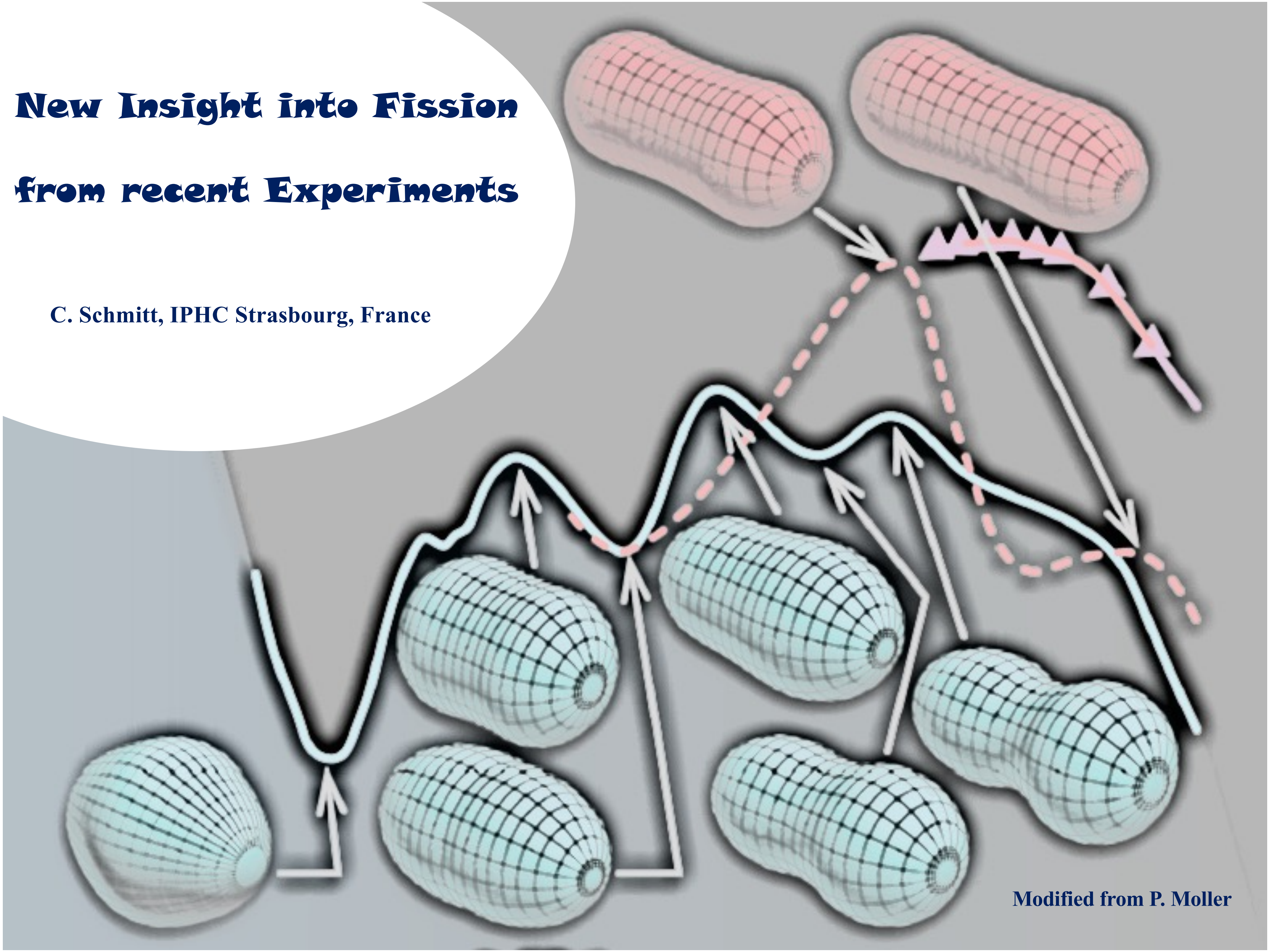
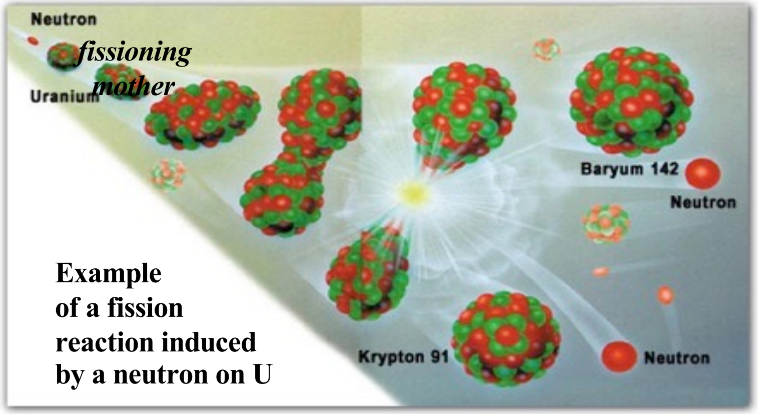
# New Insight into Fission from recent Experiments

C. Schmitt, IPHC Strasbourg, France



Modified from P. Moller

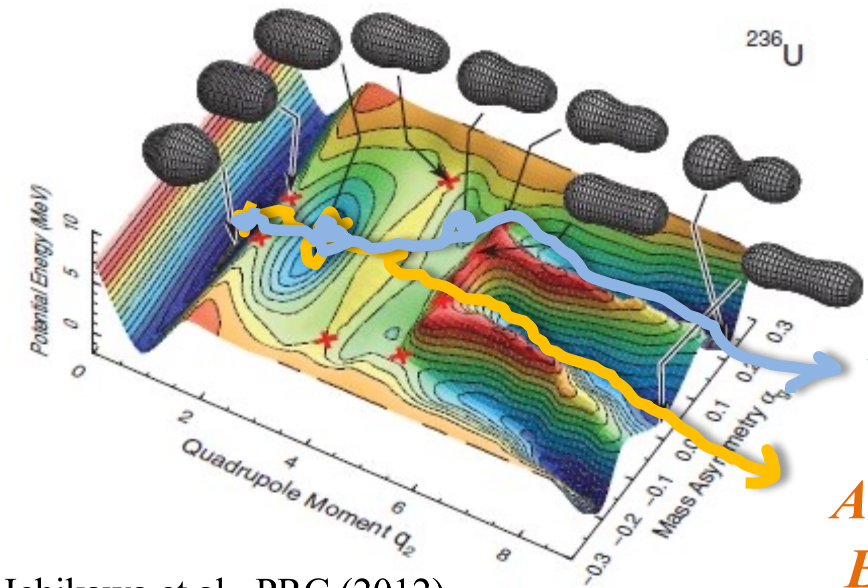
# FISSION…




. . . . a dramatic radioactive decay involving a formidable re-arrangement of the proton and neutron fluids

- ⇨ rich laboratory for fundamental physics
- ⇨ impact in astrophysics
- ⇨ societal and technological applications
- ⇨ low-energy fission ($E^* \lesssim 30$MeV)

# Why investing effort in measuring accurately fragment ($A$, $Z$, $E_{kin}$)




Ichikawa et al., PRC (2012)

## Fission:

A journey on the fissioning nucleus
**P**otential **E**nergy **L**andscape

| PRIMARY | | SECONDARY |
|---|---|---|
| $A^*_{1,2}$', $Z^*_{1,2}$', $E^*_{1,2\ kin}$' | $n,\gamma$ → | $A_{1,2}$', $Z_{1,2}$', $E_{1,2\ kin}$' |
| $A^*_{1,2}$, $Z^*_{1,2}$, $E^*_{1,2\ kin}$ | $n,\gamma$ → | $A_{1,2}$, $Z_{1,2}$, $E_{1,2\ kin}$ |

- ✓ Measure of ($A$, $Z$, $A$', $Z$') ☛ symmetric or asymmetric ( ~ *valleys*), n *vs.* p
  - ☛ evaporation n/γ ( ~ *E*/L generation/release*)
- ✓ Measure of $E_{1,2\ kin}$, ☛ ***T***otal ***K***inetic ***E***nergy ~ scission configuration

**PEL topography and « Replay » of the dynamical evolution**

# Status from experiments (~ 1950 – 2000)

Mostly: Fragment $A$ distributions with $\Delta A$ = 3-5amu; Very poor info on $Z$

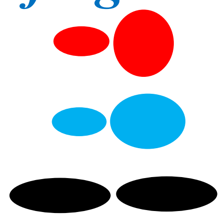
- ❐ Low-energy fission is predominantly asymmetric around uranium
- ❐ Heavy fragment located at $A$~130-150 independent on the system

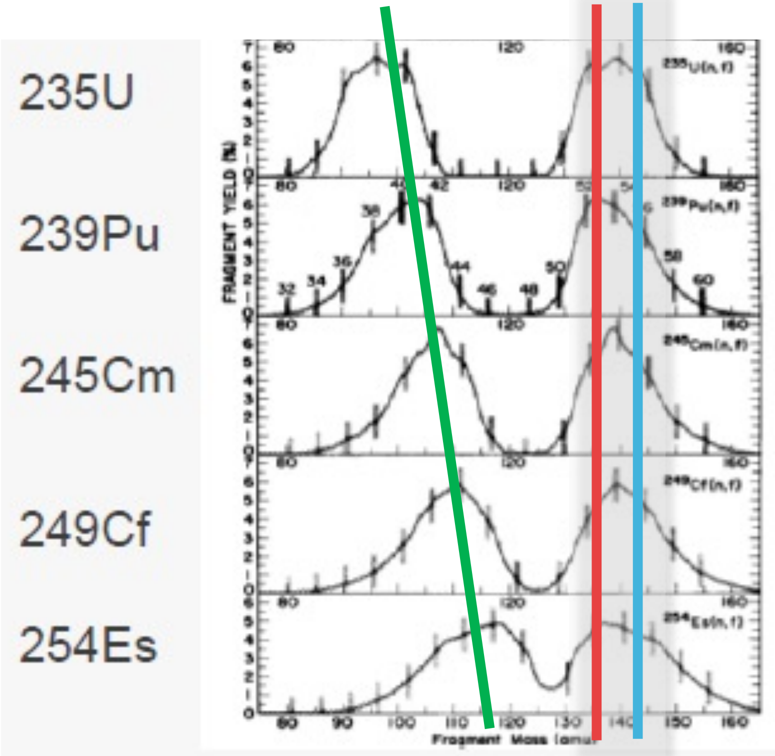
*Double-humped asymmetric peak due to shell stabilized fragments*

***S1 mode attracted by N=82 (sph. shell)***

***S2 mode attracted by N~88 (def. shell)***

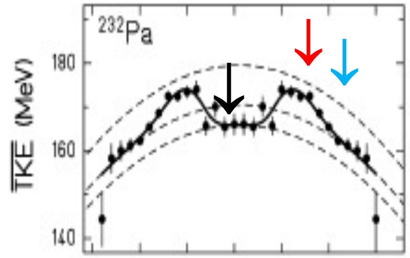
*Symmetric contribution SL due to macroscopic energy*





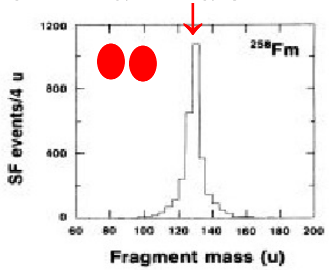

Unik et al. (1973)

❐ *TKE* confirmation




Schmidt et al., NPA (2000)

❐ Consistency with heaviest elements around fermium dominated by S1




⇨ high TKE

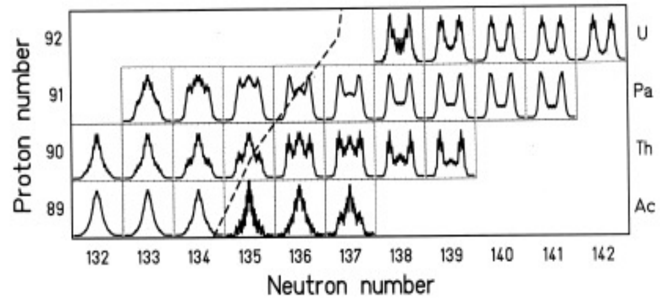
⇨ "2*magic"

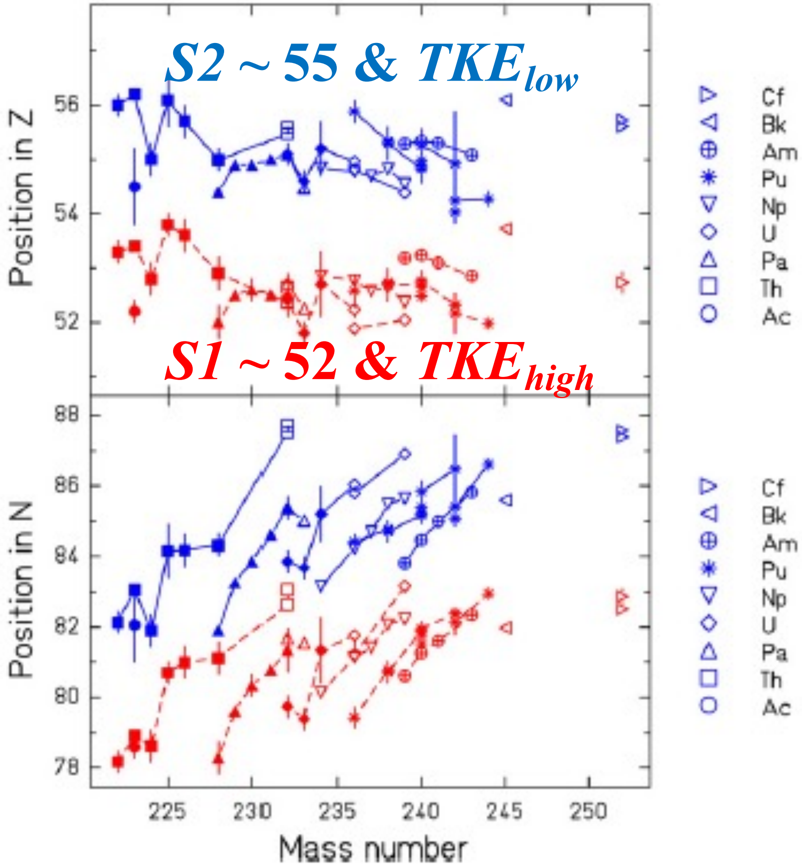
⇨ $N$ & $Z$ magic

# Complete and accurate *Z* distributions in 2000

K.-H.Schmidt et al., NPA (2000)

*inverse kinematics* + *FRS heavy-ion spectrometer*




Bockstiegel et al., NPA (2008)

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

➩ **neutron *vs.* proton role?**

**Need *A* <u>and</u> *Z***
**with unique precision**
➩ isotopic (*N*,*Z*) information

# Most recent measurements for fission of actinides

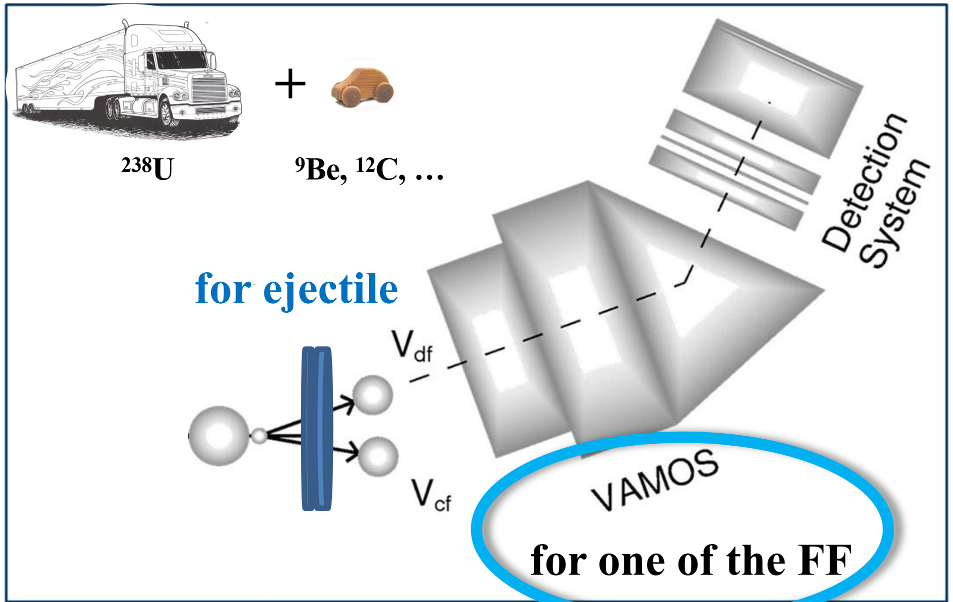
**VAMOS@GANIL**
*(Farget, Camaano, Ramos, et al.)*

**SOFIA/ALADIN@GSI**
*(Taieb, Chatillon, et al.)*

*inverse kinematics + advanced heavy-ion spectrometer*

**complete and fully resolved $A$, $Z$, $E_{kin}$ distributions for various ($A_{CN}$, $Z_{CN}$, $E^*$)**

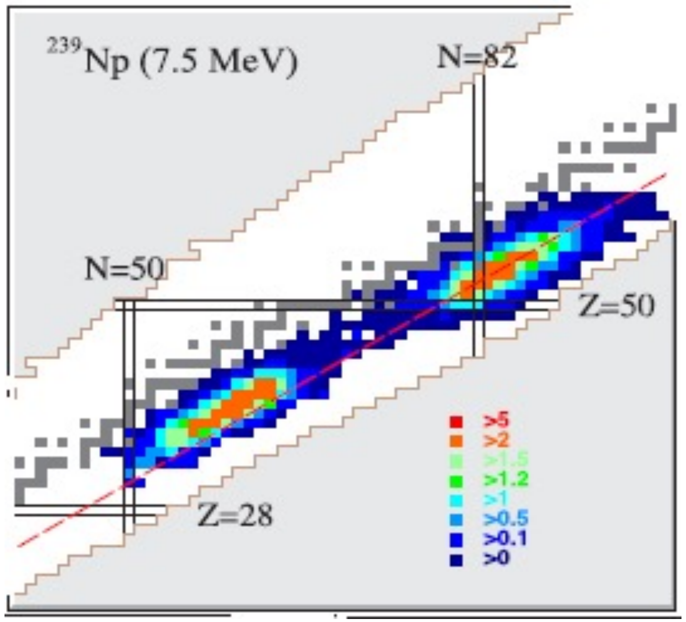
- → *Induce fission in multi-nucleon transfer*
- → *Identify the transfer channel by detecting the light ejectile (i.e. the fissioning nucleus)*
- → *Study fission by detecting in coinc. one of the FF in VAMOS*



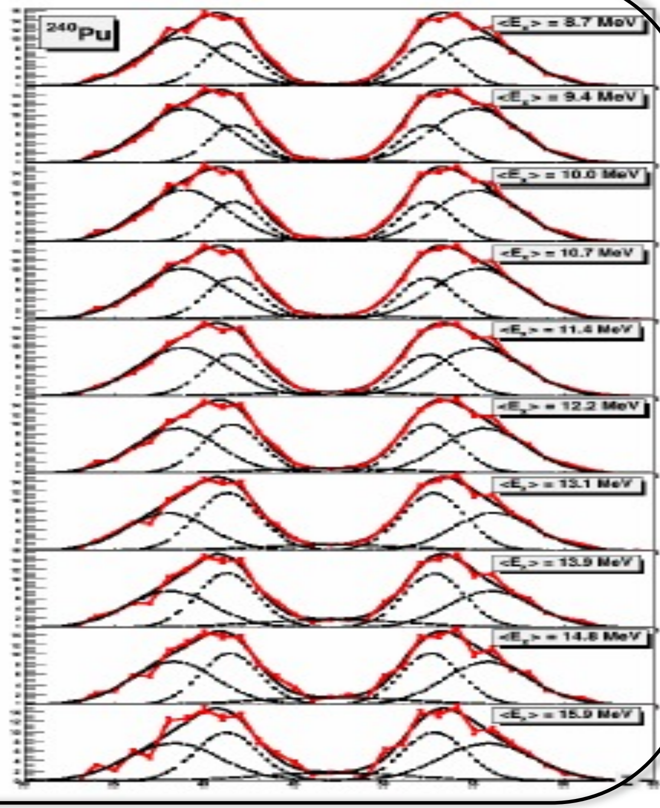

**Fission properties for $^{238-239}$U, $^{239}$Np, $^{240}$Pu, $^{244}$Cm, $^{250}$Cf, with $E^*$ ~ 6 to 46 MeV**

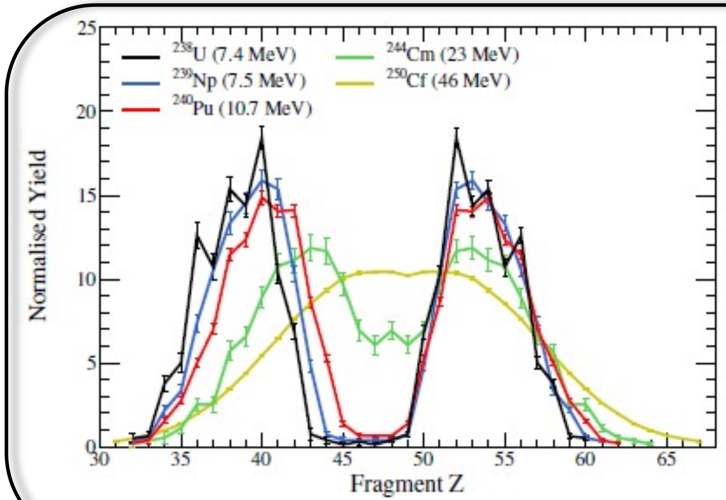
# Sample of results from VAMOS@GANIL for actinides

**Complete isotopic distribution with best resolution**




**Fission mode dependence on $E^*$ for a specific ($A_{CN}$, $Z_{CN}$)**




✓ Unique $Z$ identification

- → **proton e-o staggering**
- → **pairing in fission**

✓ Same available for $N$

- → **Favored $N$ or Z numbers?**
- → **Connection with known shells?**
- → **Washing out with E*?**

**Much more in:**

**Camaano et al.**, PRC 88,024605 (2013); 92,034606 (2015), **Ramos et al.**, PRC 97, 054612 (2018); 99,024615 (2019), 101,034609(2020), PRL 123, 092503(2020)

# Update conclusion from most accurate experiments on actinides

- ❒ **Leading role played by protons in fission**
- ❒ Minor role played by neutrons
- ❒ ***S1* observed around 52 is due to *Z* = 50 stabilization**

  *supported by high TKE*
- ❒ ***S2* observed around 55 driving by octupole stabilized (*Z*=52-56) configurations**

  *cf. Scamps and Simenel, Nature 564, 382 (2018)*

*NB:* ***Observed position vs. location of effective shell***

*$Z_{CN}$ / $N_{CN}$ dependence,*
*nucleons from the neck*

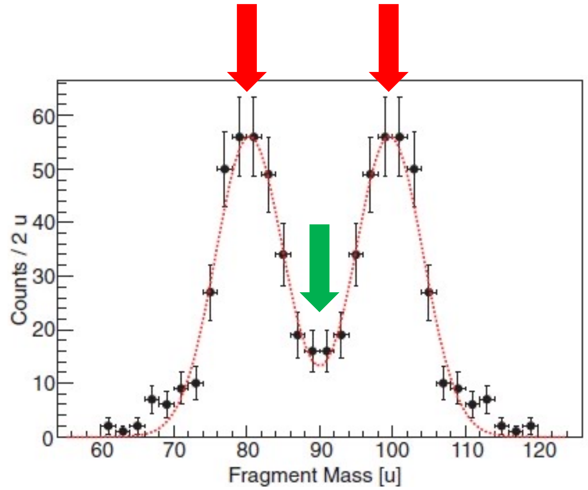
**Can we extrapolate our understanding of fission gained from actinides to other regions of the nuclear chart?**

Current knowledge: Shell effects in the nascent fragments play a key role…

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

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

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



Andreyev et al., PRL (2010)

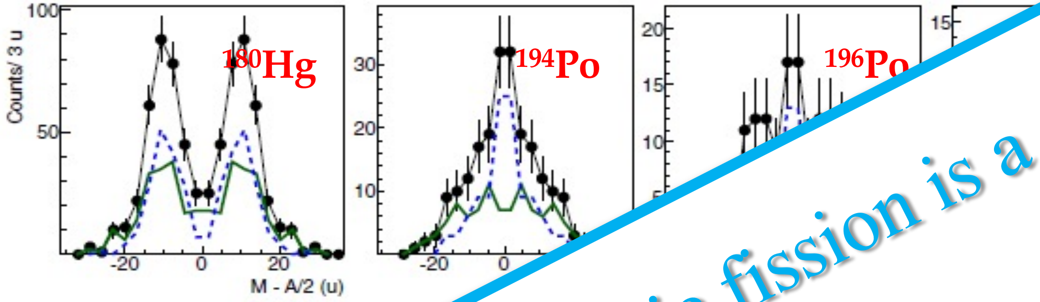
**Evidence for a "new" type of asymmetric fission in the n-deficient pre-actinide region ?**

Intense experimental/theoretical work

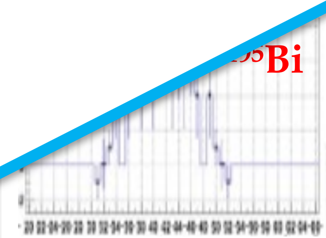
Can an independent "island" be delineated? No consensus yet

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

❒ β-delayed @ ISOLDE/CERN ($E^*$ ~ few MeV)

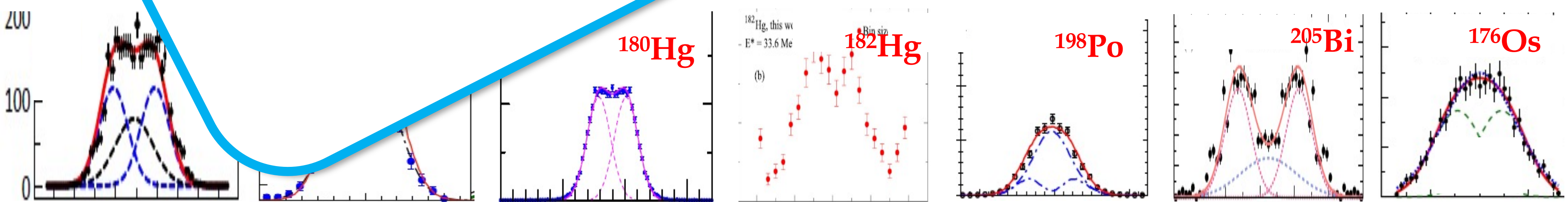



❒ Electromag…




…NG (2014)

❒ Fu… …-50 MeV)




Tsekhanovich PLB(2019) | Gupta (2019) | Nishio PLB(2015) | Prasad PRC(2015) | Gupta (2019) | Swinton (2020) | Prasad (2020)

**Asymmetric fission is a general feature in the pre-actinide region**

**… but why ?**

# Low-energy fission in the n-deficient lead region @ VAMOS

Benefit from the assets of GANIL to go beyond current information → *(A, Z)*

Method:

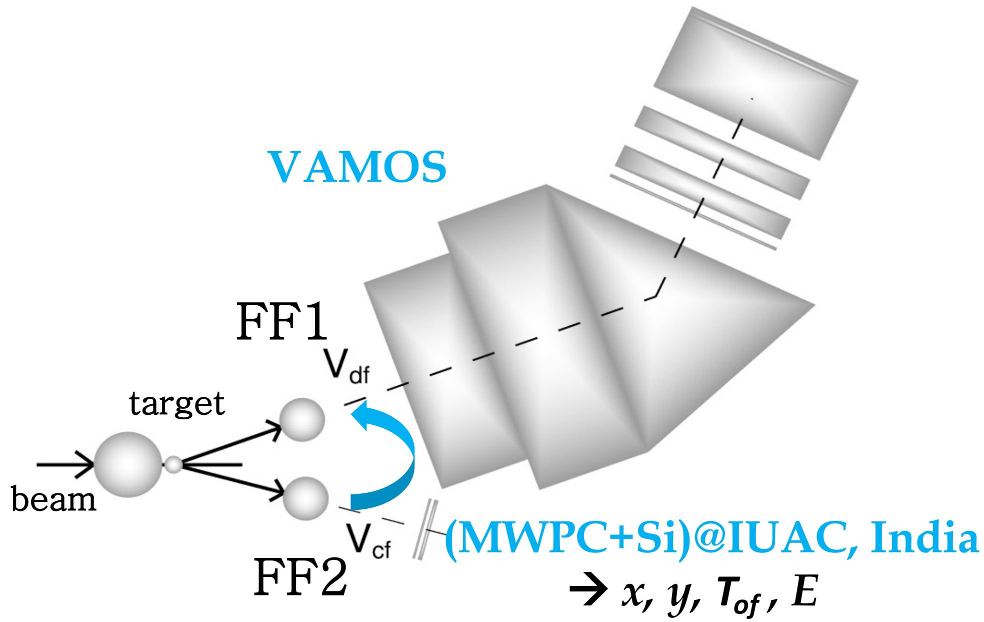
**Fusion-fission in inverse kinematics** $^{124}$Xe(4.3AMeV) + $^{54}$Fe → $^{178}$Hg ($E^*$~33MeV)

*...challenging (A,Z) identification due to slow (~1-3AMeV) fragments...*

Set-Up:

- **VAMOS @ 29°** for identifying one of the fragments ($A, Z, v, \vartheta, \varphi$)

- **2nd arm @ 35°** for identifying the partner ($A, v, \vartheta, \varphi$)



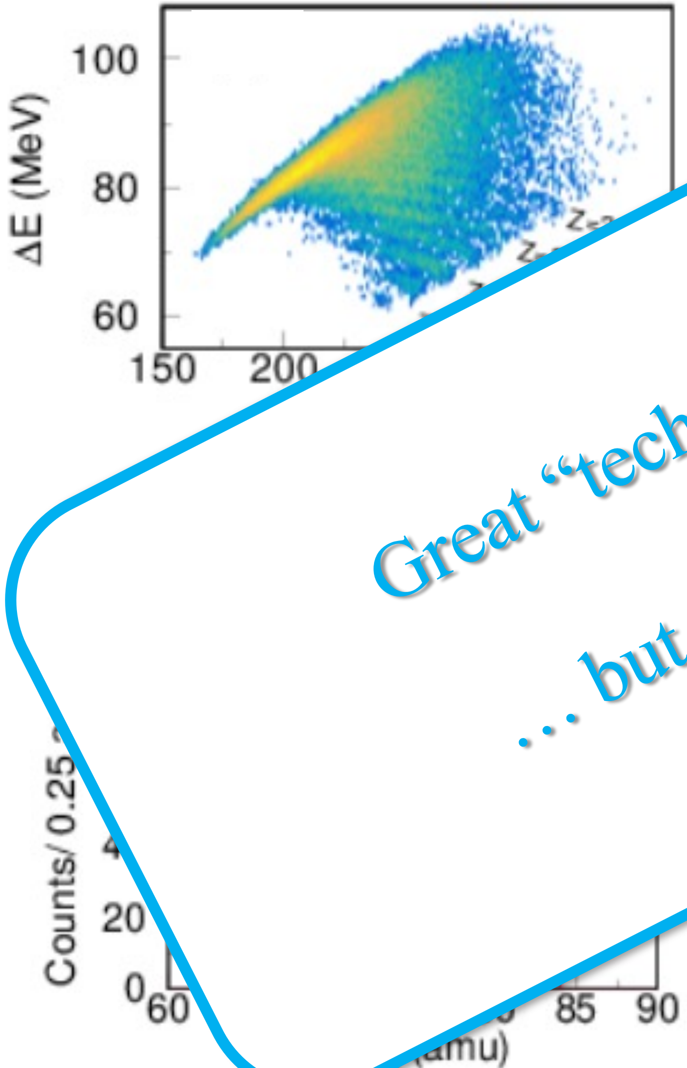

Innovative observables in the region:

- ***A, Z*** **of both fragments at scission and at rest** (NB: $A_{pre}$ within ~ 4 amu)
- **Corresponding** ***TKE*****'s** (« primary » and « secondary »)

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

*VAMOS « stand-alone »*

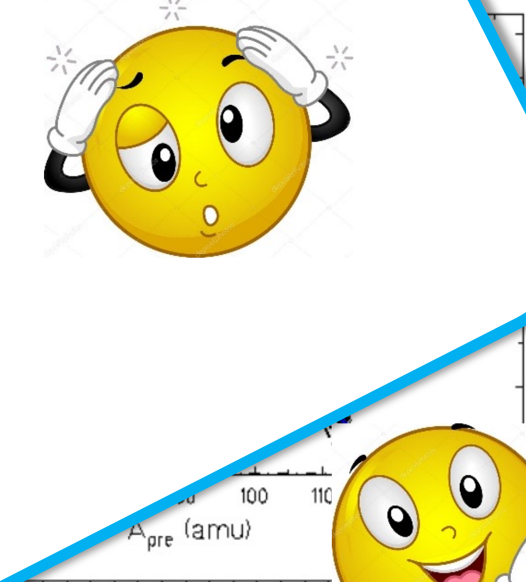
**$\Delta E$-$E$ correlation at FP**



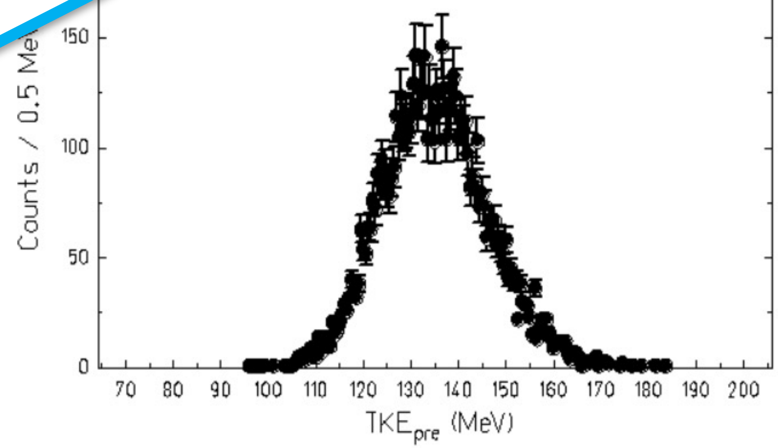

⇨ Secondary $\Delta A/A$ ~ 0.8%

*VAM... m*

↪ *Ki... d (2v)*




⇨ $\Delta$ TKE ~5MeV



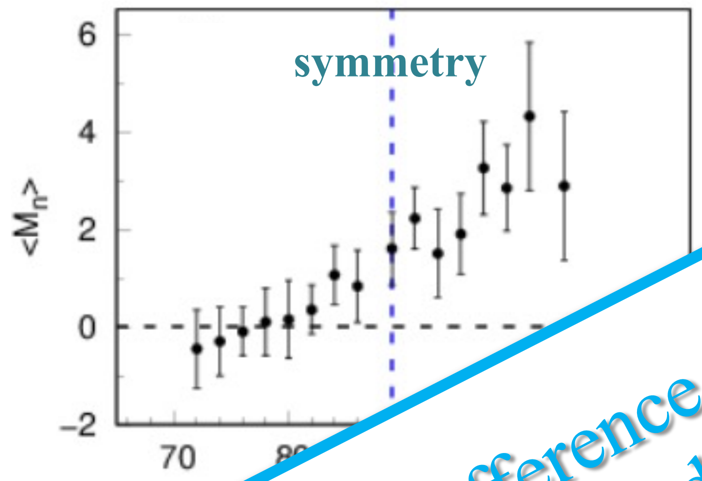

Great "technical" challenge

… but no "new" physics

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

$A_{pre} \otimes A_{post}$ ⇨ Neutron multiplicity $M_n$

$Z \otimes A_{post}$ ⇨ N/Z ... ⇨ $N/Z_{pre}$

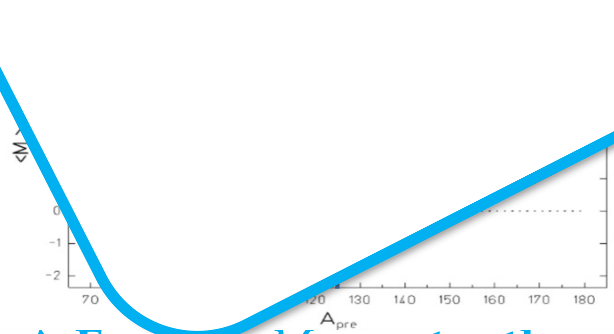



Puzzling difference in scission properties
for pre- and actinide fission

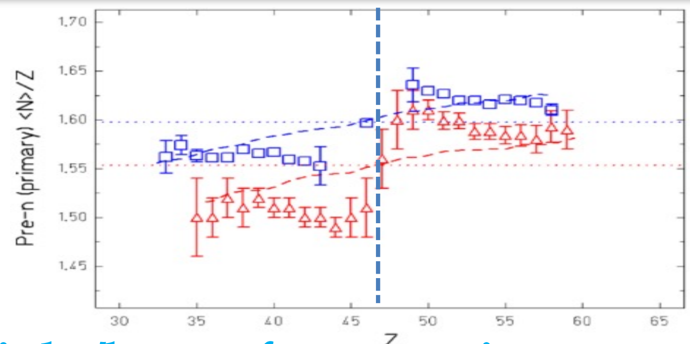
... interesting physics ?

... is n-rich/poor

... emit few neutrons!




⇨ Famous $M_n$ sawtooth

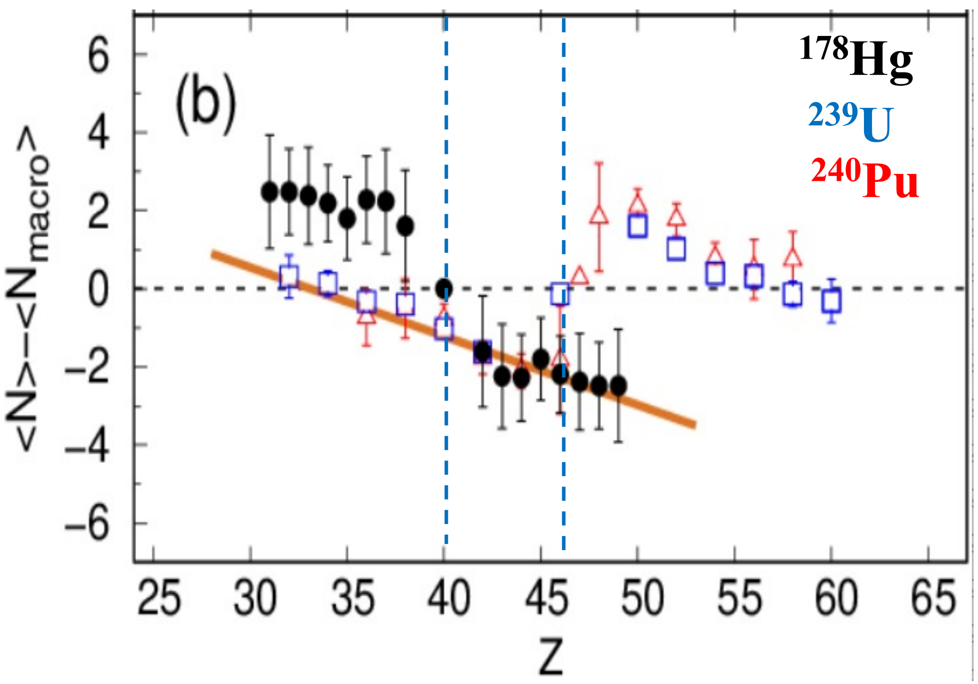



⇨ Light/heavy fragment is n-poor/rich

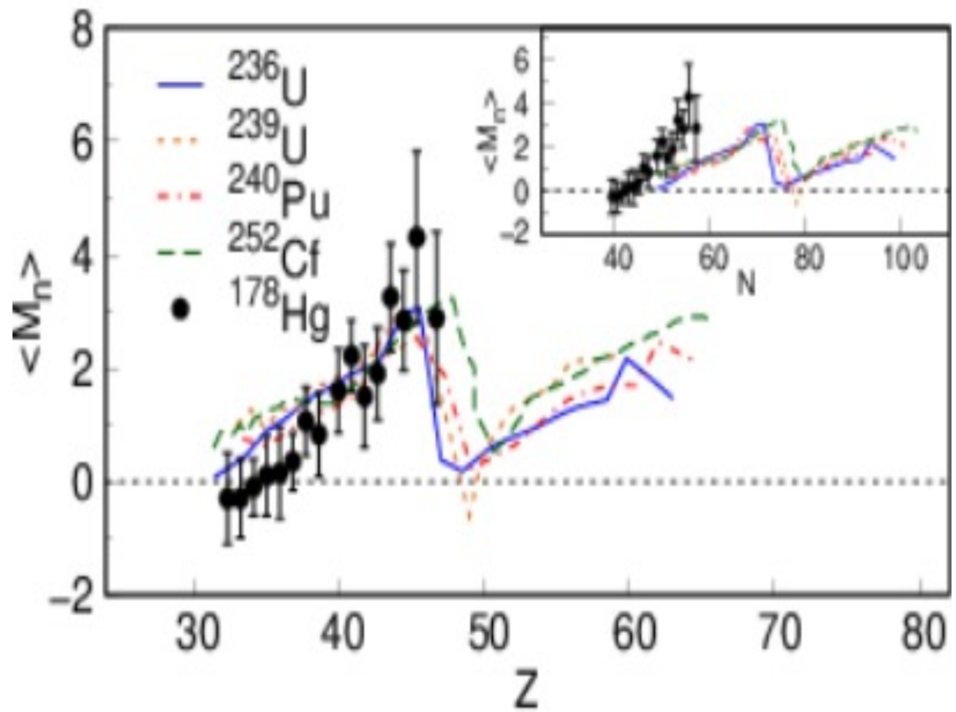
# Results on low-energy fission of $^{178}$Hg @ VAMOS (3)

*Is it consistent with the conclusions drawn for actinides?*

*Microscopic contribution to n-richness*




*Shape relaxation after scission*




⇨ **Same microscopic contribution to *N/Z* at given *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)***

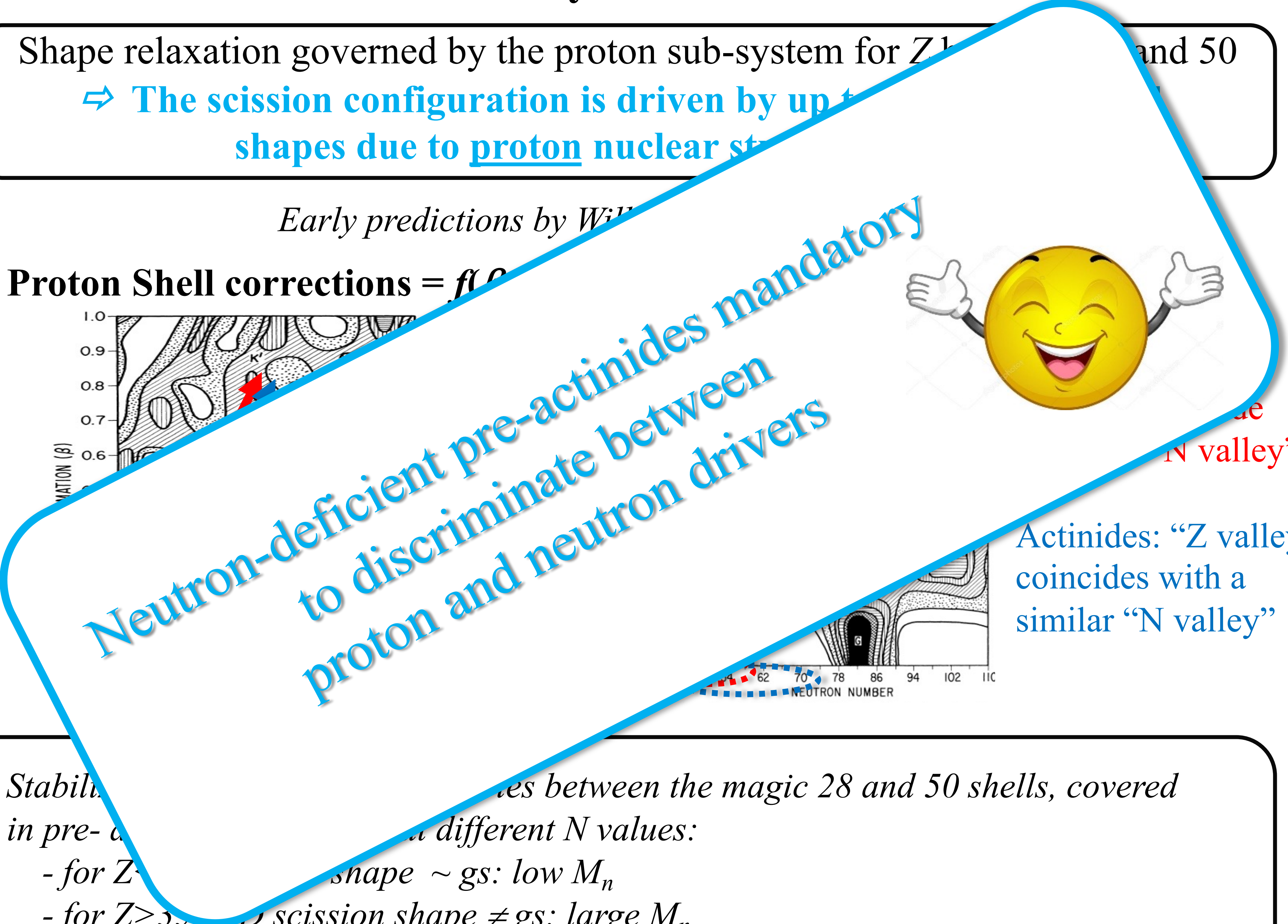
# Protons as key drivers in fission

Shape relaxation governed by the proton sub-system for Z b... and 50

⇨ **The scission configuration is driven by up t... shapes due to <u>proton</u> nuclear st...**

*Early predictions by Wi...*

**Proton Shell corrections = *f*(...**




...e
...N valley"

Actinides: "Z valley" coincides with a similar "N valley"

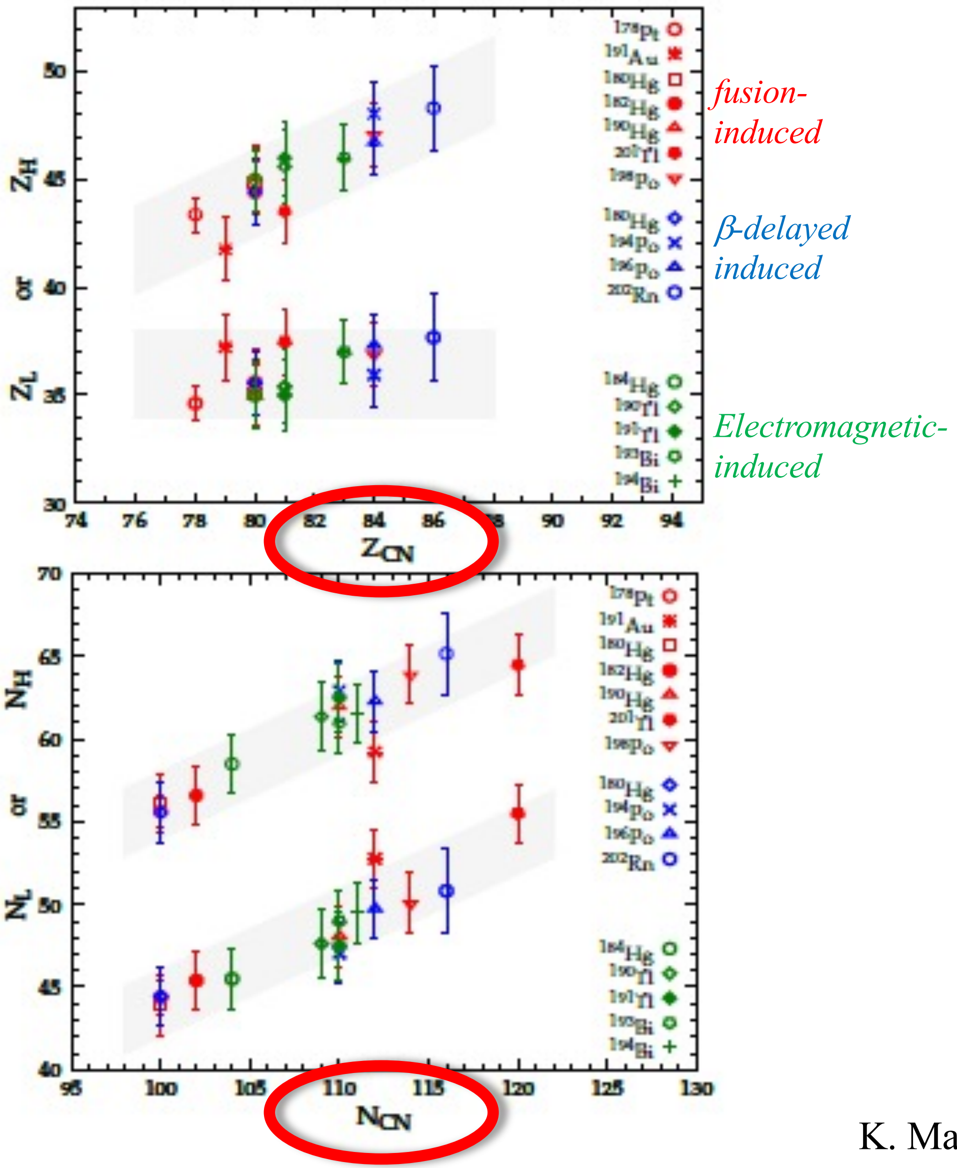
→ *Stabili... ...es between the magic 28 and 50 shells, covered in pre- a... ...t different N values:*

*- for Z... ...shape ~ gs: low $M_n$*

*- for Z>3... ...D scission shape ≠ gs: large $M_n$*

# 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±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. Schmitt, *submitted and arXiV.2007.16184 (2021)*

# Inventory of leading effects in low-energy asymmetric fission across the nuclear chart

1. Due to nuclear structure of the nascent fragment(s):

- ❒ **$Z$ = 50 spherical configuration** *(NB: seen 52 in actinides, 50 in Fm's)*
- ❒ **$Z$ ~ 55 deformed (octupole) configuration**
- ❒ **$Z$ ~ 36 deformed (octupole) configuration**

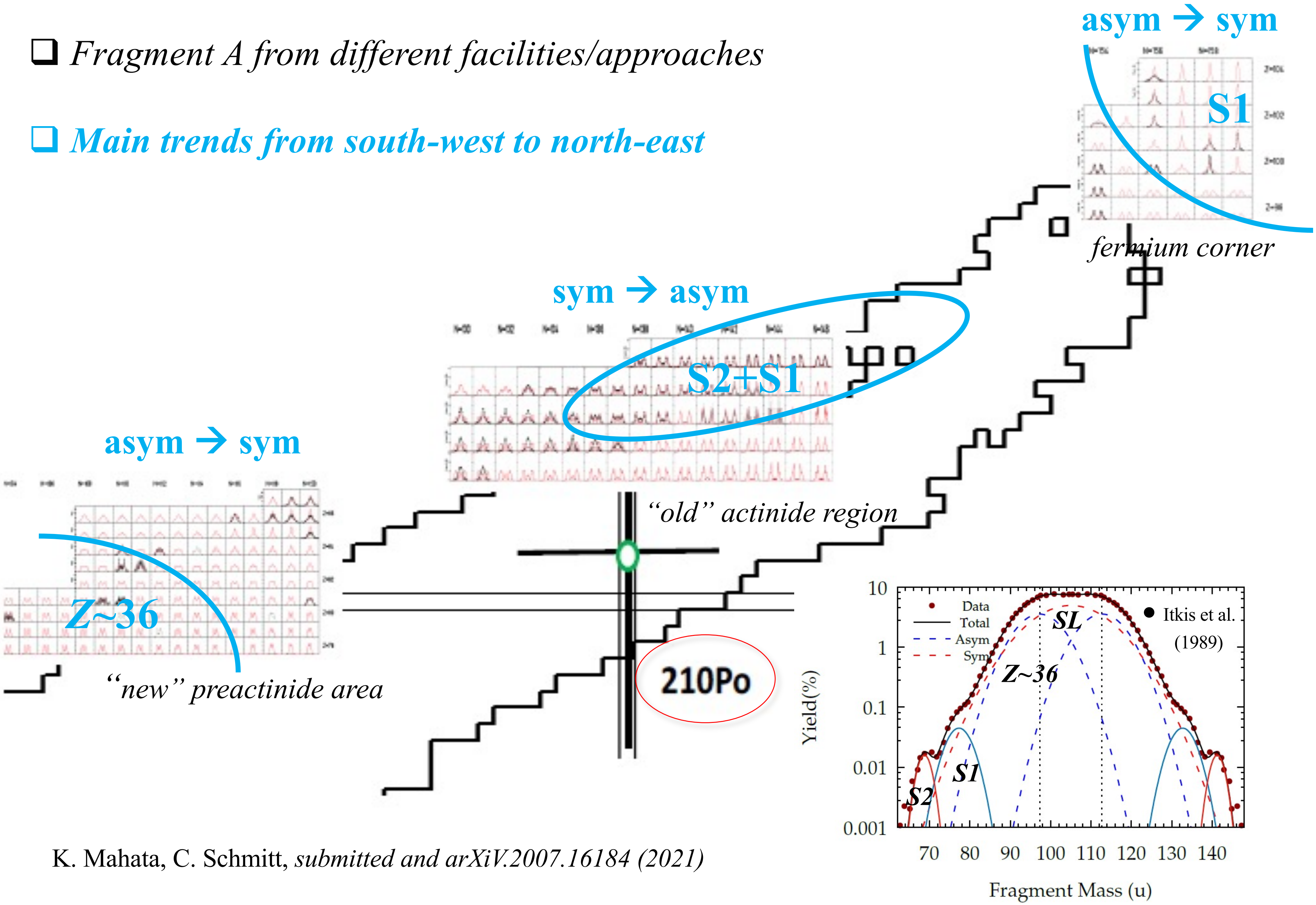
2. Due to the fissioning system macroscopic potential energy ~ $N/Z$

⇨ Competition = $f\,(A_{fiss}, Z_{fiss})$

**Can we « reconcile » the asymmetric fission properties observed in the « old » actinide and « new » lead regions?**

# Look across the chart

- ❑ *Fragment A from different facilities/approaches*
- ❑ ***Main trends from south-west to north-east***




K. Mahata, C. Schmitt, *submitted and arXiV.2007.16184 (2021)*

# Theory (1)

C A T E G O R Y

- ❒ Ab initio calculations impossible for heavy nuclei
- ❒ **Microscopic self-consistent models (mean-field and beyond)**
- ❒ **Macro-microscopic models**
- ❒ **(Semi-)empirical models**

T Y P E

- ❒ **Statistical approaches** (static considerations+Boltzman thermodynamics)
- ❒ **Dynamical (time-dependent) approaches** (Schrödinger/Langevin equation)

L I M I T A T I O N S

- ❒ **« Conceptual » unknowns** (*n*-*n* interaction, friction,…) → ***phenomenology***
- ❒ **Limited number of degrees of freedom** (in shapes, *A, Z, N/Z,* pairing…)
- ❒ **Issue of computing resources**

# Theory (2)

- ✓ Impressive progress by fundamental theories
  Some « tuning » remains necessary
  Mitigate quantitative achievement – Uncertain predictive power

***BUT DEFINITIVELY PROMISING***

- ✓ **Constrained time-dependent HF+BCS calculations for isotopic composition of fission fragments ⇨ *strong influence of protons***

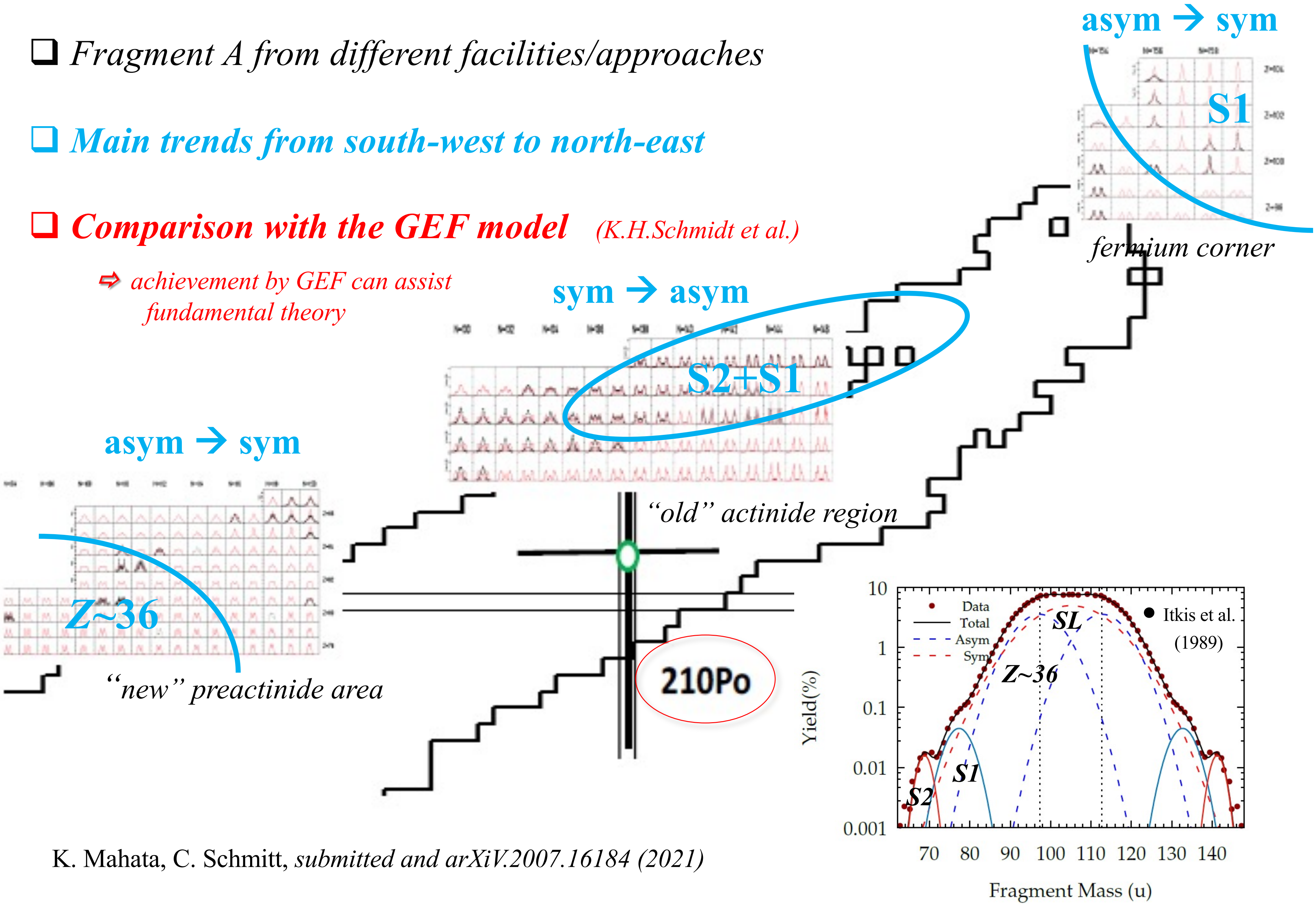
Scamps and Simenel, Nature 564, 382 (2018), PRC 100, 041602(2019)

$Z_H \sim 52\text{-}56$ octupole configurations drive fission of actinides

$N_H \sim 52\text{-}56$ and/or $Z_L \sim 34$ } quadrupole-octupole configurations drive fission of pre-actinides

# Look across the chart

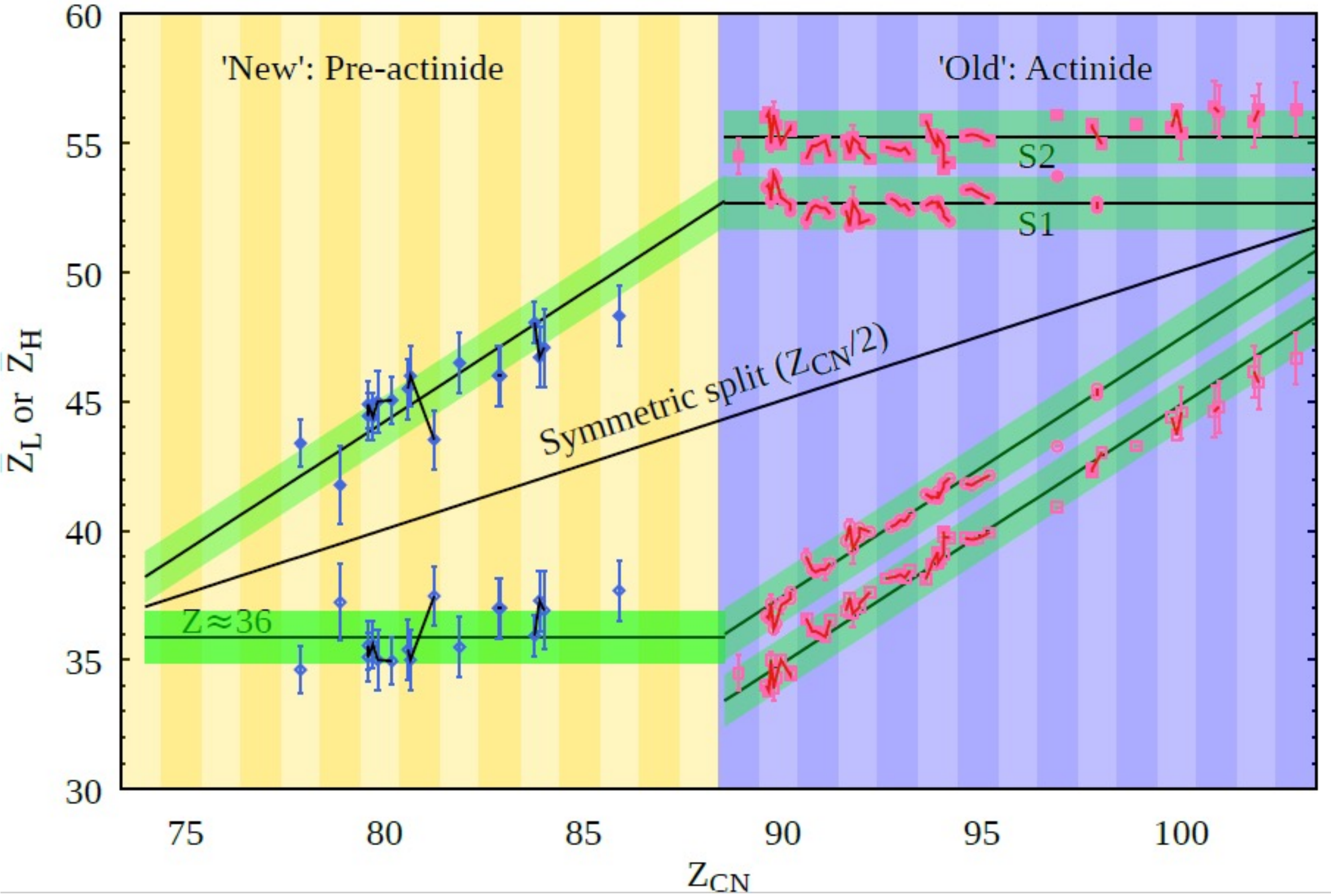
- ❑ *Fragment A from different facilities/approaches*
- ❑ ***Main trends from south-west to north-east***
- ❑ ***Comparison with the GEF model*** *(K.H.Schmidt et al.)*
  - ➩ *achievement by GEF can assist fundamental theory*




K. Mahata, C. Schmitt, *submitted and arXiV.2007.16184 (2021)*

# … About further extrapolation…

K. Mahata, C. Schmitt, *submitted and arXiV.2007.16184 (2021)*




**How do these trends evolve towards {rare-earth / super-heavy} regions?**

## Some conclusion

- *Fission is an exciting, intringuing, complex and rich process, which spreads over various domains*

- *Crucial fragment (A,Z) accurate information*
  *Leading quantal effects are identified*
  *Room for much effort on their competition + dynamics*

- *Essential widespread investigations in ($A_{fiss}$ , $Z_{fiss}$) over the nuclear chart*

**P E R S P E C T I V E S….**

# Thank you for your attention

**Special thanks to:**

K.-H.Schmidt, A. Lemasson, P. Moller