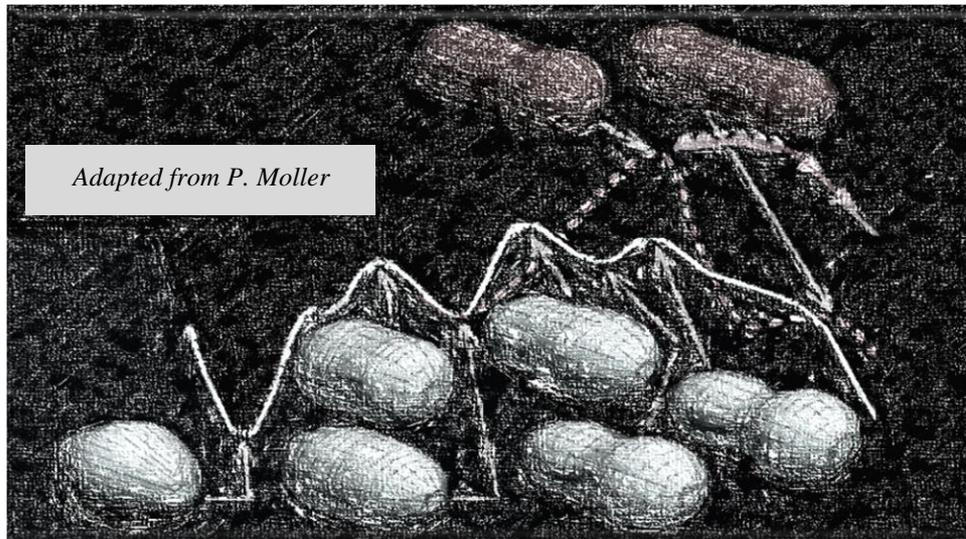


Fission across the nuclear chart:

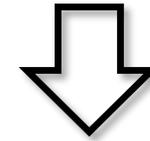
***Experimental Evidence for Common Driving Effects
in Low-Energy Fission from Sublead to Actinides***



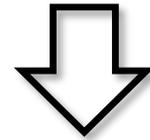
Fresh insight from recent experiments on low-energy fission



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



Trace the story back *via* models

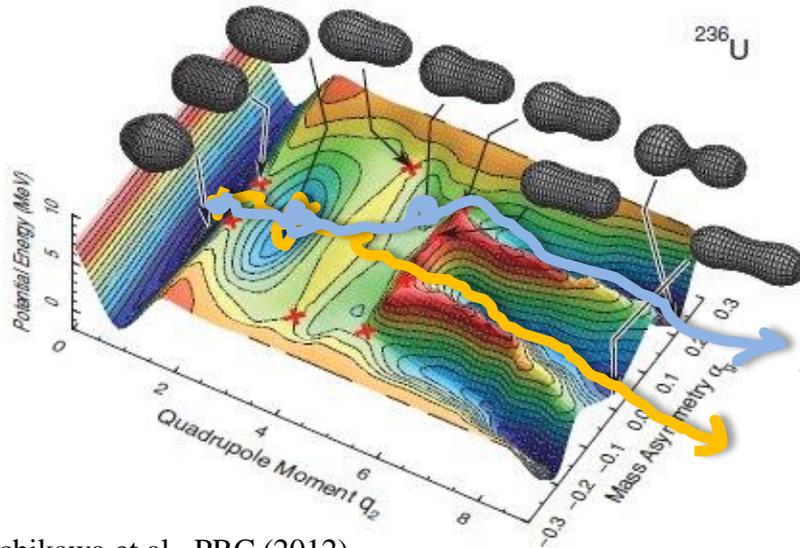


Insight into

- ☛ 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)

T O D A Y

PRIMARY

$A^*_{1,2}, Z^*_{1,2},$
 $E^*_{1,2 \text{ kin}}, L^*_{1,2}$



n, γ

$A^*_{1,2}, Z^*_{1,2},$
 $E^*_{1,2 \text{ kin}}, L^*_{1,2}$



n, γ

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_γ

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

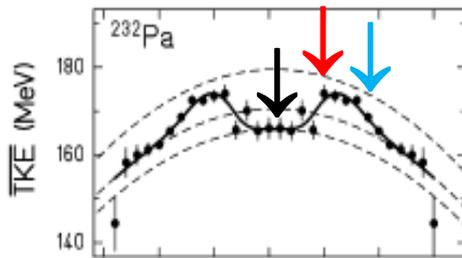
Experimental status on fission observables (1950-2012)

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

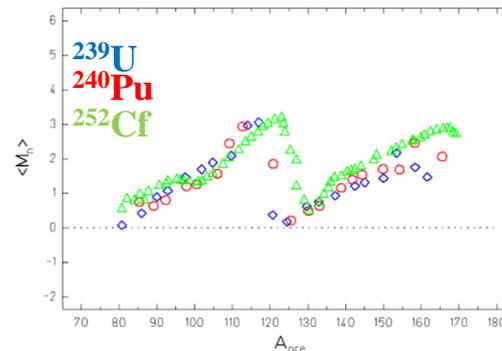


- ☐ TKE confirmation



Schmidt et al., NPA (2000)

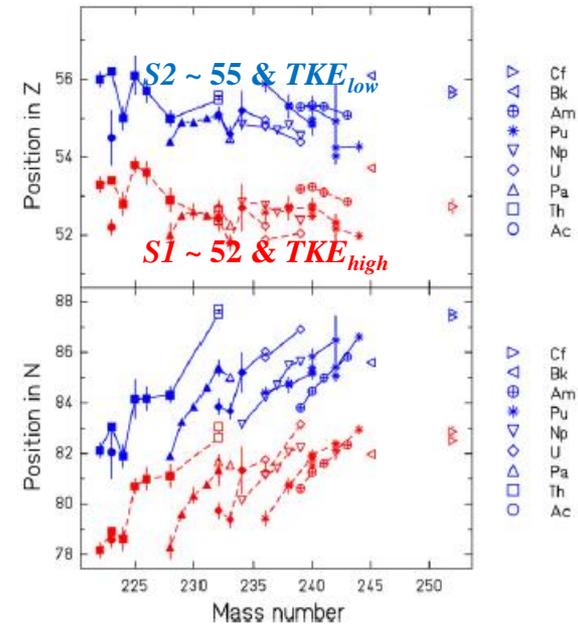
~1960-present: Neutrons



- ☐ 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?

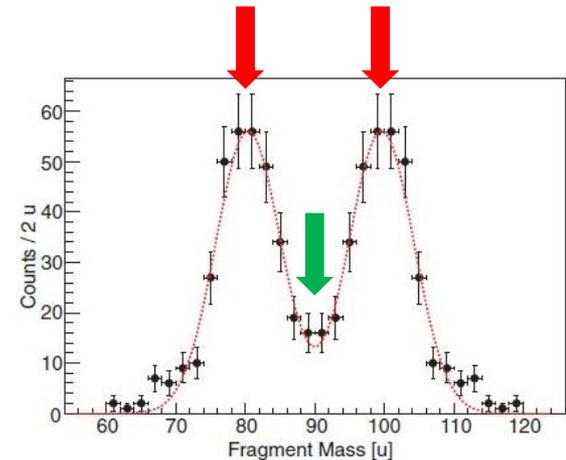
Current knowledge (from actinides):

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

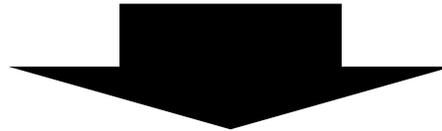
BUT how to reconcile it with observation of asymmetric low-energy fission of ^{180}Hg ?

expected: $2 \times {}^{90}\text{Zr}_{50}$

observed: $\sim A_{1,2} \sim 80 + 100$



Andreyev et al., PRL (2010)



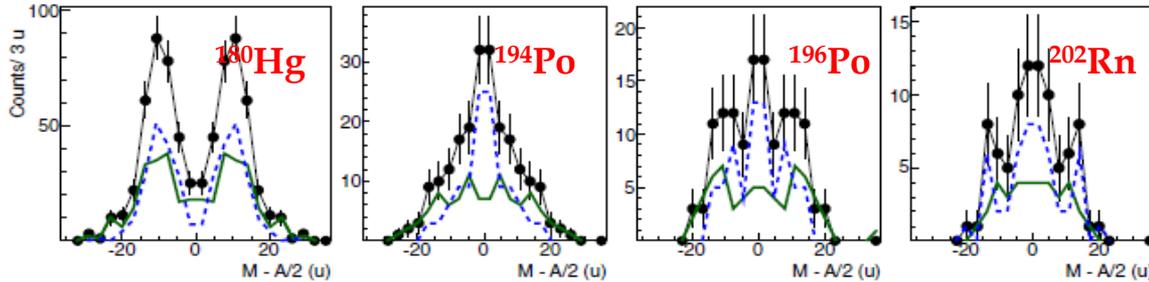
Intense experimental/theoretical work



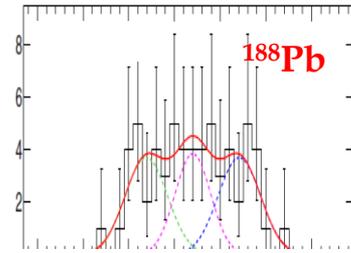
Can an independent asymmetric fission “island” be delineated?
What’s its origin? Which (shell) effect(s) drive(s) it?

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

□ β -delayed @ ISOLDE/CERN ($E^* \sim$ few MeV)

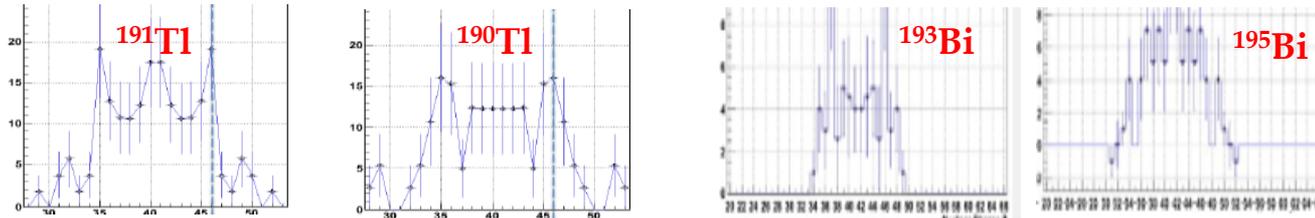


Ghys et al., PRC (2014)



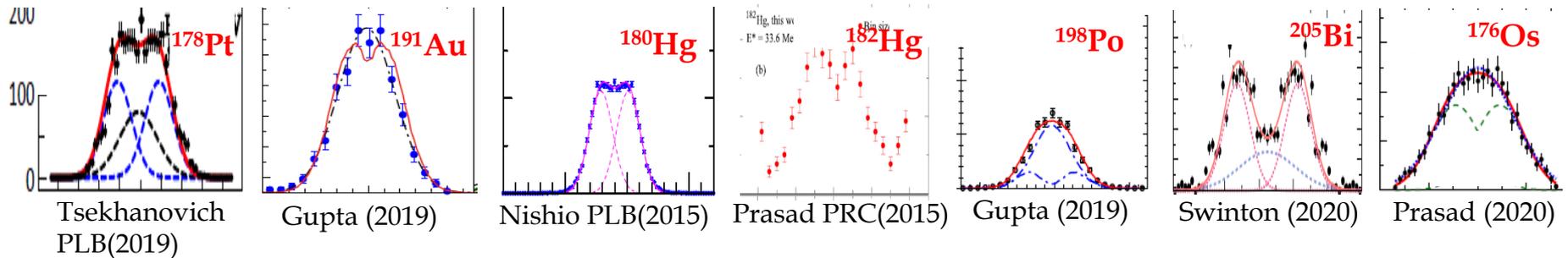
Andel et al., PRC (2020)

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



Gorbinet for SOFIA2, WFDEPNG (2014)

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



Tsekhanovich
PLB(2019)

Gupta (2019)

Nishio PLB(2015)

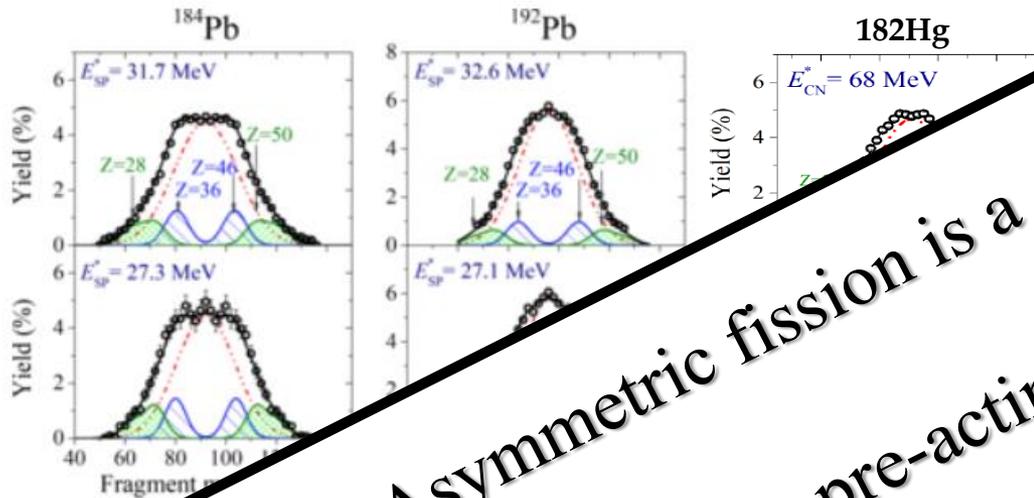
Prasad PRC(2015)

Gupta (2019)

Swinton (2020)

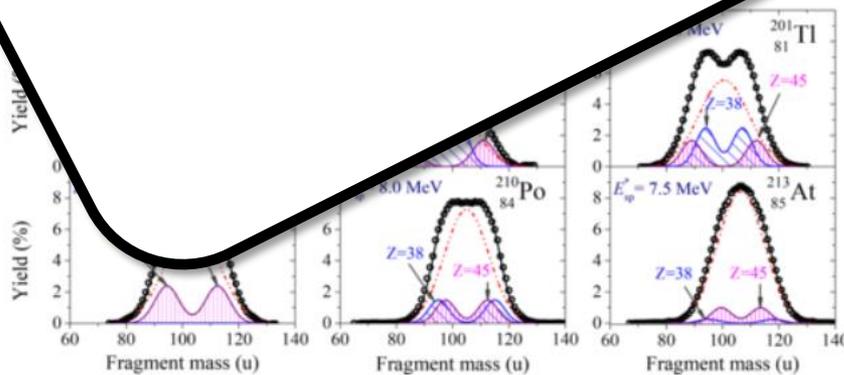
Prasad (2020)

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**

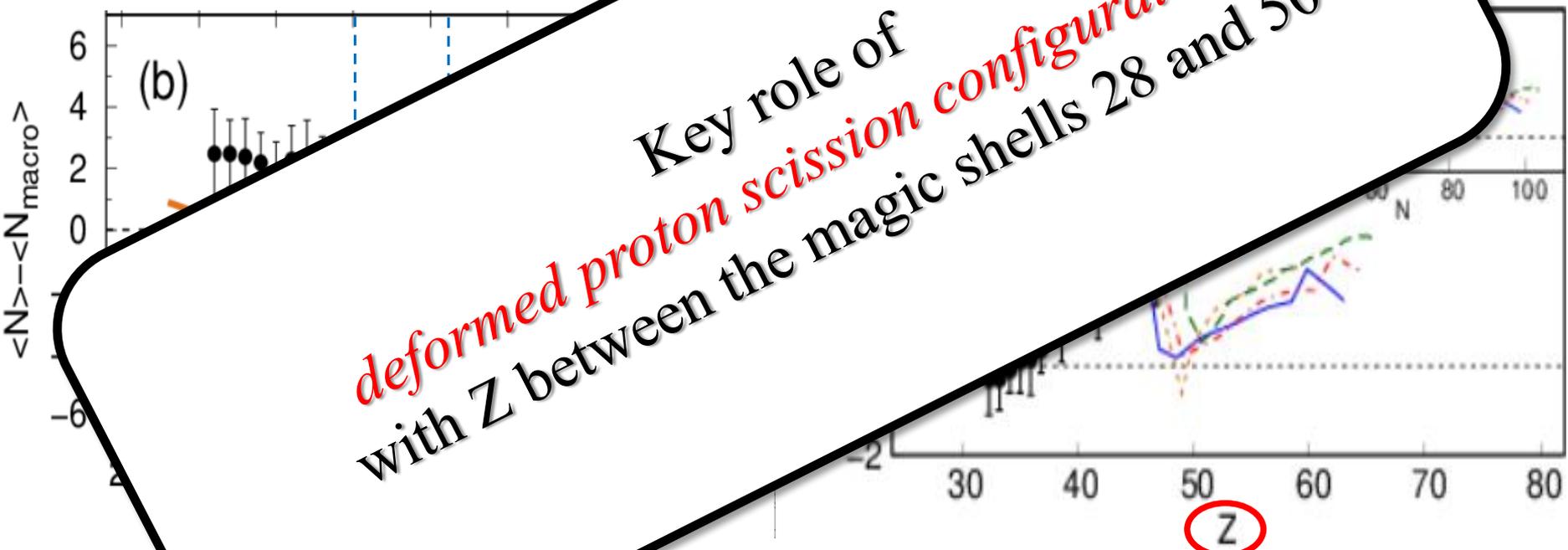
Results on low-energy fission of ^{178}Hg @ VAMOS (1)



Results on low-energy fission of ^{178}Hg @ VAZ (2)

Is it consistent with the conclusions of ...

Microscopic contribution to n-rich ...



⇒ Same ... contribution to N/Z ... for different N 's

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

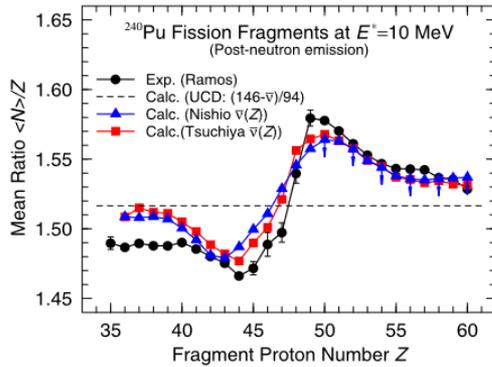
e.g. for $Z=42$ $\left[\begin{array}{l} N \sim 56 \text{ for } ^{178}\text{Hg} \\ N \sim 66 \text{ for actinides} \end{array} \right.$

... 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

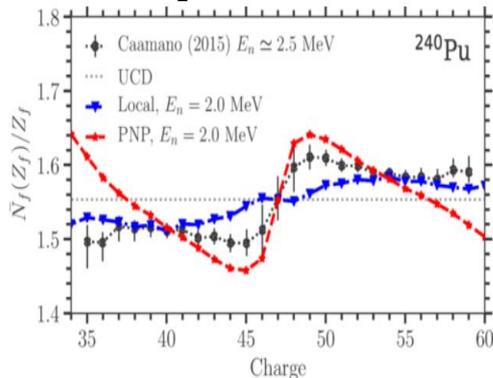
N/Z

Macro-microscopic 6D BSM



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

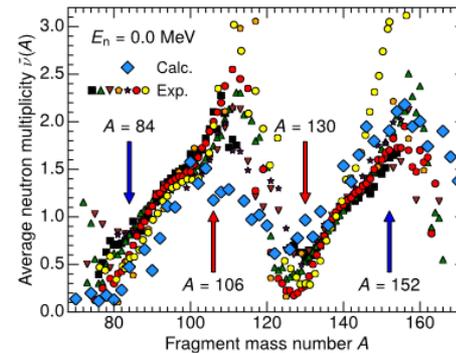
Microscopic TDGCM+GOA



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

M_n

Macro-microscopic 5D BSM



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

S no.	η	E^*	E_n	q_{zz}	q_{zzz}	t_{SS}	TKE ^{sys}	TKE	A_L^{sys}	A_L	N_L^{sys}	N_L	Z_L^{sys}	Z_L	E_{II}^*	E_I^*	ν_{II}	ν_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	29.78	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

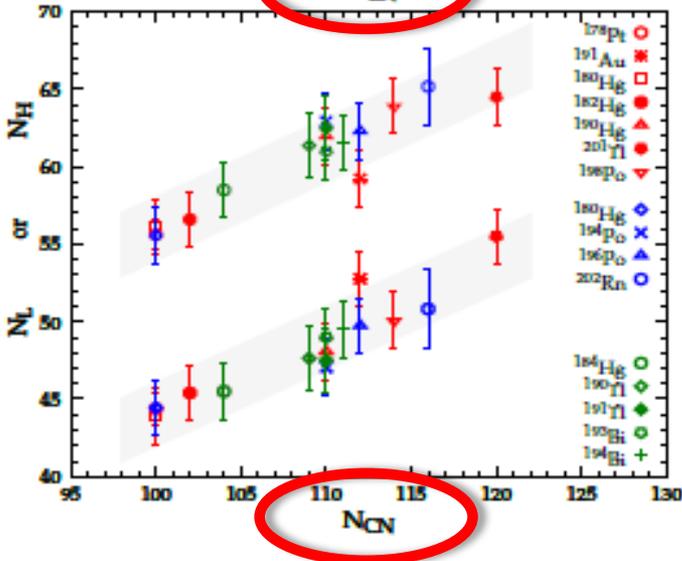
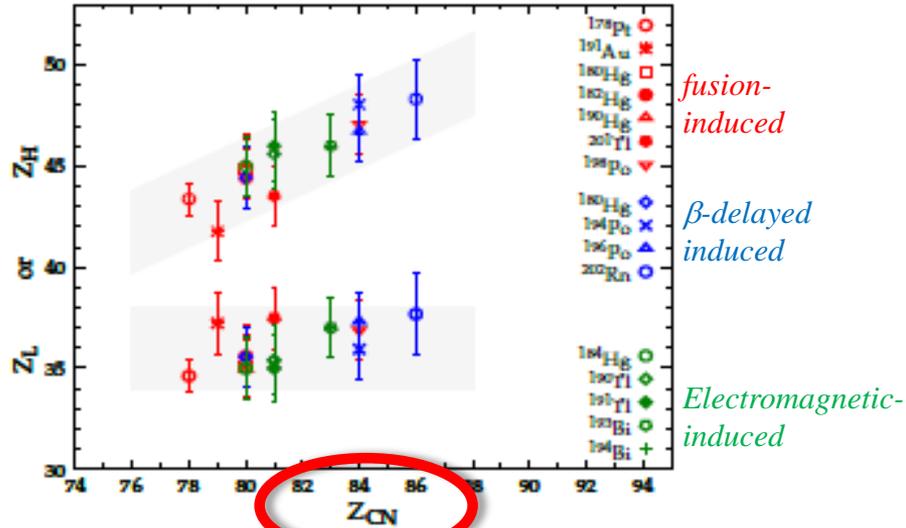
A. Bulgac et al., PRL 116(2016)122504



- ✓ 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



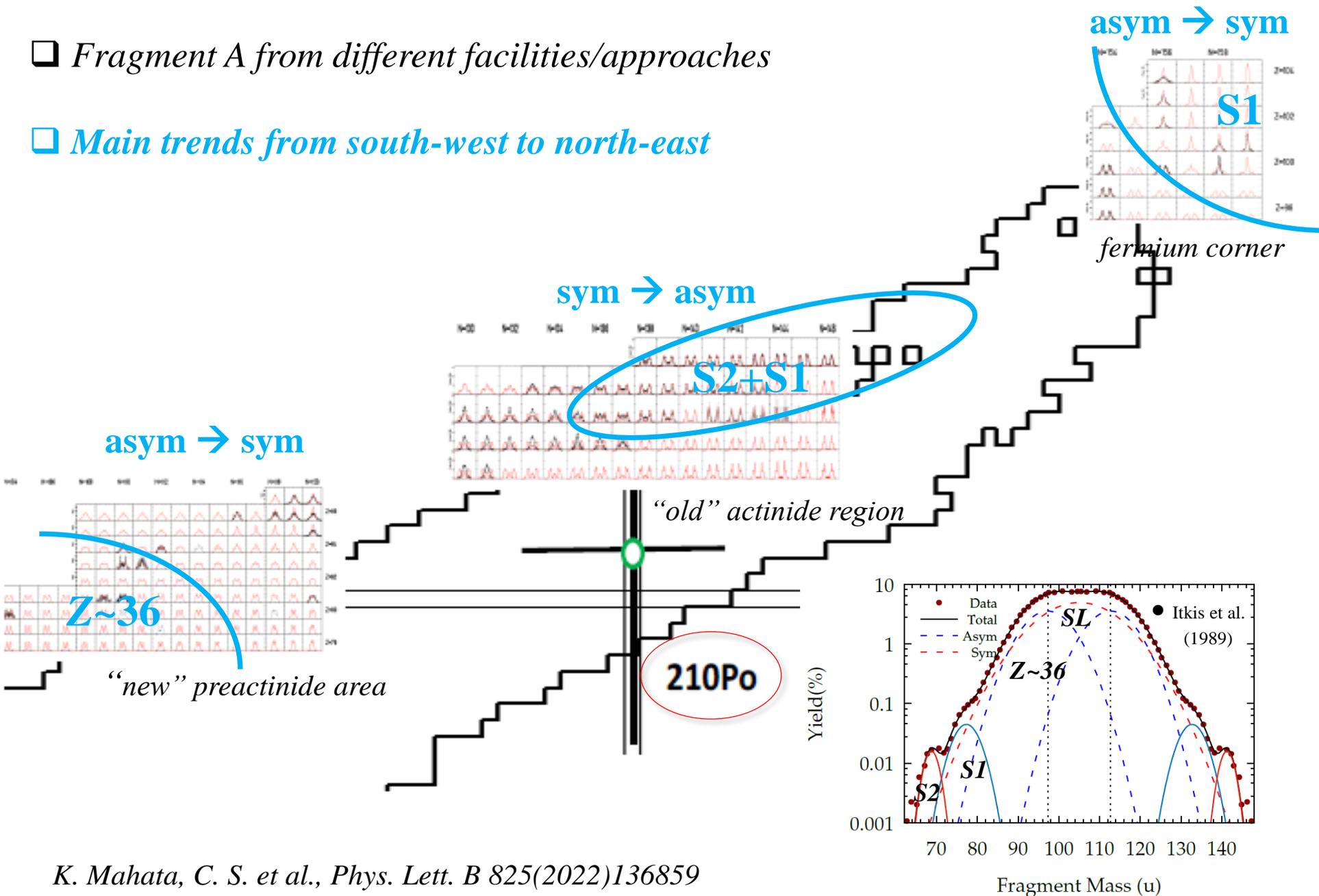
- $Z_L = (36 \pm 2)$
 Z_H follows from Z_{CN}
 $N_{L,H}$ increase with N_{CN}
- Leading role of the **light fragment proton number**
- No “trap” at $N_{L,H} = 50$
- Attributable to stabilized deformed **octupole shell effects** at scission around $Z=34,38$ within HF+BCS approach

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

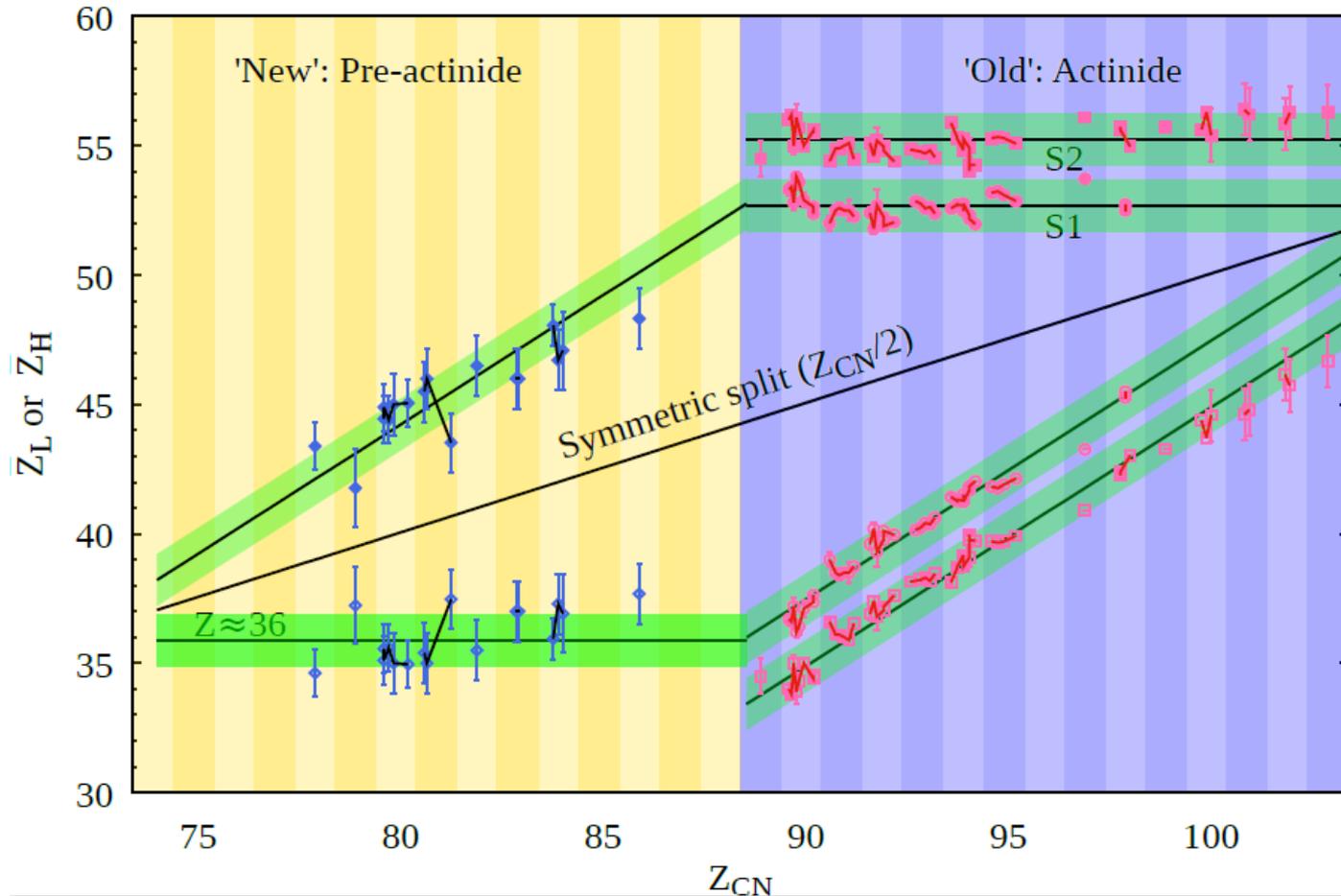
Look across the chart

❑ *Fragment A from different facilities/approaches*

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



... About further extrapolation...



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