U_1)_{(ee)} \rho_2(U_{tot} - U_1)_{(ee)} dU_1 + \int_{-\Delta_1}^{U_{tot}+\Delta_2} \rho_1(U_1)_{(eo)} \rho_2(U_{tot} - U_1)_{(eo)} dU_1, \quad (32)$$

$$N_{Z_1=o}^{ee}(Z_1) = \int_{-\Delta}^{U_{tot}-\Delta_2} \rho_1(U_1)_{(oe)} \rho_2(U_{tot} - U_1)_{(oe)} dU_1 + \int_0^{U_{tot}} \rho_1(U_1)_{(oo)} \rho_2(U_{tot} - U_1)_{(oo)} dU_1, \quad (33)$$

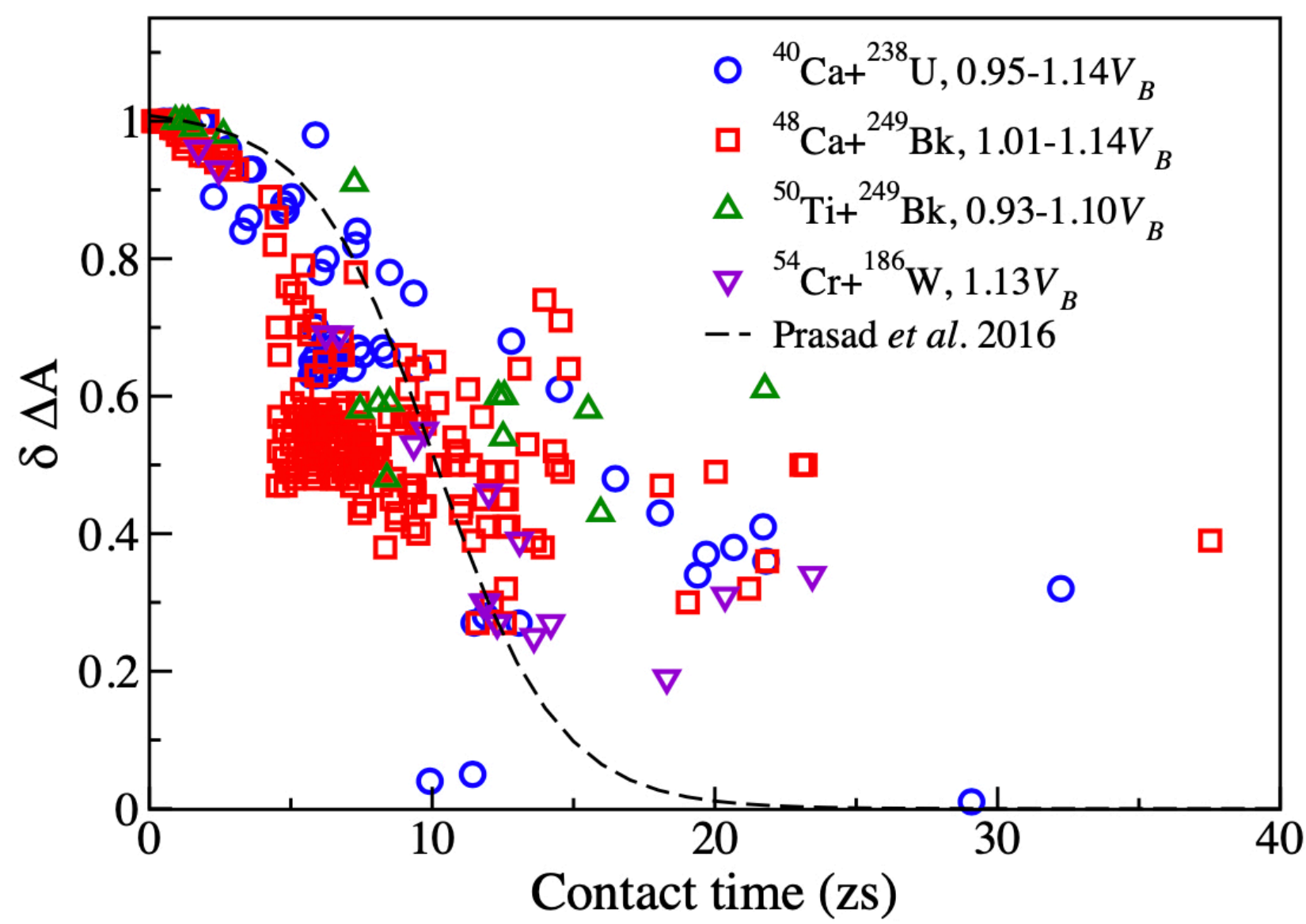
$$Y_{\text{even } Z_1}^{ee}(Z_1) = \frac{N_{\text{even } Z_1}^{ee}(Z_1)}{N_{\text{even } Z_1}^{ee}(Z_1) + N_{\text{odd } Z_1}^{ee}(Z_1)}.$$

B. Jurado & K.-H. Schmidt, JPG **42** (2015) 055101

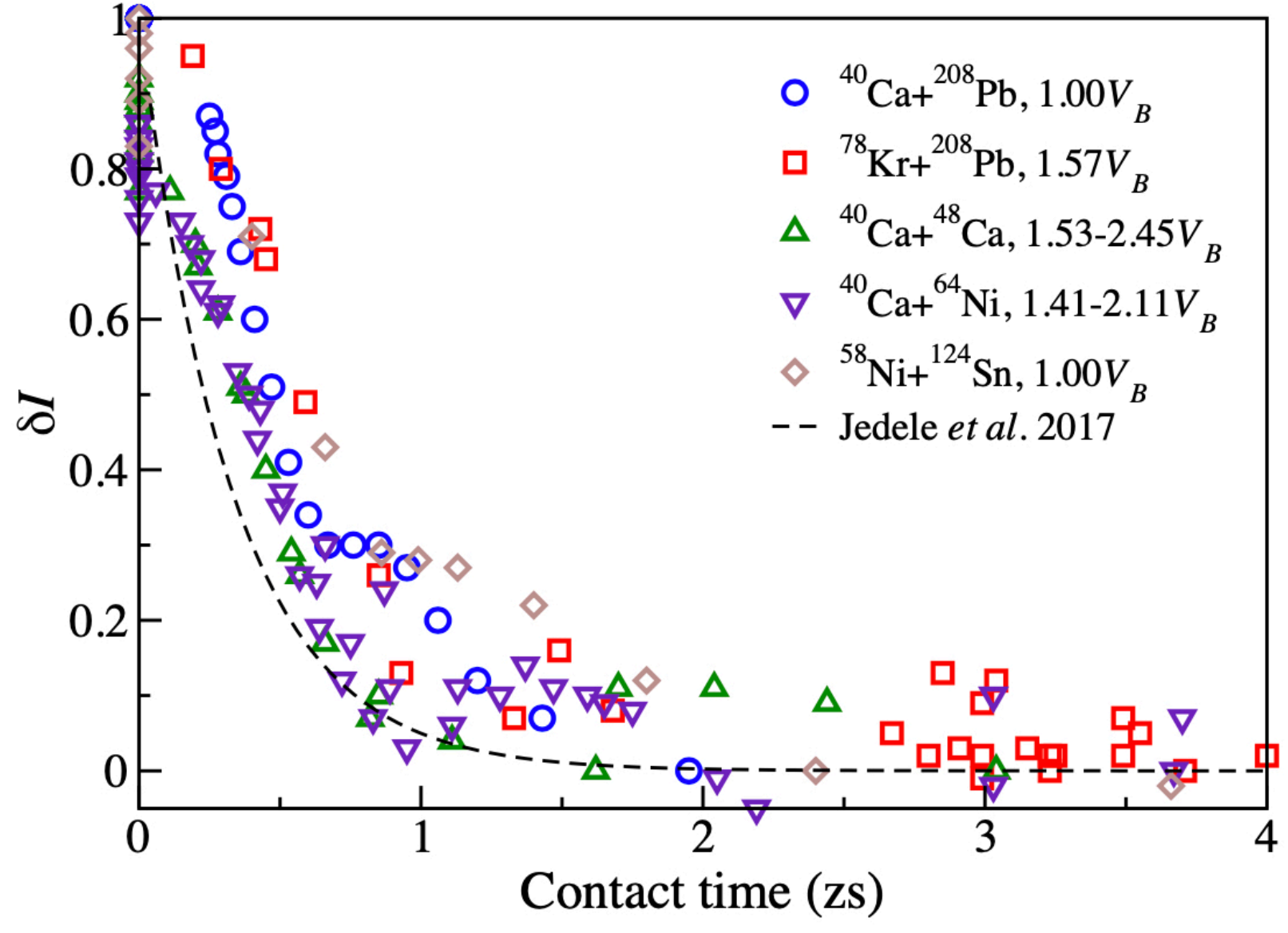


Being out of equilibrium, the emission angle and the mass drift keep track of the contact time.

C. Simenel, K. Godbey, A.S. Umar, PRL **124**, 212504 (2020)

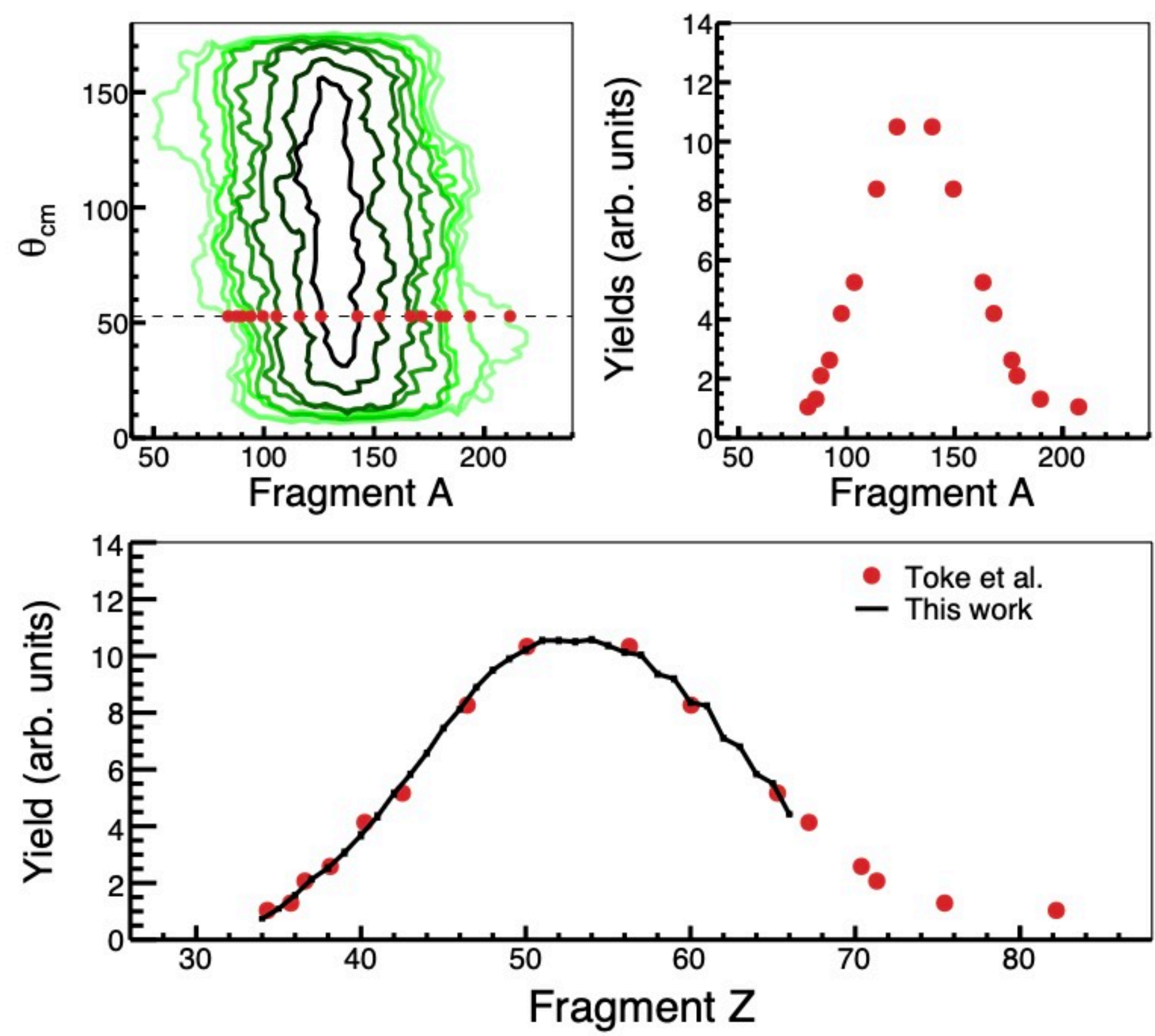
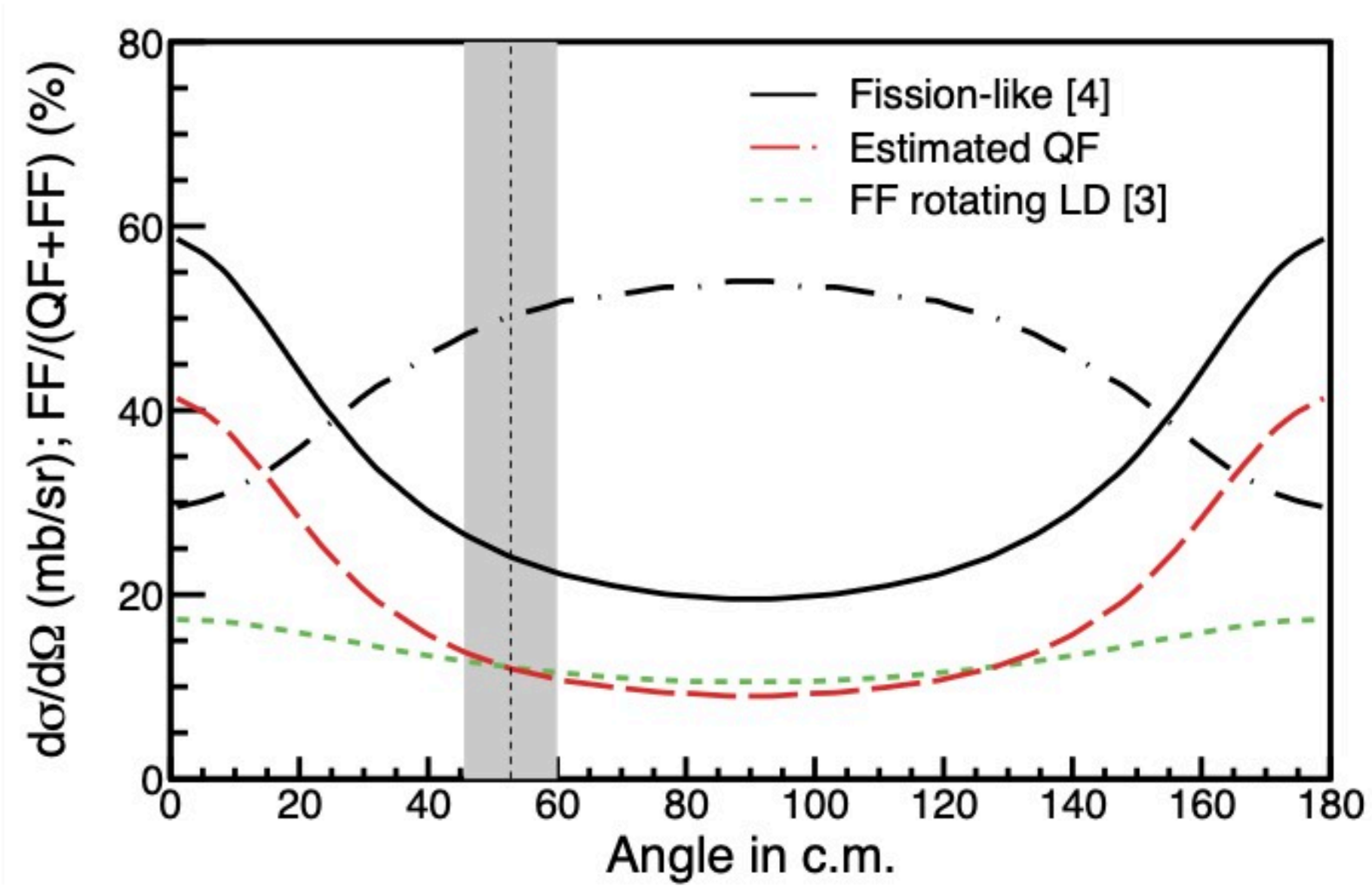


$$\delta \Delta A = \frac{|\Delta A|}{\Delta A_0} \quad \Delta A = A_1 - A_2$$
$$\Delta A_0 = A_{\text{beam}} - A_{\text{target}}$$

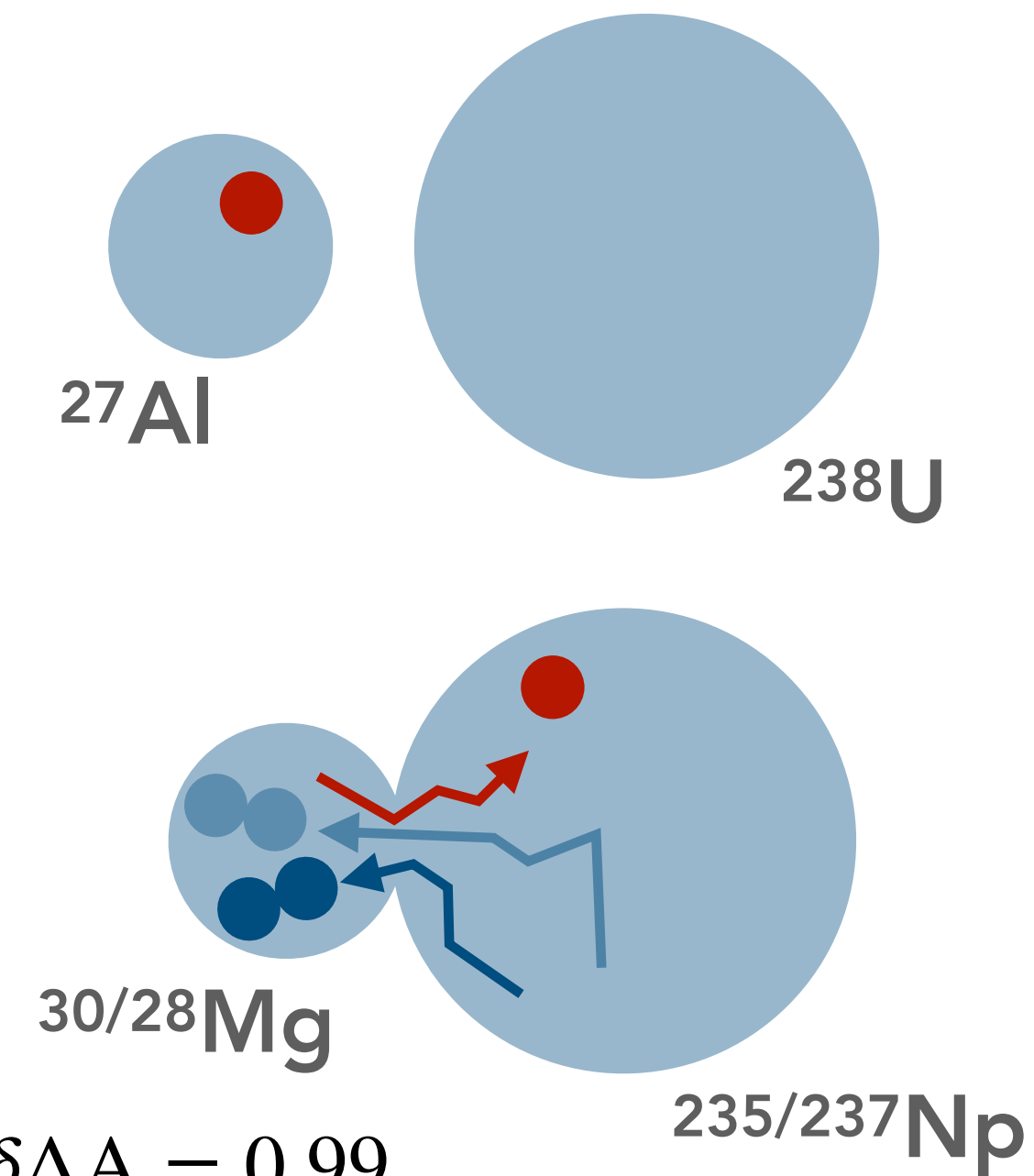
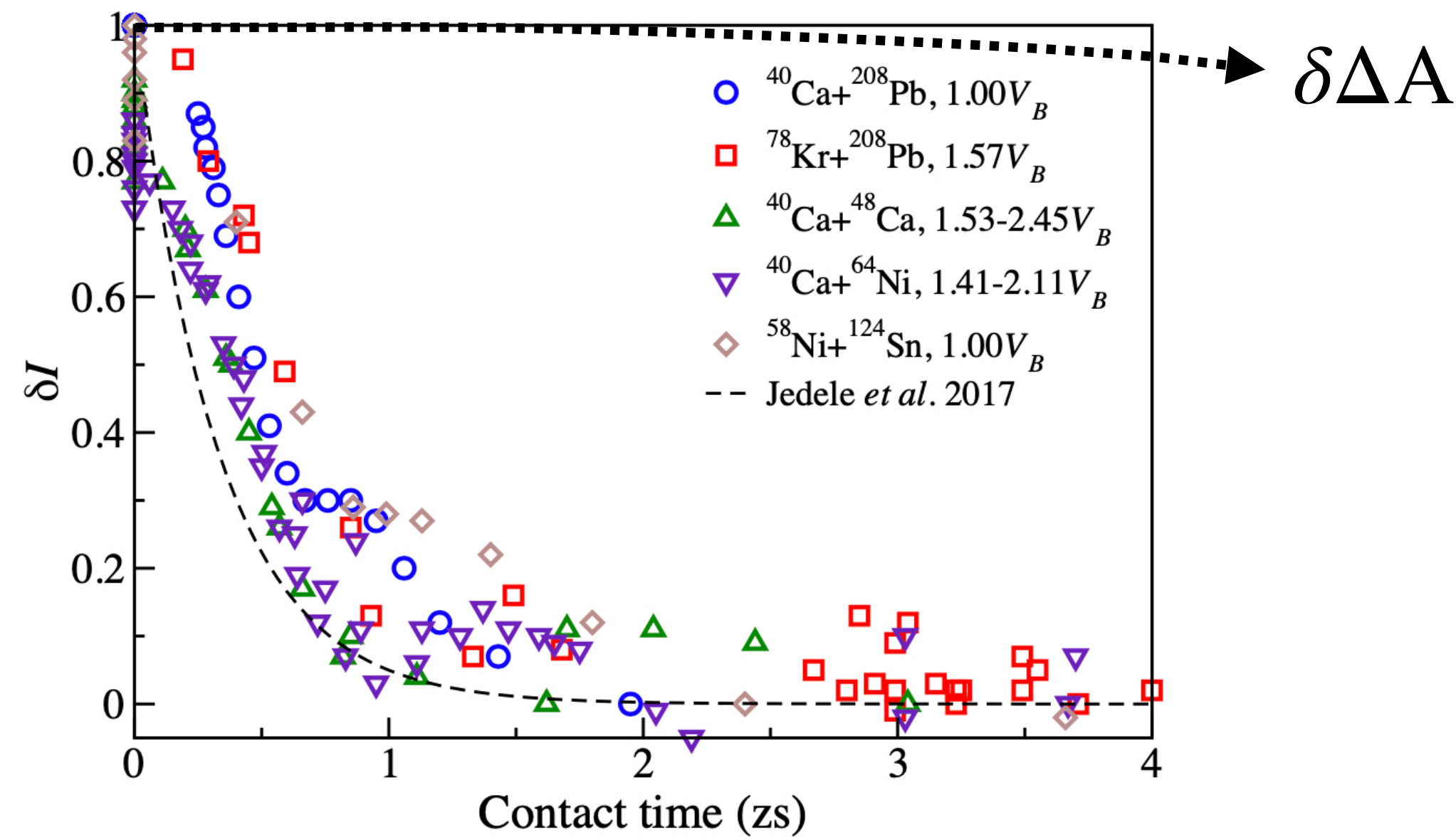


$$\delta I = \frac{|I - I_\infty|}{I_0 - I_\infty} \quad I = \left(\frac{N - Z}{A} \right)_1 - \left(\frac{N - Z}{A} \right)_2$$
$$I_\infty \approx 0 \quad I_0 = \left(\frac{N - Z}{A} \right)_{\text{beam}} - \left(\frac{N - Z}{A} \right)_{\text{target}}$$

For the purpose of this presentation, we will be following these like gospel.



Even-odd effect as a marker of nucleon dynamics

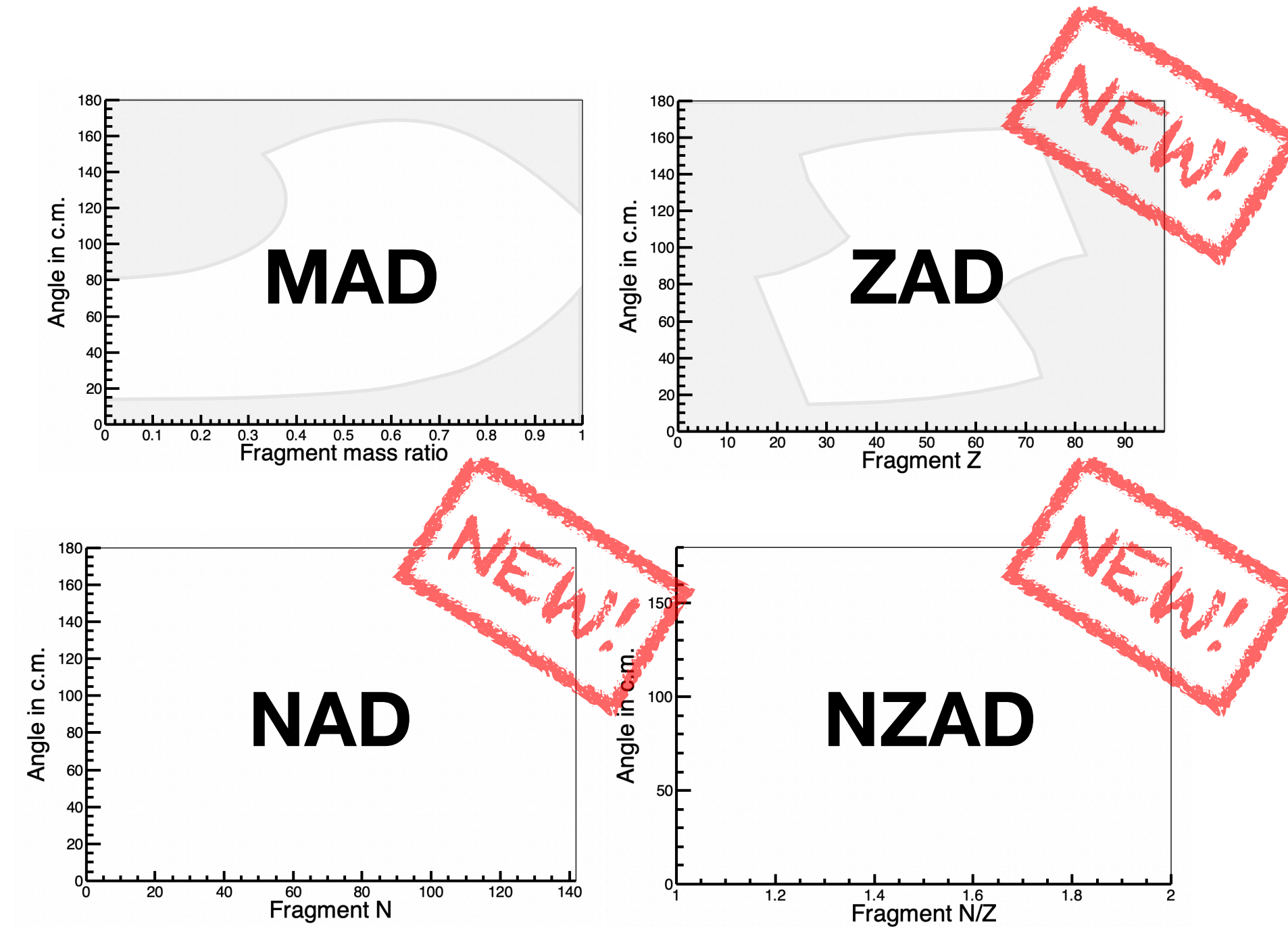


$^{28}\text{Mg} \delta I = 0.37, \delta\Delta A = 0.99$

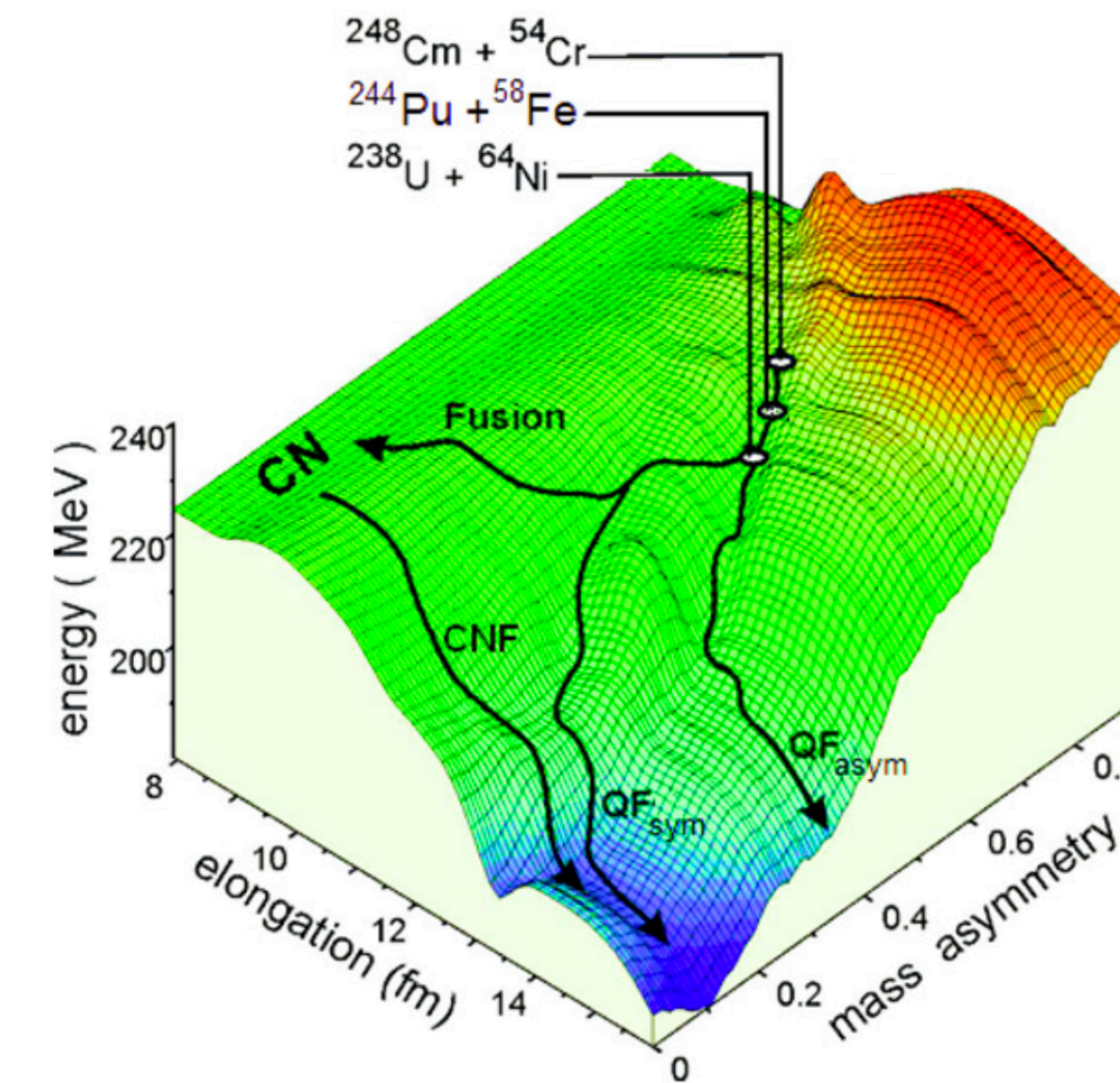
$^{30}\text{Mg} \delta I = 0.05, \delta\Delta A = 0.97$

- How can we end up with an odd-Z heavy fragment when the mass drift moves nucleons from the heavy to the light partner?
- **Isospin equilibration is very fast compared to the mass drift.**
- The ever-single proton can work as a marker to track proton dynamics.

New proposal at VAMOS/GANIL

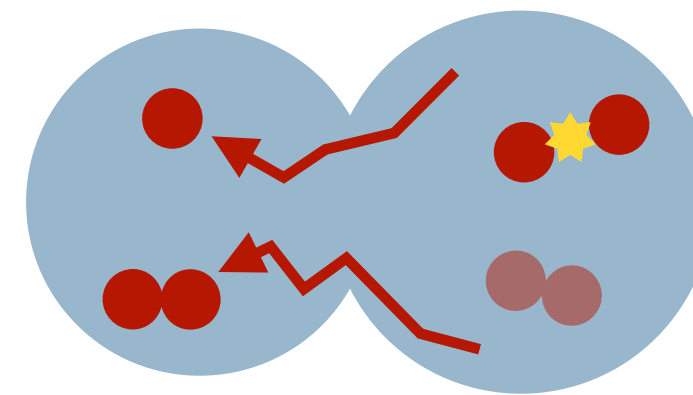
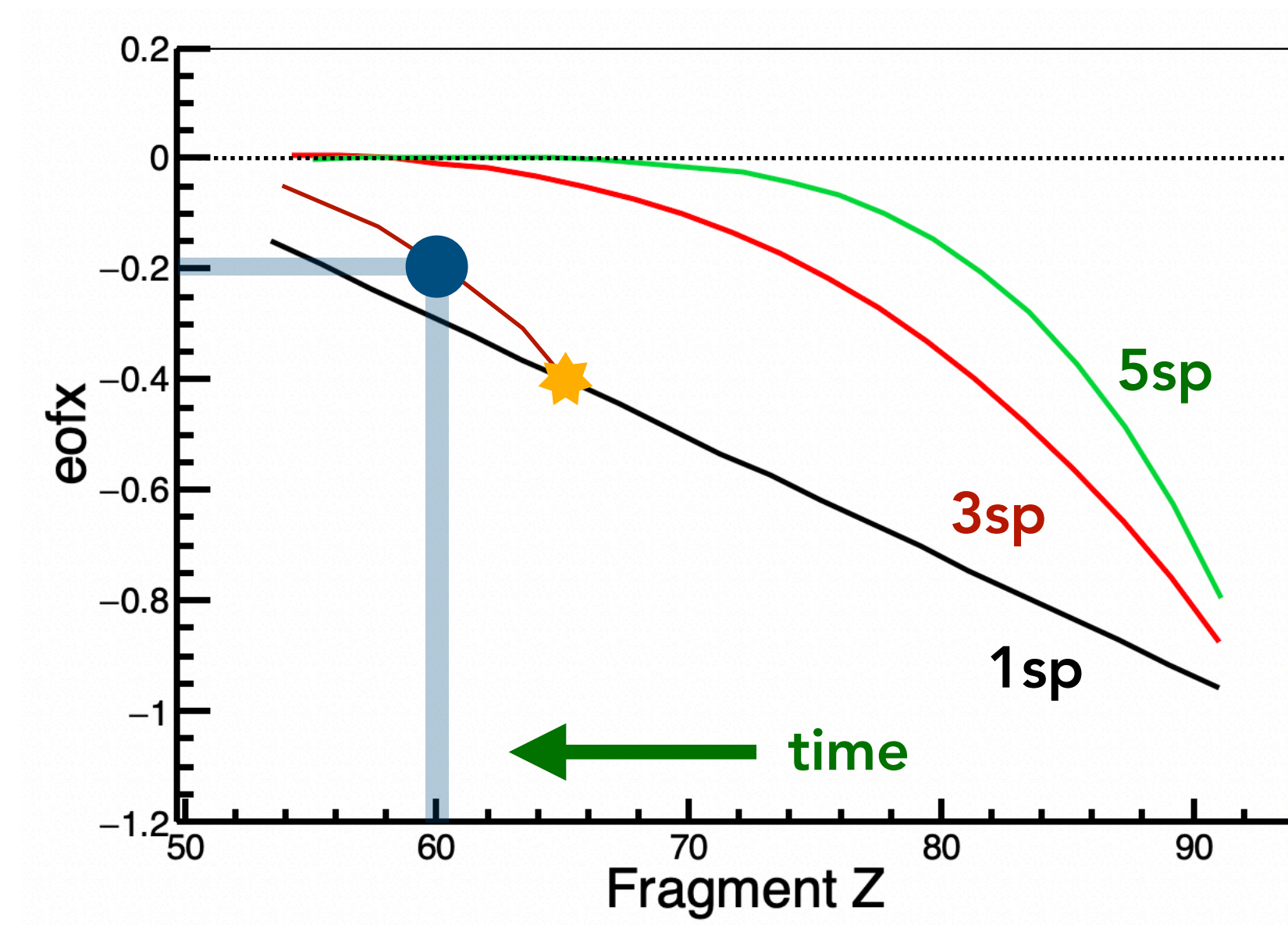


E.M. Kozulin et al., PLB **686**, 227 (2010)



- We want to go beyond **MAD** and study the evolution and dynamics of the **Z, N, and N/Z drift** of the fragments.
- With TXE, TKE, and the neutron evaporation, we can access the energetics and thus the **configuration at scission and a hint of the PES**.

Even-odd effect as a marker of nucleon dynamics

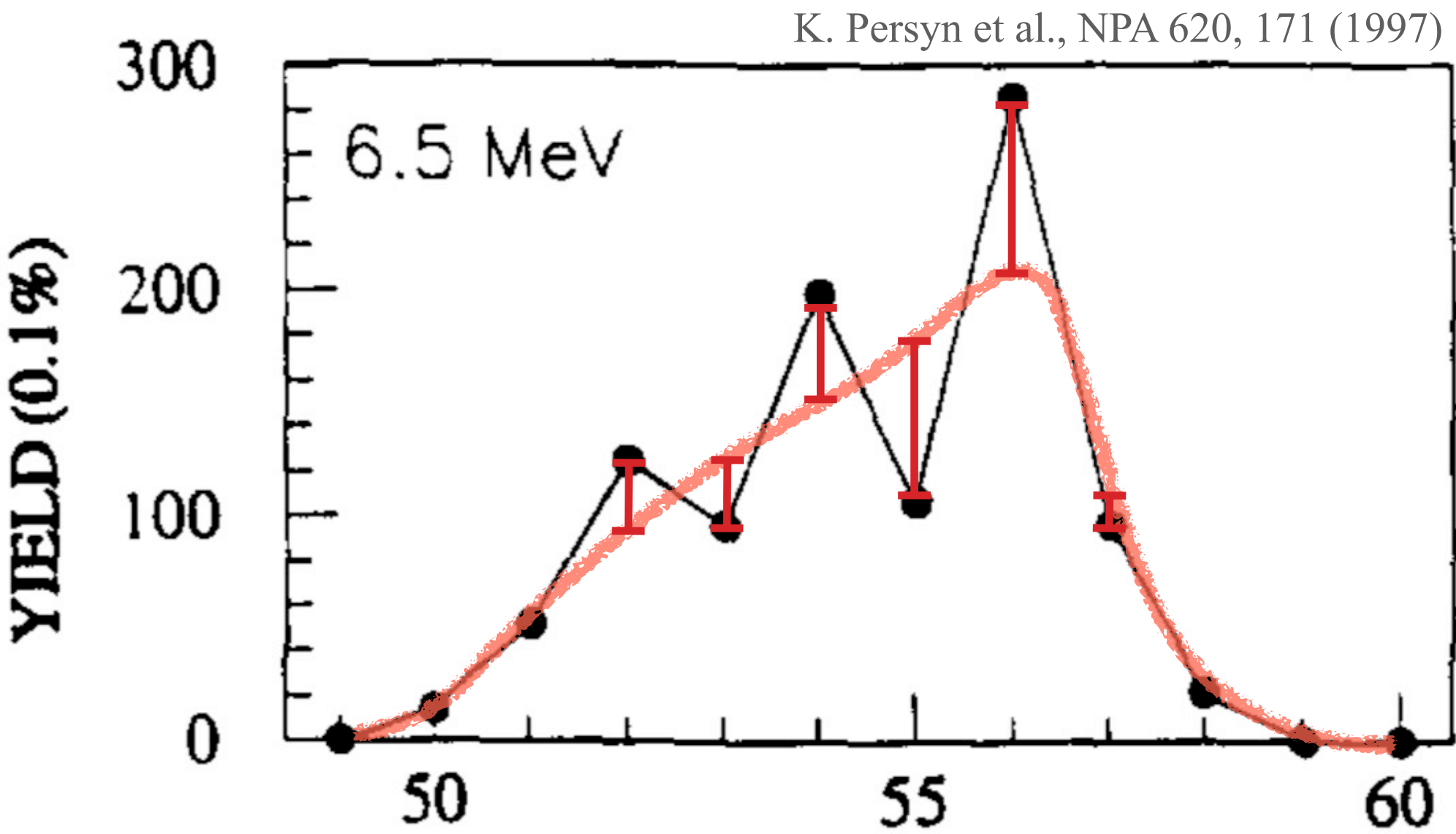


We can reproduce the data if ***just one proton pair breaks*** at the end of the contact time.

From global to local

As data started to amount, the access to the evolution of the *eofx* as a function of the split was possible.

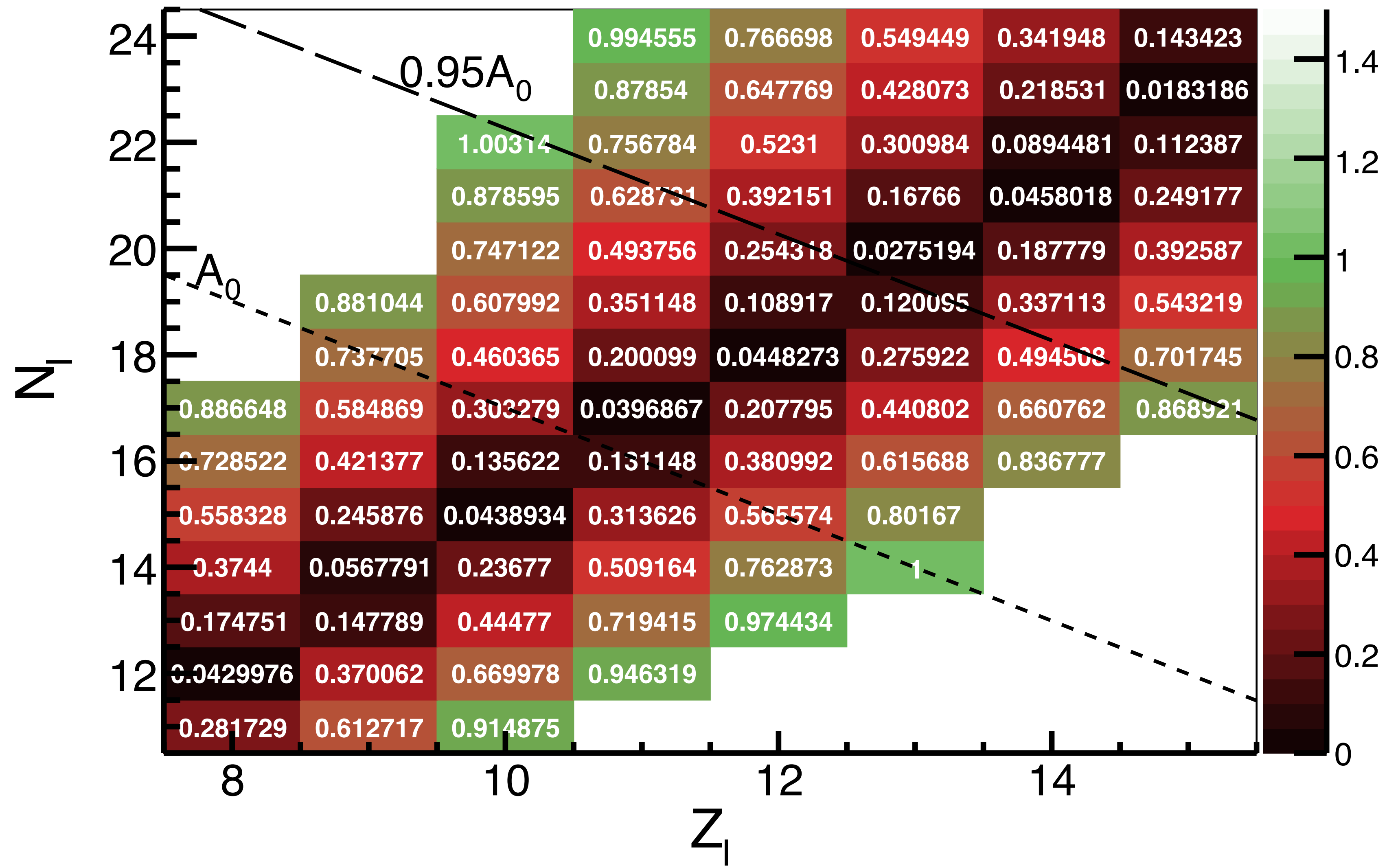
But how can one calculate the local *eofx*?

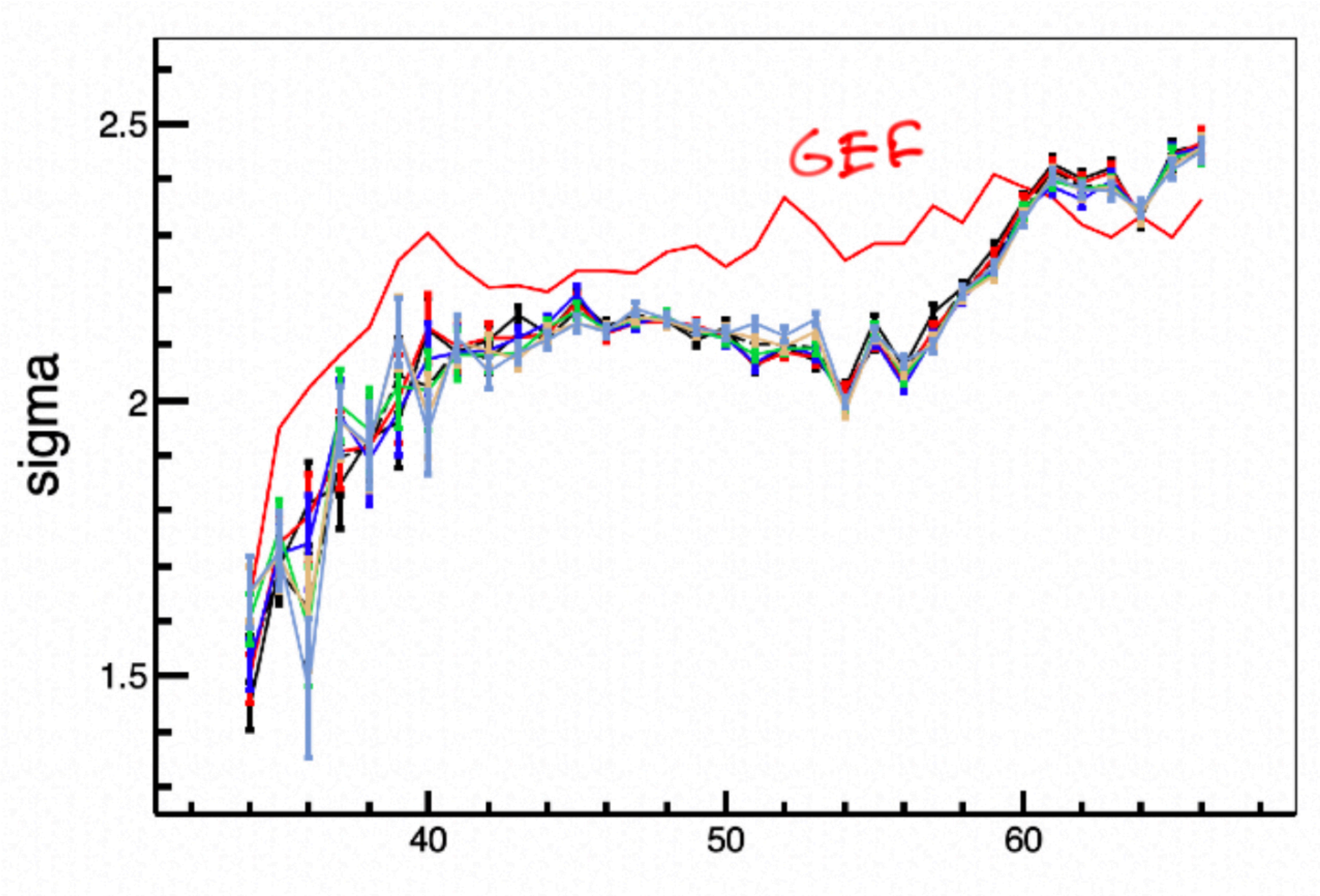


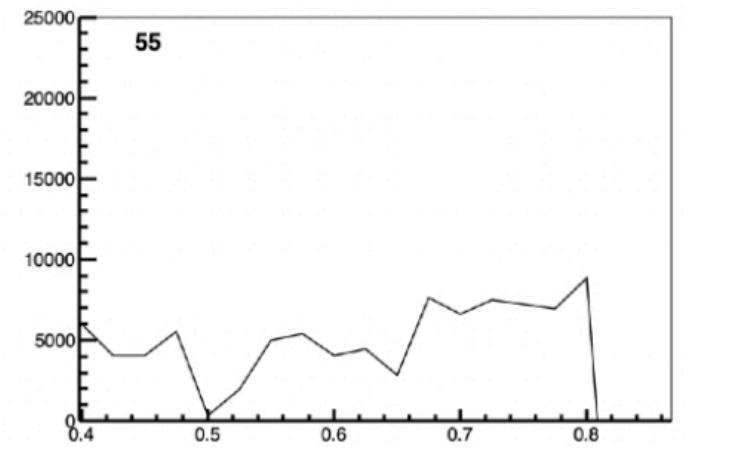
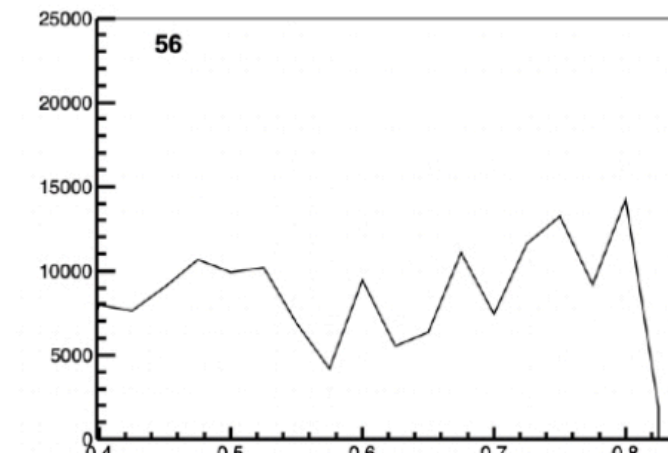
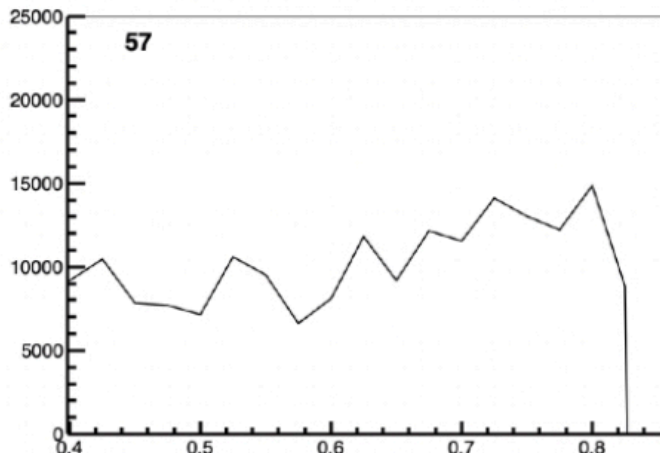
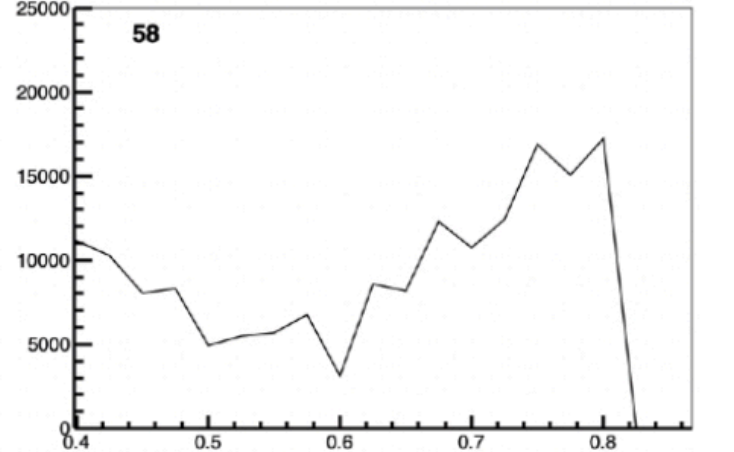
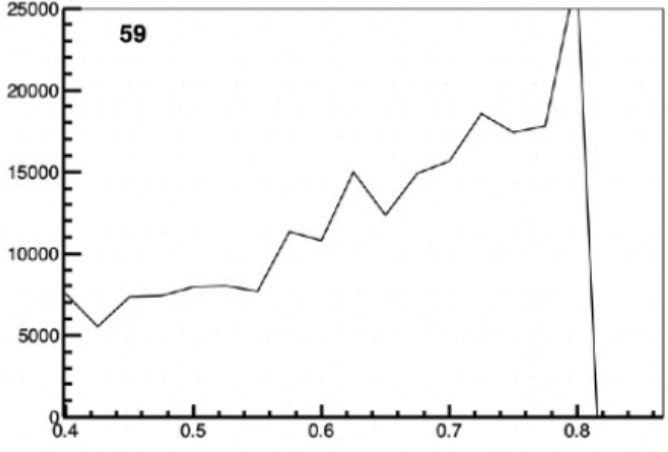
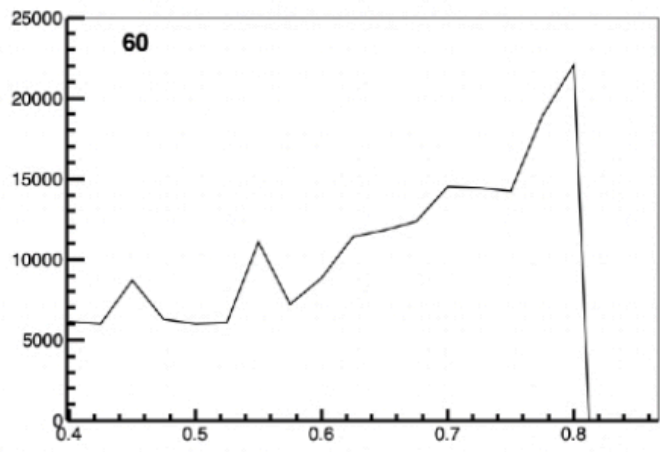
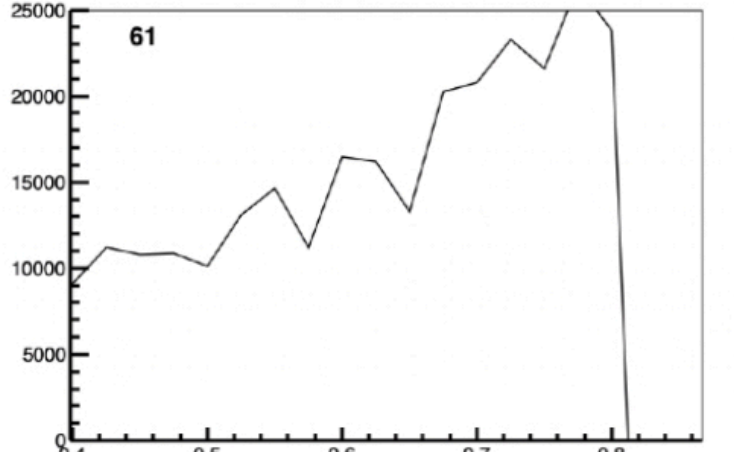
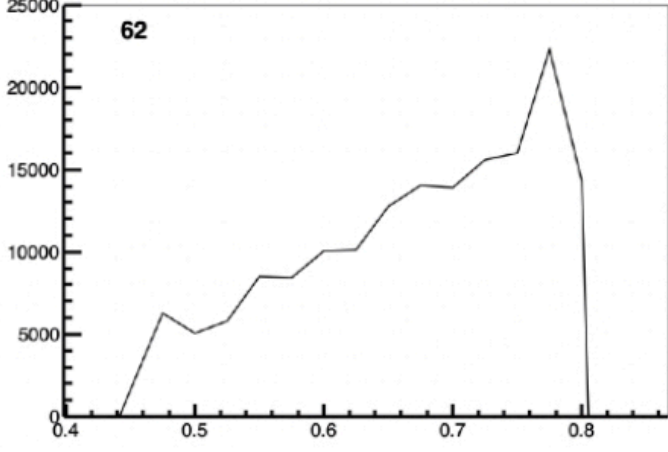
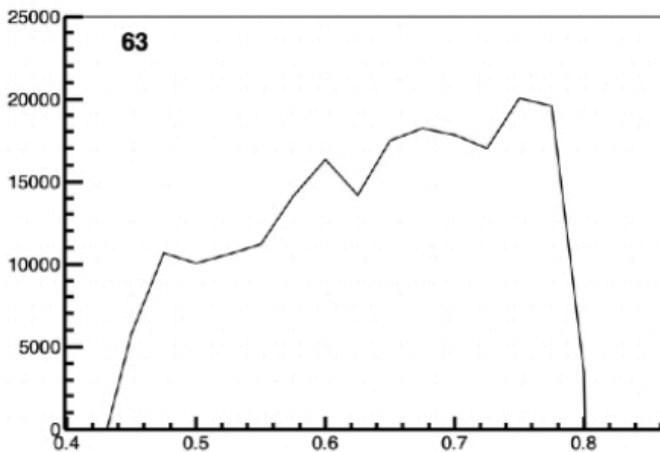
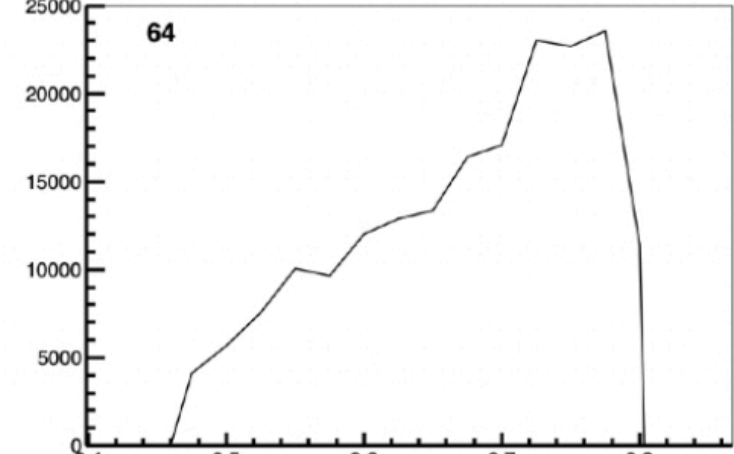
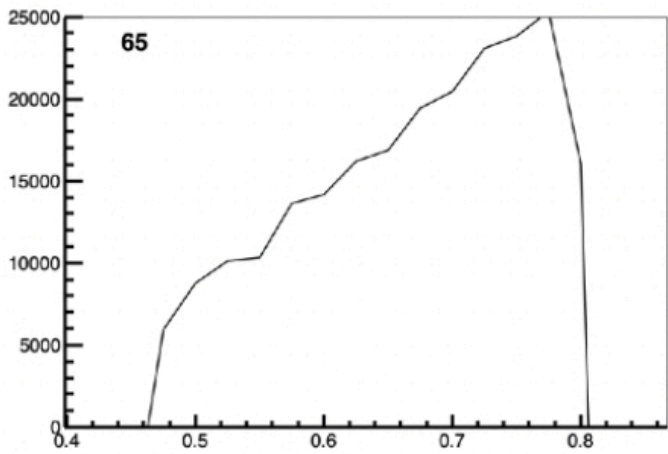
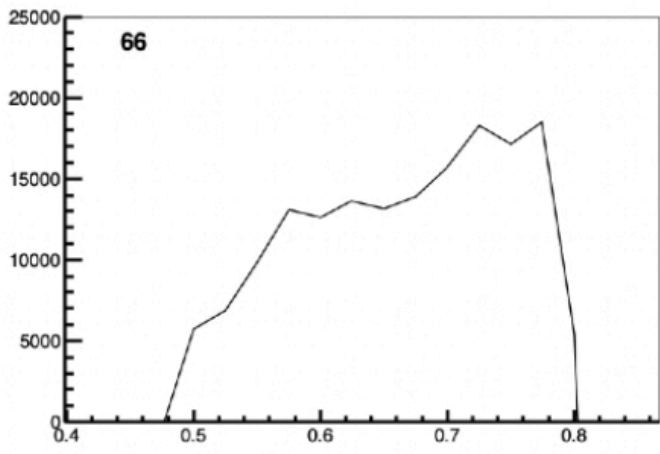
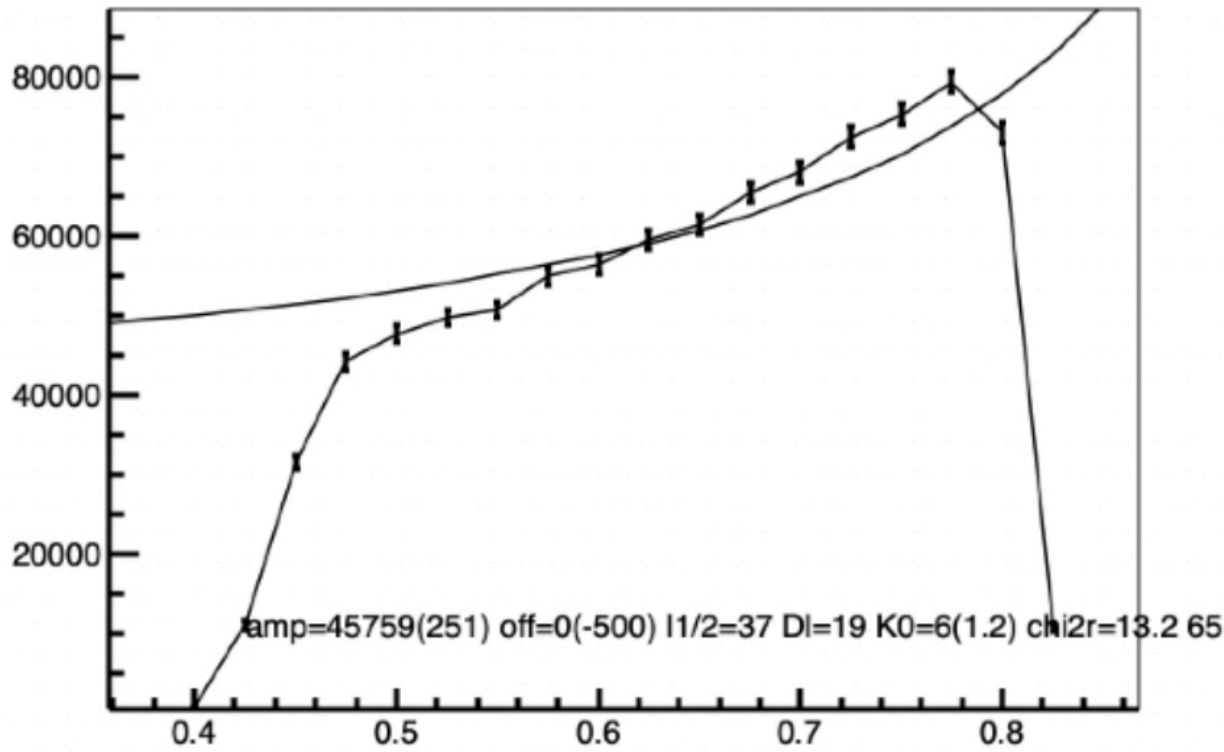
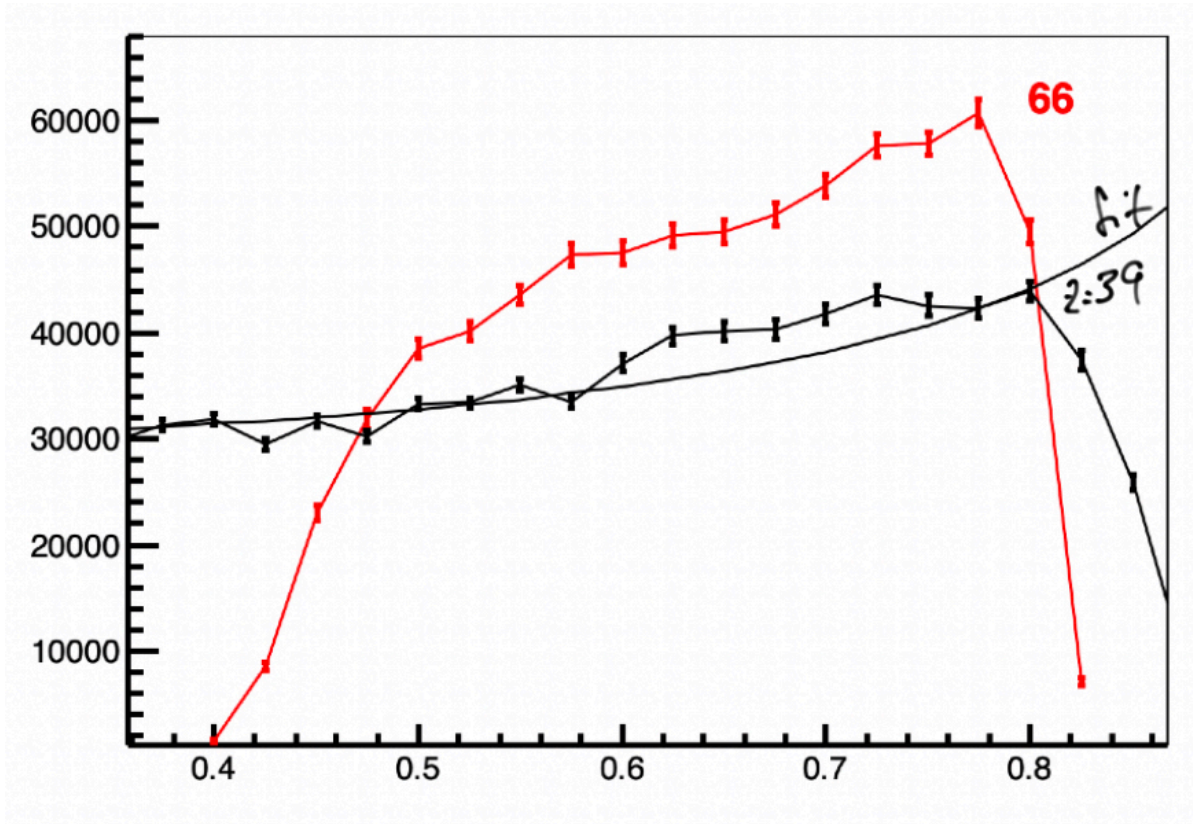
There are many methods, but the most widely used is that of Tracy et al:

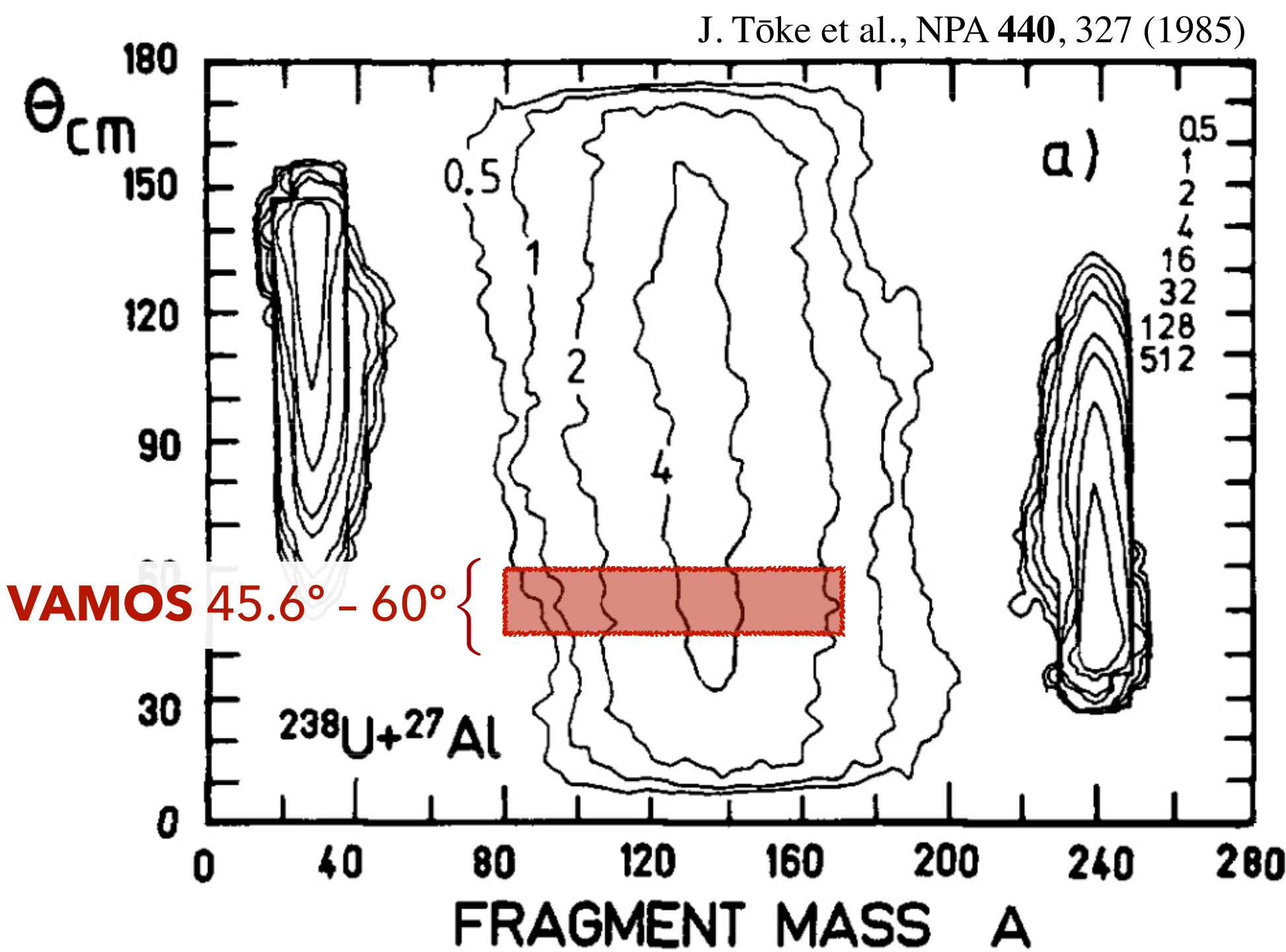
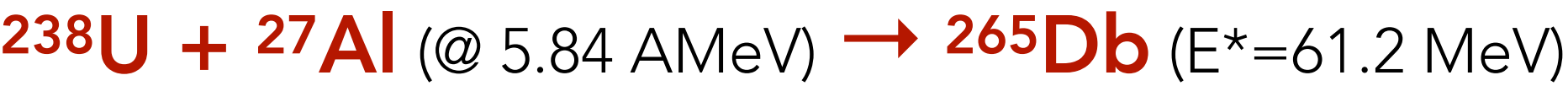
$$\delta_z(Z + 1.5) = \frac{(-1)^Z}{8} \left([\ln(Y_{Z+3}) - \ln(Y_Z)] - 3[\ln(Y_{Z+2}) - \ln(Y_{Z+1})] \right)$$

B. L. Tracy et al., PRC 5, 222 (1972)

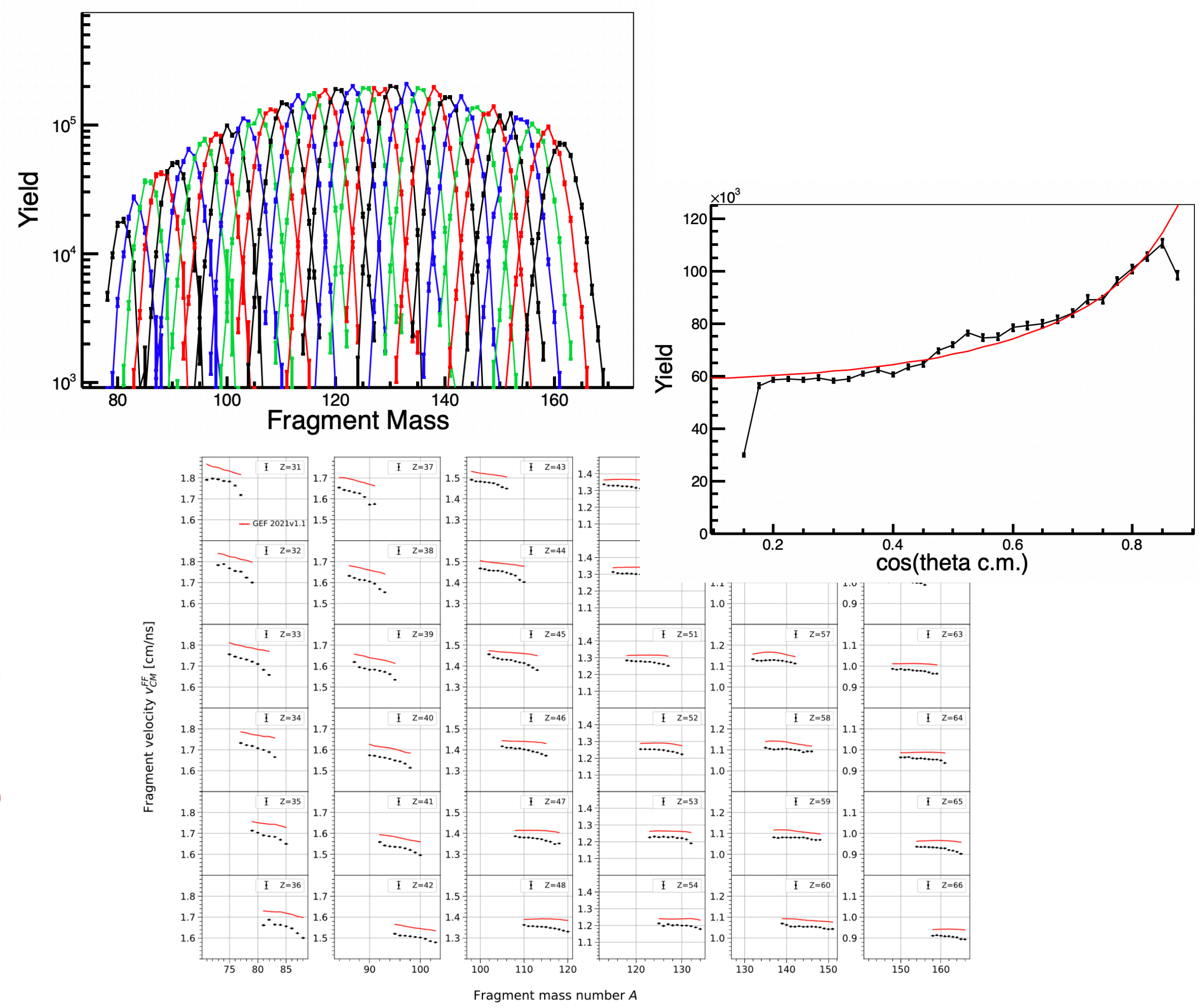








- VAMOS
- FRAGMENT MASS POST-n (78 - 170)
 - FRAGMENT Z (36 - 66)
 - FRAGMENT N POST-n (42 - 104)
 - FRAGMENT N/Z POST-n
 - FRAGMENT V_{cm}



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