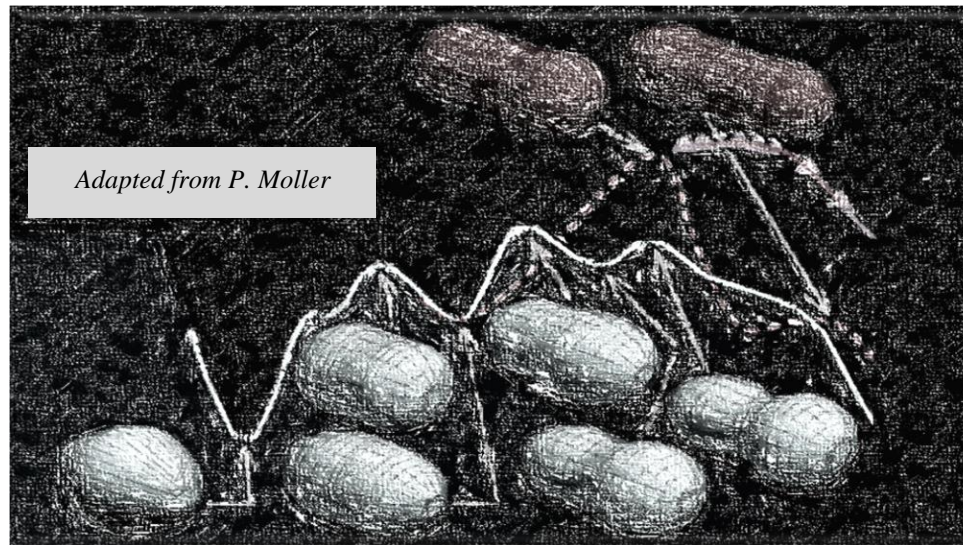


# *Fission across the nuclear chart:*

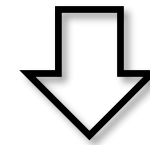
## ***Experimental Evidence for Common Driving Effects in Low-Energy Fission from Sublead to Actinides***



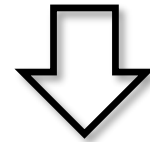
*Fresh insight from recent experiments on low-energy fission*



A photograph of the situation at scission is the “closest” one can approach the fission process



Trace the story back *via* models

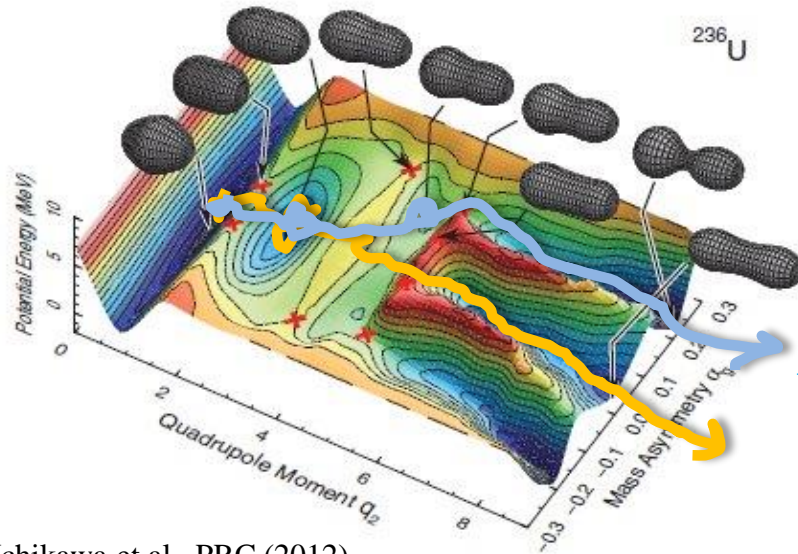


Insight into

- ☛ the potential energy landscape  
(*e.g.* shell effects at large deformation)
- ☛ the dynamics  
(*e.g.* viscosity, inertia)

**FUNDAMENTAL NUCLEAR PROPERTIES**

# Fission: A journey on the nucleus potential energy landscape



Ichikawa et al., PRC (2012)

TODAY

PRIMARY

$A_{1,2}^*, Z_{1,2}^*,$   
 $E_{1,2 \text{ kin}}^*, L_{1,2}^*$

$A_{1,2}^*, Z_{1,2}^*,$   
 $E_{1,2 \text{ kin}}^*, L_{1,2}^*$



$n, \gamma$

$n, \gamma$



SECONDARY

$A_{1,2}', Z_{1,2}',$   
 $E_{1,2 \text{ kin}}, L_{1,2}$

$A_{1,2}, Z_{1,2},$   
 $E_{1,2 \text{ kin}}, L_{1,2}$

conservation laws & kinematics

## OBSERVABLES

- ✓ Measure of  $(A, Z)$
- ✓ Measure of  $E_{1,2 \text{ kin}}$
- ✓ Measure of  $M_n$
- ✓ Measure of  $M_\gamma$

## PHYSICS

- ☛ symmetric or asymmetric ( $\sim$  valleys)
- ☛ role of neutrons vs. protons
- ☛ Total Kinetic Energy  $\sim$  scission configuration
- ☛ excitation energy, and sharing, at scission
- $\approx$  angular momentum, and sharing, at scission

# Experimental status on fission observables (1950-2012)

## 1950-2000: Mass distributions

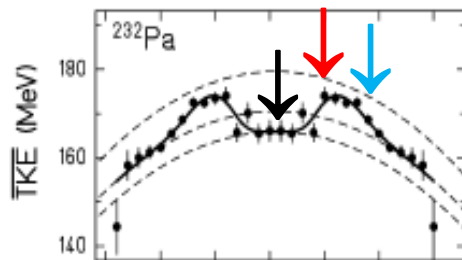
- ☐ Low-energy fission is asymmetric in actinides
- ☐ Heavy fragment « sitting » at  $A \sim 130-150$

*due to shell stabilized fragments*

- $S1$  mode attracted by  $N=82$  (sph. shell)
- $S2$  mode attracted by  $N \sim 88$  (def. shell)
- $SL$  mode due to macroscopic energy

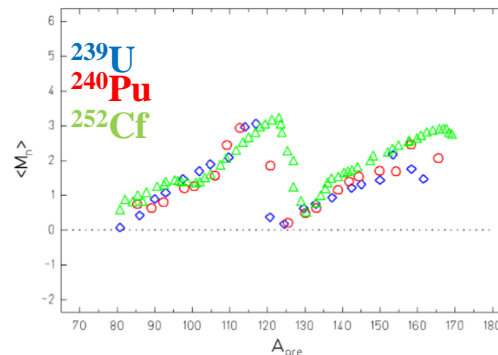


- ☐ TKE confirmation



Schmidt et al., NPA (2000)

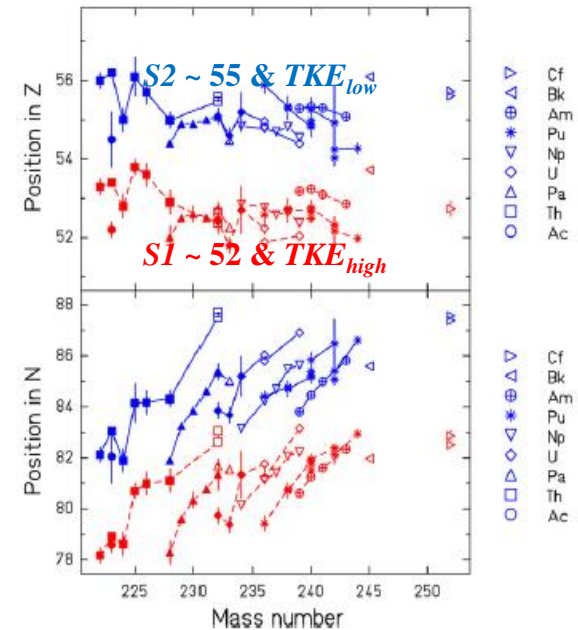
## ~1960-present: Neutrons



- ☐ Sawtooth shape of  $M_n = f(A)$   
 $N \sim 82$  and/or  $Z \sim 50$  (sph. shell)

## 2000 on: Charge distributions

- ☐ Heavy fragment « sitting » at  
 $Z \sim 52$  in  $S1$   
 $Z \sim 55$  in  $S2$



Bockstiegel et al., NPA (2008)

⇒ **why are these  $Z$  favored?**  
shell(s) behind?



⇒ **neutron vs. proton role?**

**Need  $A$  and  $Z$**   
**with unique precision**  
⇒ isotopic ( $N, Z$ ) information

**VAMOS@GANIL**

**and**

**SOFIA@GSI**

**Uniquely resolved ( $A, Z$ ) distributions + *Total Kinetic Energies***

for various systems ranging from Th to Cf

with excitation energy of  $E^* = 7$  up to 40 MeV

- ❑ **Shell effects in the nascent fragments** play a key role in driving asymmetric fission
- ❑ **Specific stabilized proton configurations** dominate Strength of neutron effects to be revisited

*S1* observed around 52 is due to  $Z = 50$  shell  
(supported by high TKE)

*S2* observed around 55 due to stable octupole configurations at ( $Z \sim 54$ )  
(Scamps and Simenel, *Nature* 564 (2018) 382)

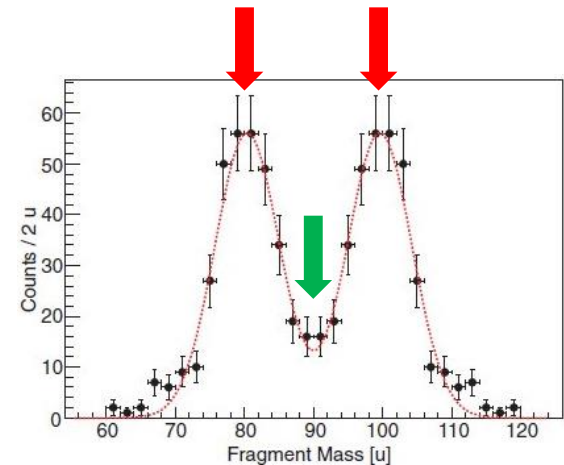
# What about fission properties in other regions of the nuclear chart?

Current knowledge (from actinides):

Shell effects in the nascent fragments play a key role...

BUT how to reconcile it with observation of asymmetric low-energy fission of  $^{180}\text{Hg}$  ?

**expected:**  $2 \times {}^{90}\text{Zr}_{50}$   
**observed:**  $\sim A_{1,2} \sim 80 + 100$



Andreyev et al., PRL (2010)

Intense experimental/theoretical work

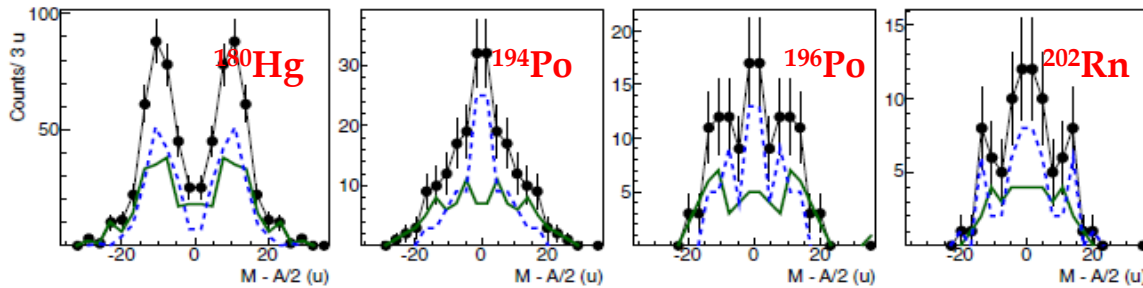


Can an independent asymmetric fission “island” be delineated?  
What’s its origin? Which (shell) effect(s) drive(s) it?

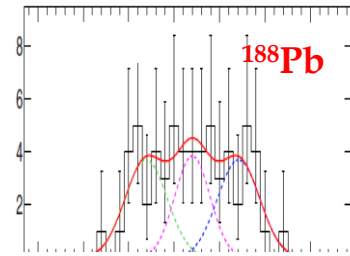


# Status on fission measurements in the n-deficient region around lead

## □ $\beta$ -delayed @ ISOLDE/CERN ( $E^* \sim \text{few MeV}$ )

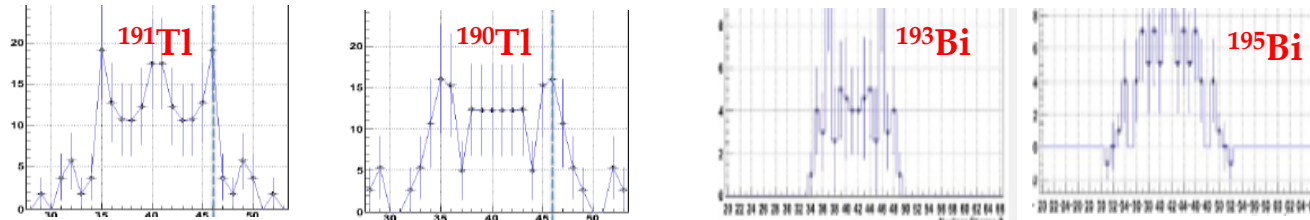


Ghys et al., PRC (2014)



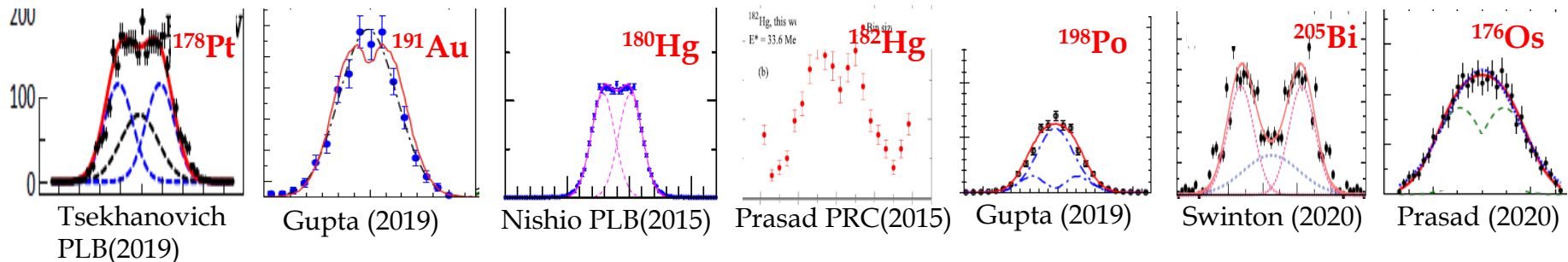
Andel et al., PRC (2020)

## □ Electromagnetic-induced @ SOFIA/GSI ( $E^* \sim 12 \text{ MeV}$ )



Gorbinet for SOFIA2, WFDEPNG (2014)

## □ Fusion-induced @ worldwide ( $E^* \sim 25\text{-}50 \text{ MeV}$ )



Tsekhanovich  
PLB(2019)

Gupta (2019)

Nishio PLB(2015)

Prasad PRC(2015)

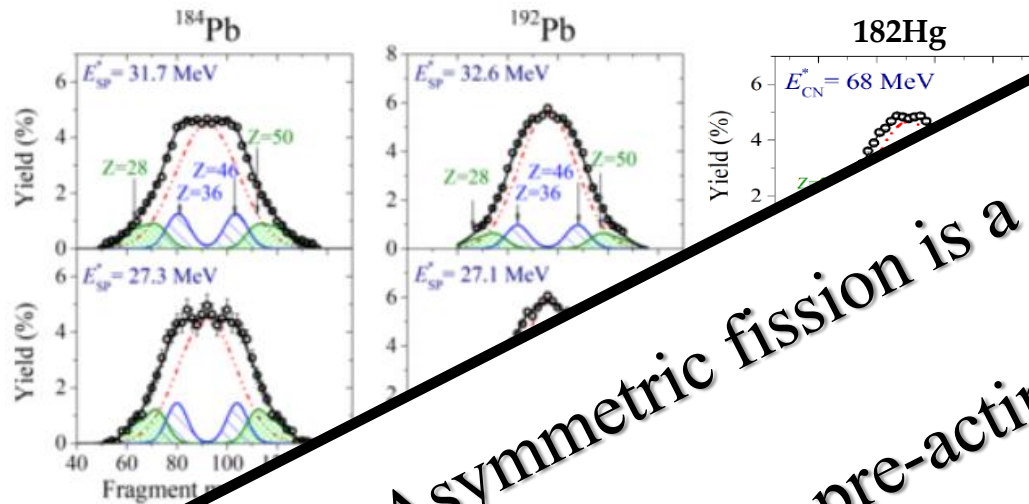
Gupta (2019)

Swinton (2020)

Prasad (2020)

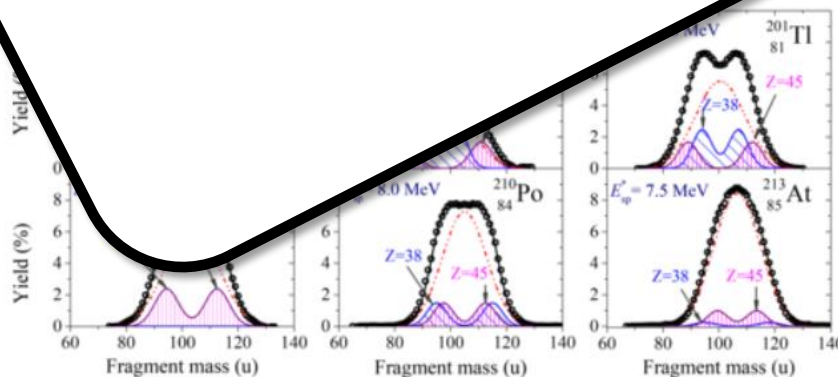


# Most recent experimental results from fusion-fission



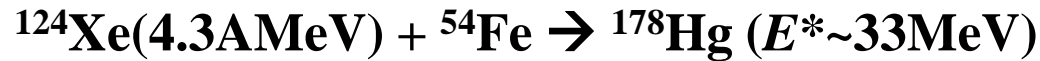
Asymmetric fission is a general feature in the pre-actinide region ... but why?

ambiguous  
 independent,  
 ions-dependent,  
 beam-dependent,  
 no "solid" theory behind)



➡ Crucial need of information of fragment (N, Z) content

➡ Benefit from the VAMOS@GANIL specific capabilities within the approach of fusion-fission in inverse kinematics



*...challenging identification due to slow ( $\sim 1\text{-}3\text{A MeV}$ ) fragments...*



**Completely new observables  
for fission of pre-actinides**

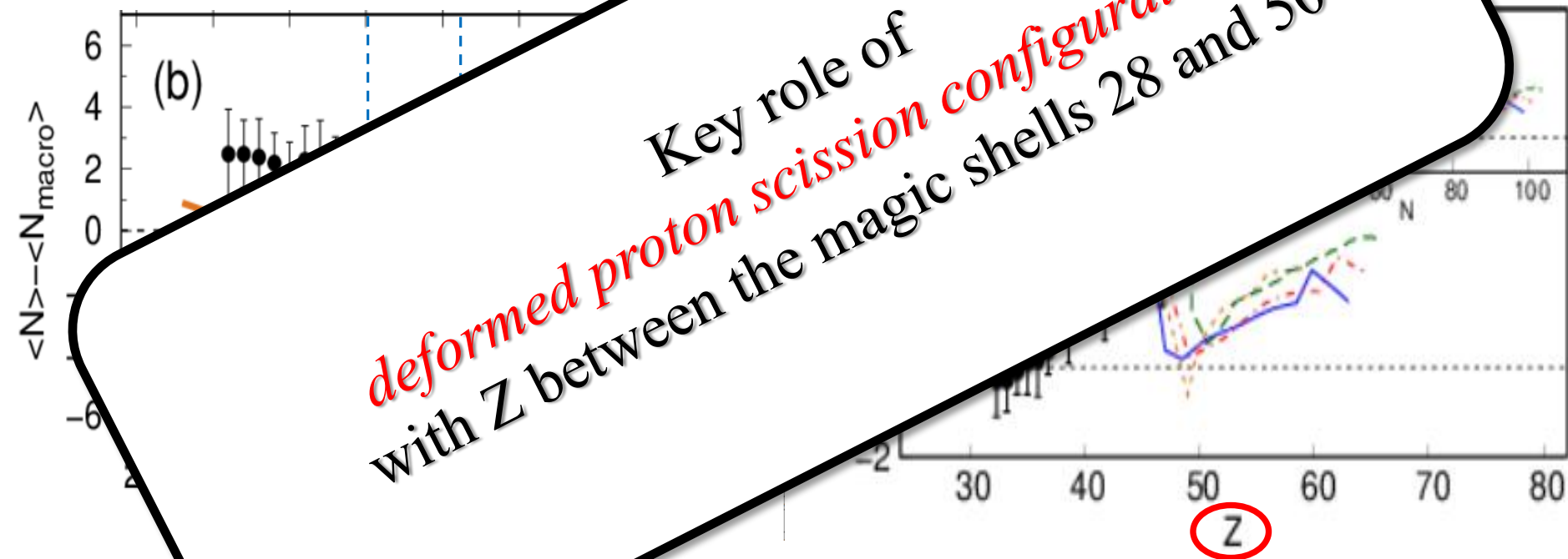
# Results on low-energy fission of $^{178}\text{Hg}$ @ VAMOS (1)



# Results on low-energy fission of $^{178}\text{Hg}$ @ VA2022 (2)

*Is it consistent with the conclusions of ...*

*Microscopic contribution to n-rich ...*



⇒ Same ... distribution to  $N/Z$  ... for different  $N$ 's

⇒ Same magnitude of shape relaxation at given Z for different  $N$ 's

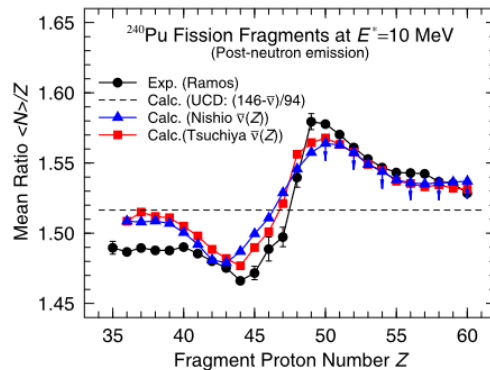
e.g. for  $Z=42$   $\begin{cases} N \sim 56 \text{ for } ^{178}\text{Hg} \\ N \sim 66 \text{ for actinides} \end{cases}$

... and more in C.S. et al., PRL 126, 132502(2021)

# Crucial need of elaborate theory for elucidating the role of critical orbitals/states/configurations/shells

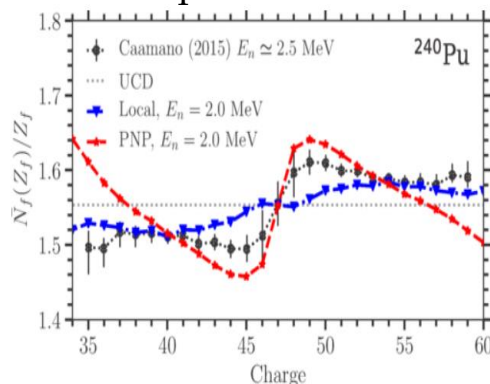
**N/Z**

## Macro-microscopic 6D BSM



P. Moller and C.S., PLB 812(2021)136017

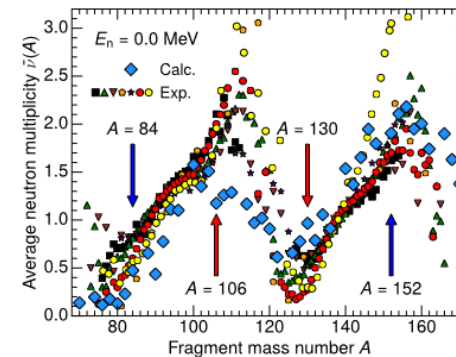
## Microscopic TDGCM+GOA



M. Verriere et al., PRC 103(2021)054602

**$M_n$**

## Macro-microscopic 5D BSM



M. Albertsson et al., PLB 803(2020)135276

S no.	$\eta$	$E^*$	$E_n$	$q_{zz}$	$q_{zzz}$	$t_{SS}$	TKE <sup>syst</sup>	TKE	$A_L^{\text{syst}}$	$A_L$	$N_L^{\text{syst}}$	$N_L$	$Z_L^{\text{syst}}$	$Z_L$	$E_{II}^*$	$E_I^*$	$\nu_{II}$	$\nu_L$
S1	0.75	8.05	1.52	1.78	-0.742	14419	177.27	182	100.55	104.0	61.10	62.8	39.45	41.2	5.26	17.78	0	1.9
S2	0.5	7.91	1.38	1.78	-0.737	4360	177.32	183	100.56	106.3	60.78	64.0	39.78	42.3	9.94	11.57	1	1
S3	0	8.08	1.55	1.78	-0.737	14010	177.26	180	100.55	105.5	60.69	63.6	39.81	41.9	3.35	29.73	0	2.9
S4	0	6.17	-0.36	2.05	-0.956	12751	177.92	181		103.9		62.6		41.3	7.85	9.59	1	1

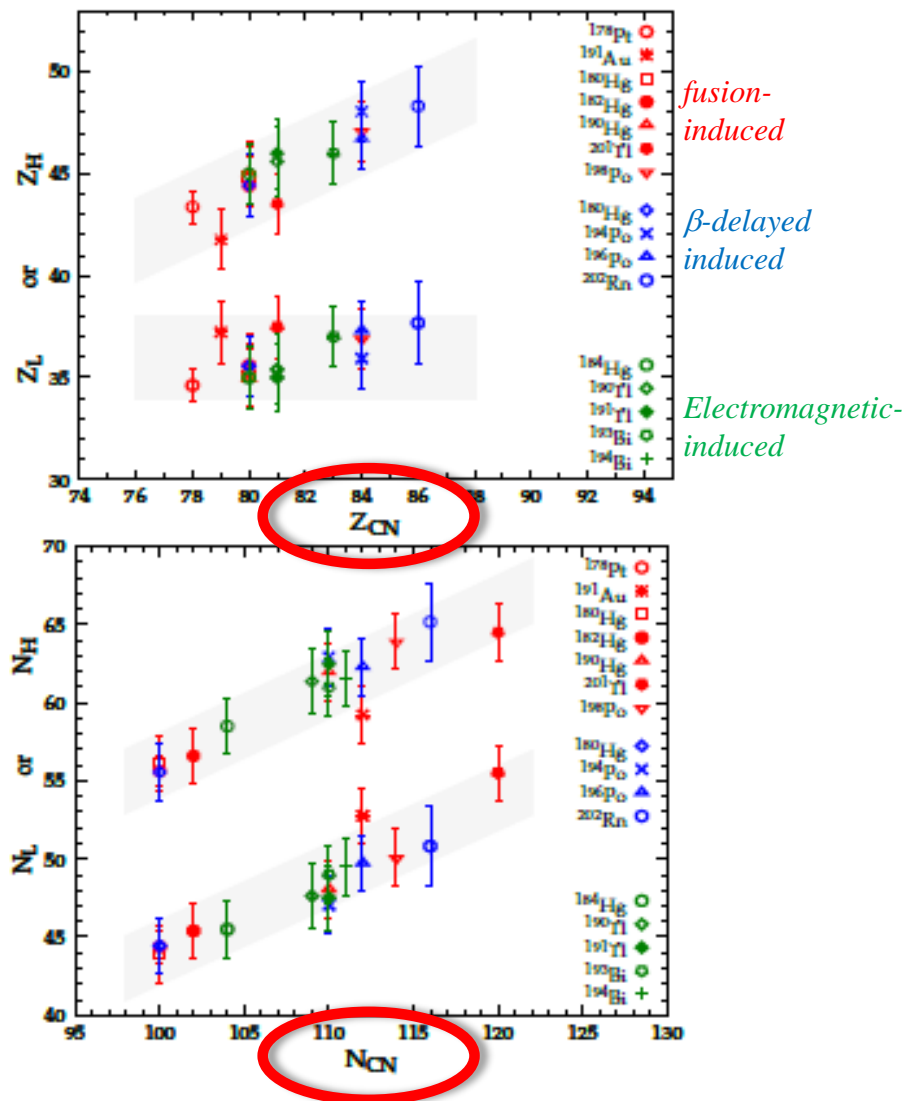
A. Bulgac et al., PRL 116(2016)122504

**JOB TO BE DONE**

- ✓ Extract from existing calculations (?)
- ✓ For pre-actinides also

# Summing up of most recent data in the n-deficient lead region

*Extraction of the light and heavy fragment mean  $Z$  and  $N$*



□  $Z_L = (36 \pm 2)$

$Z_H$  follows from  $Z_{CN}$

$N_{L,H}$  increase with  $N_{CN}$

□ Leading role of the **light fragment proton** number

□ No “trap” at  $N_{L,H} = 50$

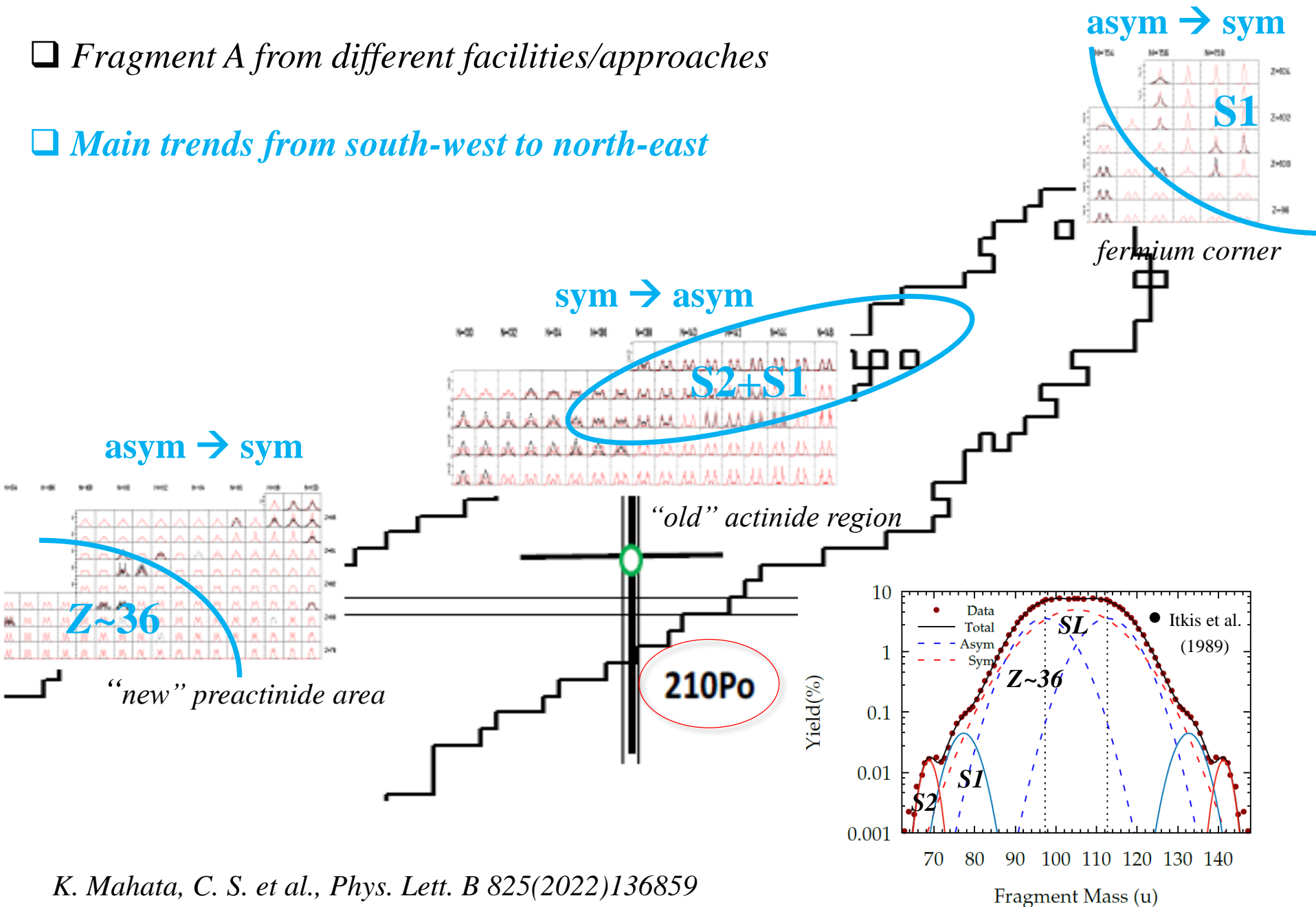
□ Attributable to stabilized deformed **octupole shell effects** at scission around  $Z=34,38$  within HF+BCS approach

*K. Mahata, C. S., G. Scamps et al.,  
Phys. Lett. B 825(2022)136859*

# Look across the chart

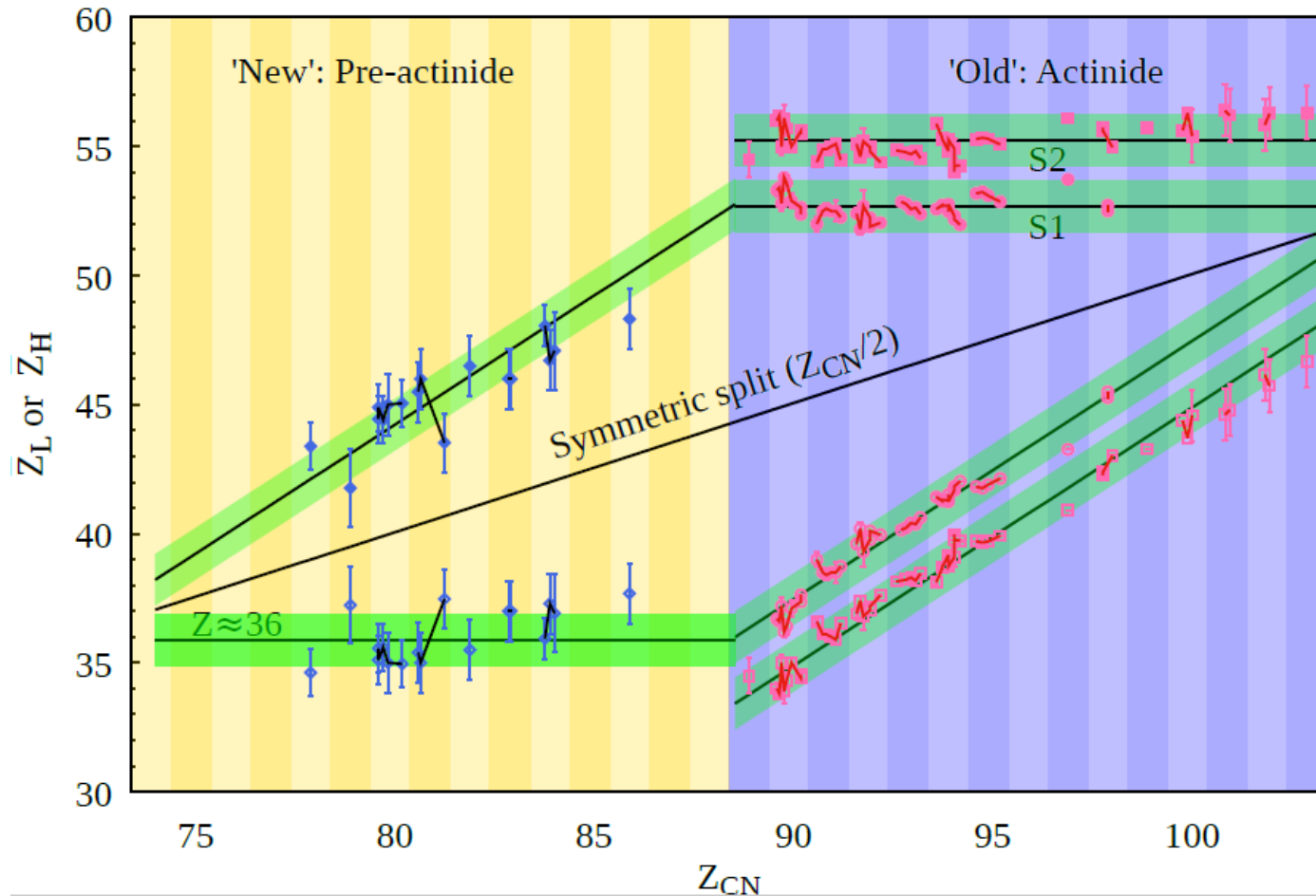
❑ *Fragment A from different facilities/approaches*

❑ *Main trends from south-west to north-east*





## ... About further extrapolation...



How do these trends evolve towards  $\left[ \begin{array}{c} \text{rare-earth} \\ \text{super-heavy} \end{array} \right]$  regions?

## Some conclusion



- ↪ Fission is an exciting, intriguing, and rich process
- ↪ Essential widespread investigations in  $(A_{\text{fiss}}, Z_{\text{fiss}})$  over the nuclear chart

**Thank you for your attention**

**Special thanks to:** K.-H.Schmidt, A. Lemasson