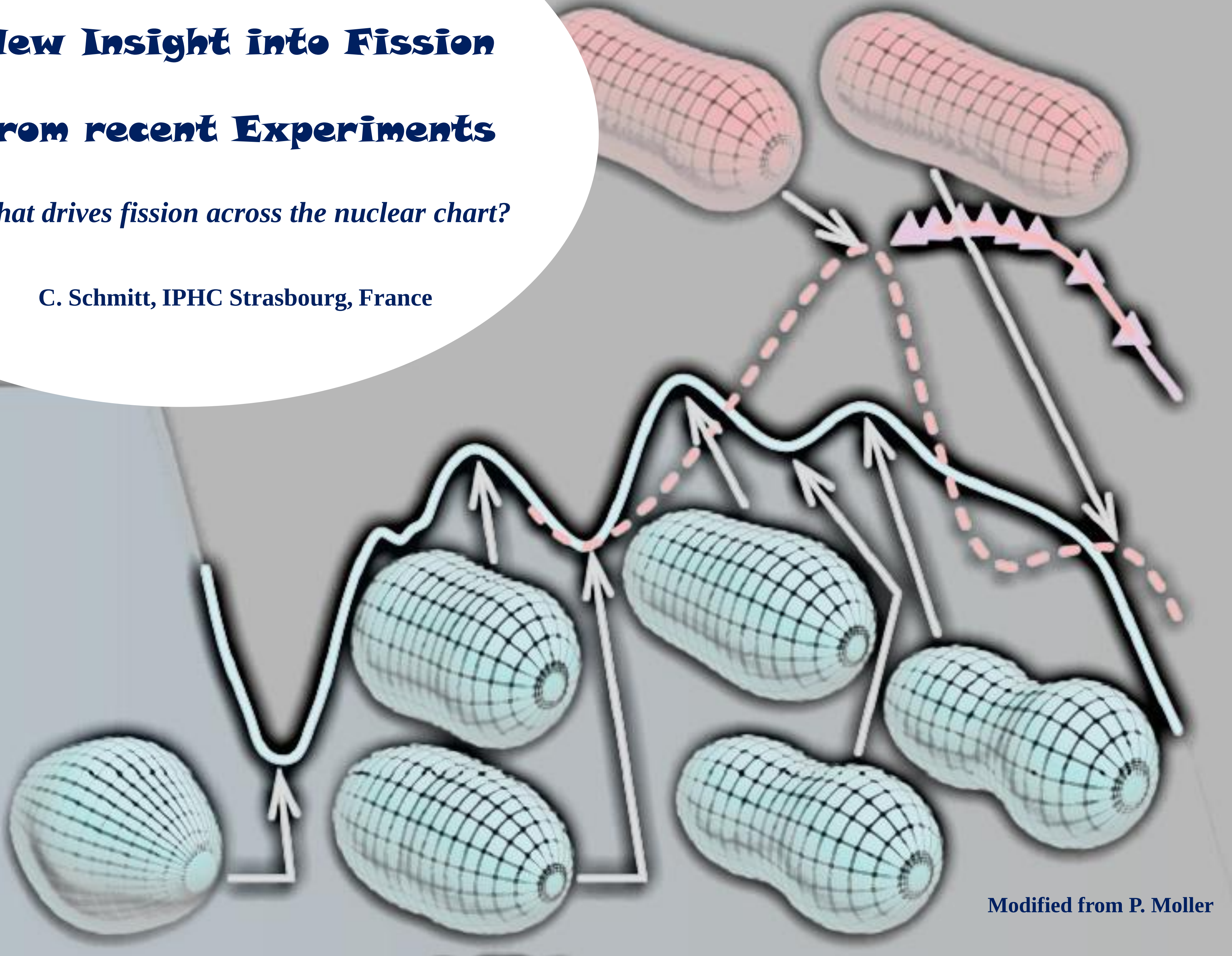
New Insight into Fission from recent Experiments

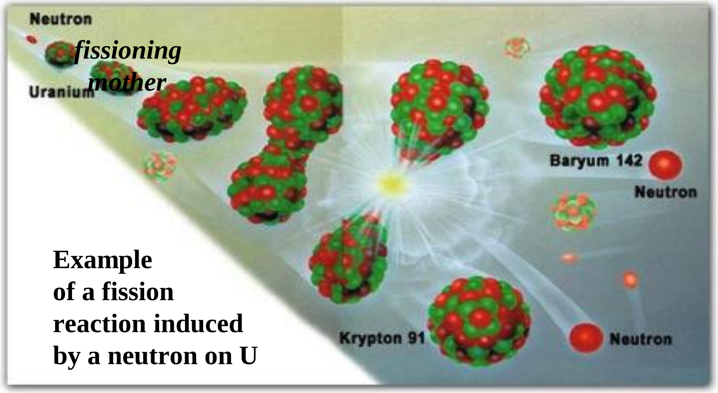
What drives fission across the nuclear chart?

C. Schmitt, IPHC Strasbourg, France



Modified from P. Moller

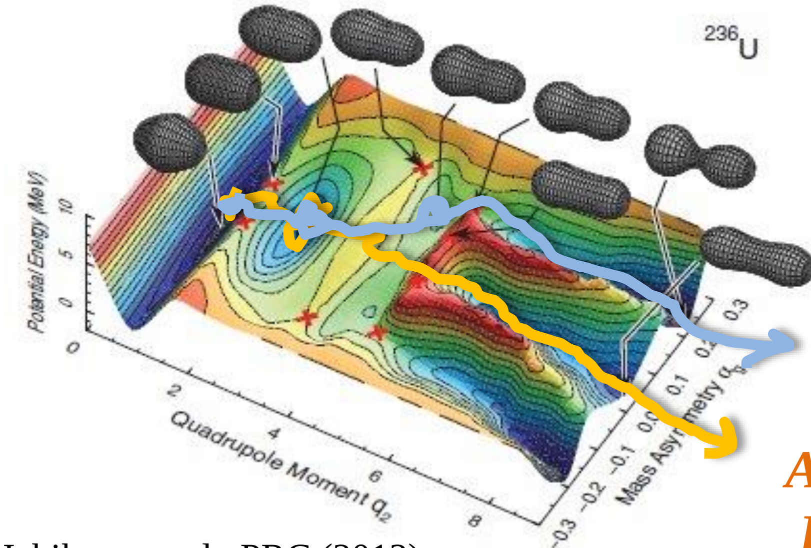
FISSION…



. . . . 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,γ ⟹	$A_{1,2}$', $Z_{1,2}$', $E_{1,2\,kin}$'
$A^*_{1,2}$, $Z^*_{1,2}$, $E^*_{1,2\,kin}$	n,γ ⟹	$A_{1,2}$, $Z_{1,2}$, $E_{1,2\,kin}$

✓ 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 *ΔA* = 3-5amu; Very poor info on *Z*

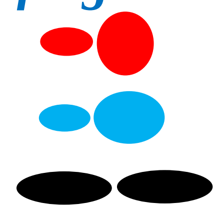
- ❒ Low-energy fission is predominantly asymmetric around uranium
- ❒ Heavy fragment located at *A*~130-150 independent on the system

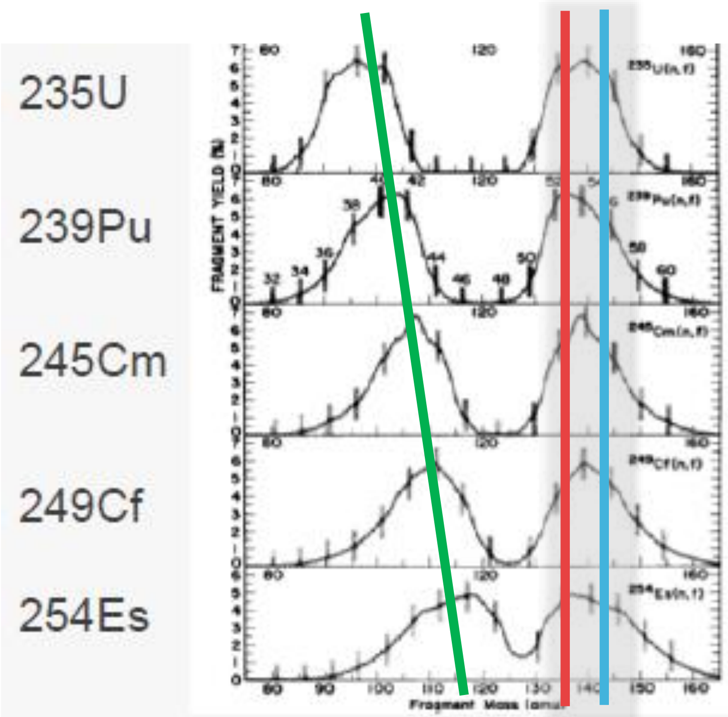
Double-humped asymmetric peak due to shell stabilized fragments

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

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

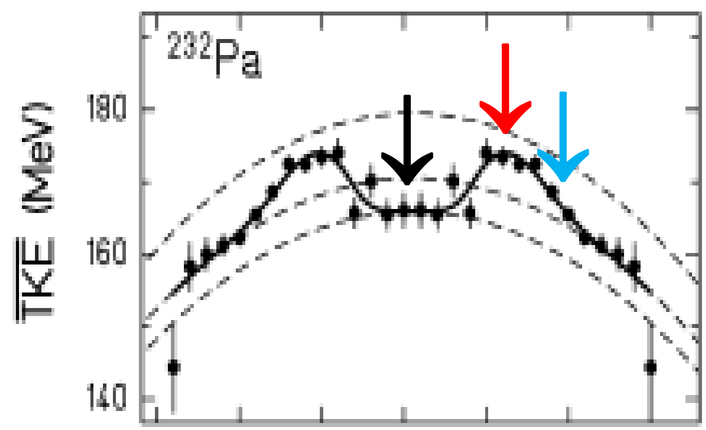
Symmetric contribution SL due to macroscopic energy





Unik et al. (1973)

❒ *TKE* confirmation

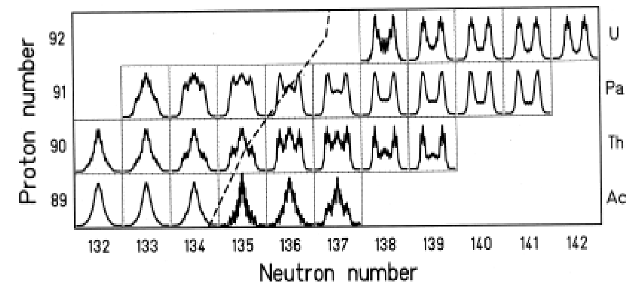


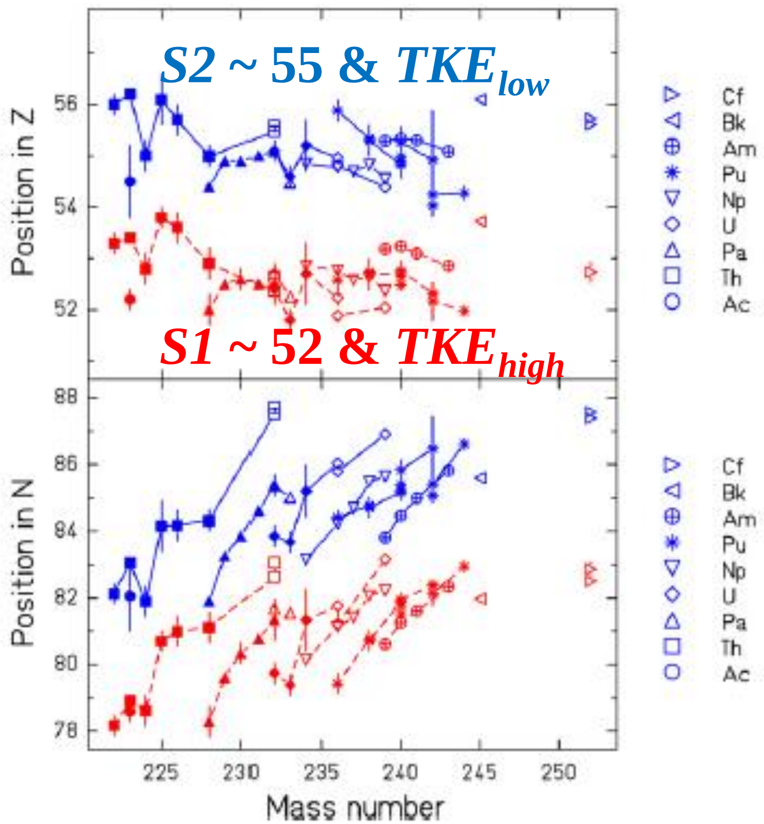
Schmidt et al., NPA (2000)

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.)

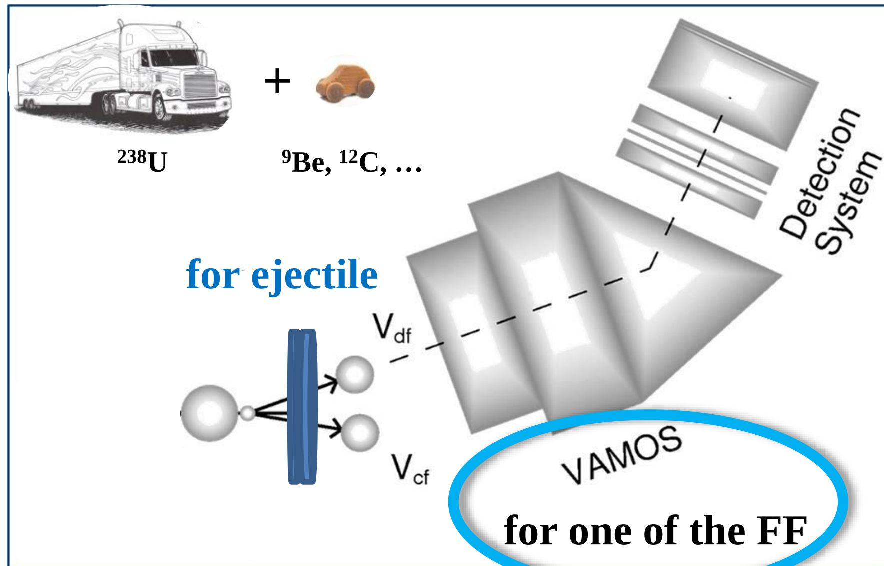
inverse kinematics + advanced heavy-ion spectrometer

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)*

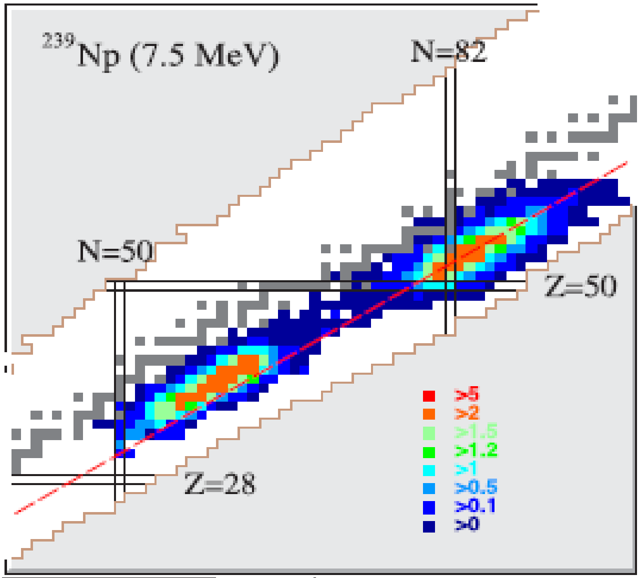
→ *Study fission by detecting in coinc. one of the FF in VAMOS*



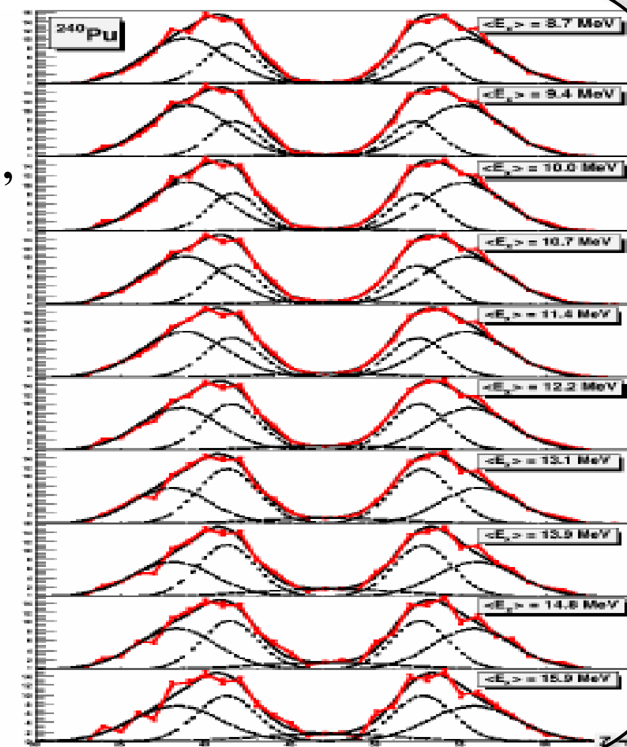
Fission properties for $^{238-239}$U, ^{239}Np, ^{240}Pu, ^{244}Cm, ^{250}Cf, with E^* ~ 6 to 46 MeV

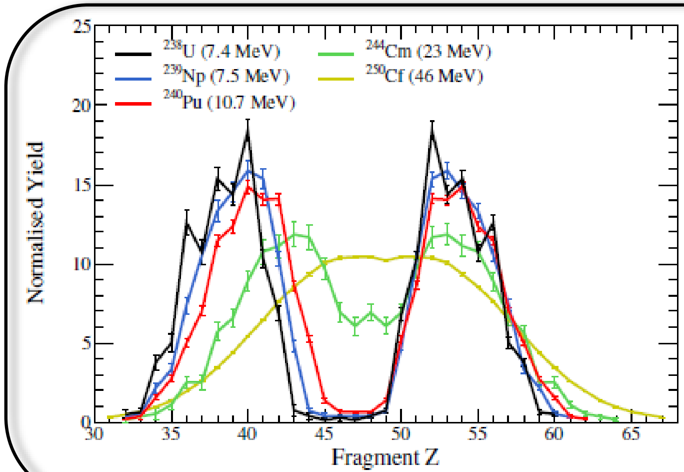
Sample of results from VAMOS@GANIL for actinides

Complete isotopic distribution with best resolution



Fission modes' 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?**

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 ***

supported by predictions by TDHF

(Scamps and Simenel, Nature 564, 382 (2018))

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

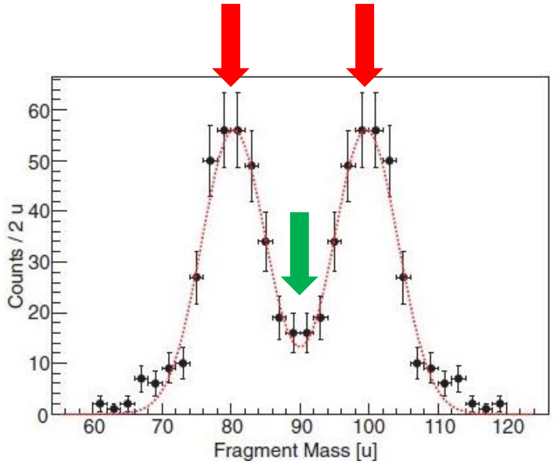
Z_{CN} / N_{CN} dependence,
nucleons from the neck

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

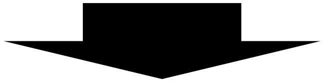
Current knowledge: Shell effects in the nascent fragments play a key role…

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

expected: 2 × ^{90}Zr $_{50}$
observed: ~ $A_{1,2}$ ~ 80 + 100



Andreyev et al., PRL (2010)



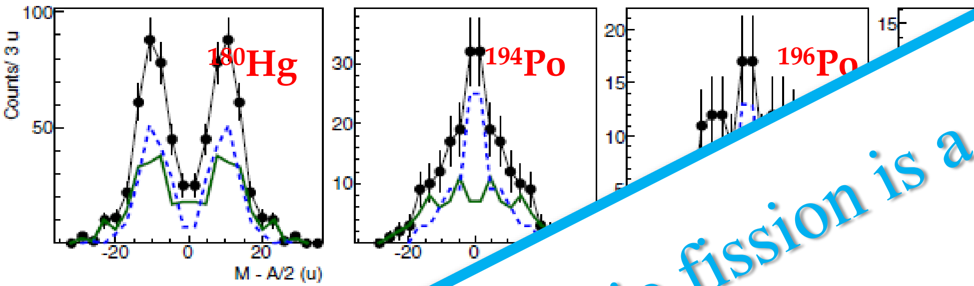
Evidence for a "new" type of asymmetric fission in the n-deficient pre-actinide region ?

Intense experimental/theoretical work

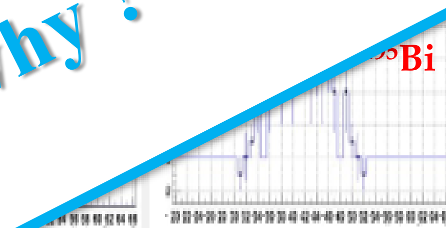
Can an independent "island" be delineated? No consensus yet

Status on fission measurements in the n-deficient re... ...round lead

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



❐ Electromag...

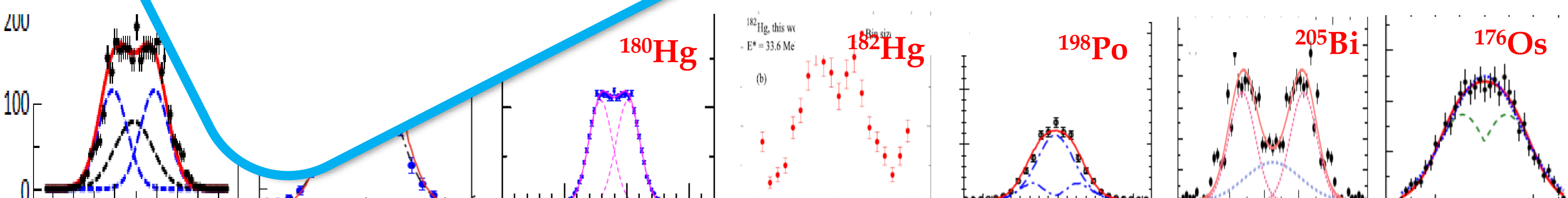


...G (2014)

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

… but why ?

❐ Fu... ...-50 MeV)



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

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

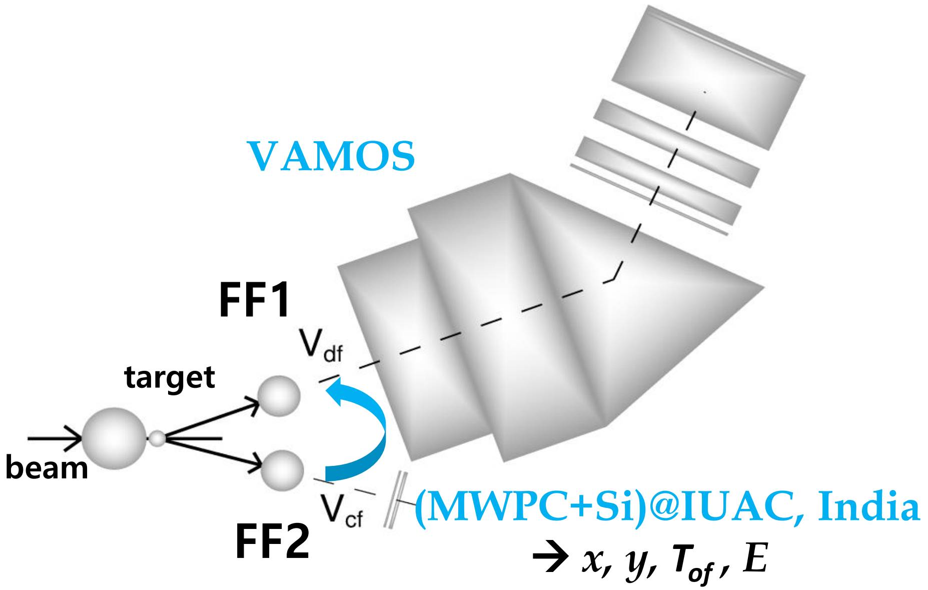
Benefit from the assets of GANIL to go beyond current information → ***(A, Z)***

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,ϑ,φ)

- **2nd arm @ 35°** for identifying the partner (A,v,ϑ,φ)



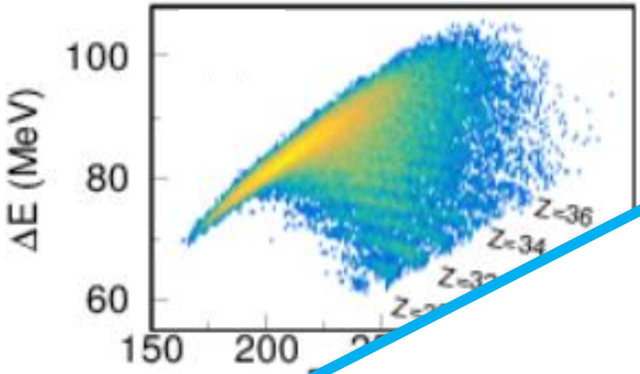
Innovative observables in the region:

- ***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 »

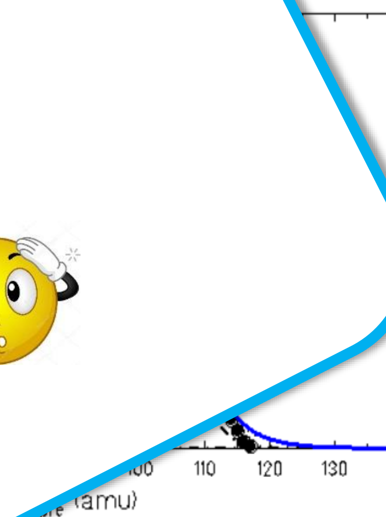
ΔE-E correlation at focal plane



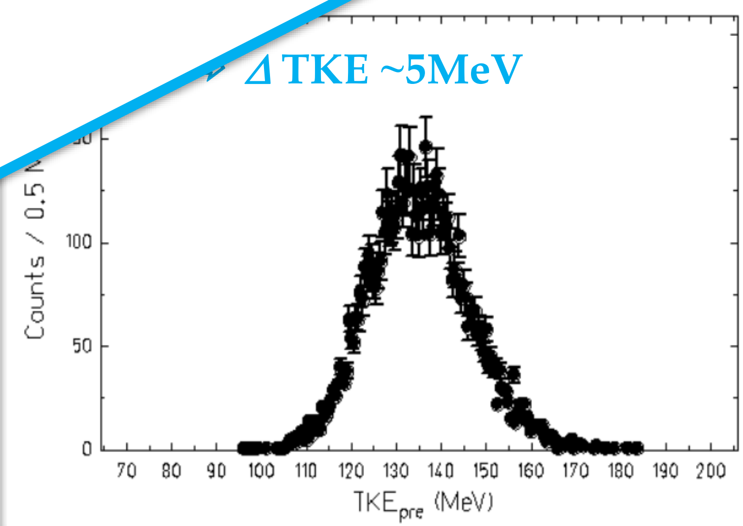
⇨ S... ary $\Delta A/A$ ~ 0.8%

VAMO... arm

↪ *Kin... thod (2v)*

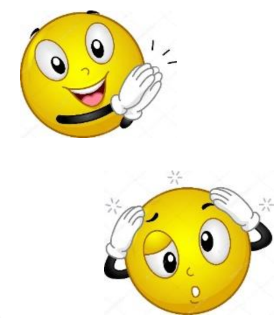


⇨ Δ TKE ~5MeV



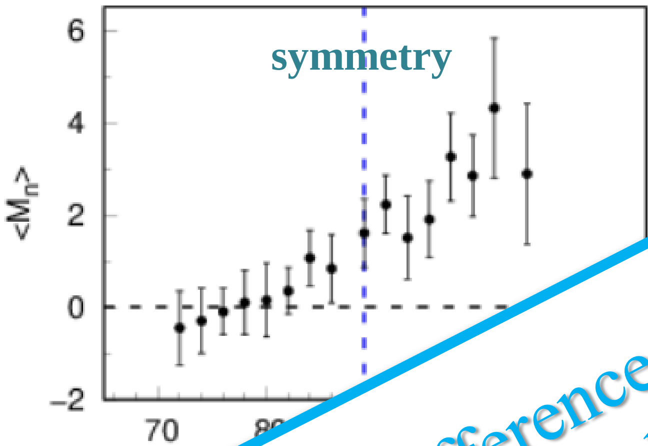
Great "technical" challenge

… 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 ?

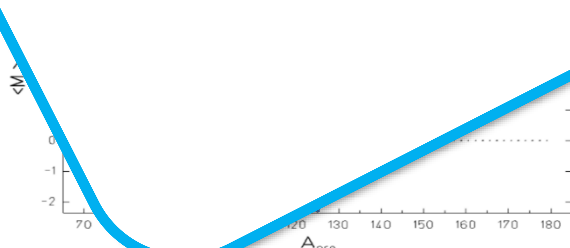
...t is n-rich/poor

...s emit few neutrons!

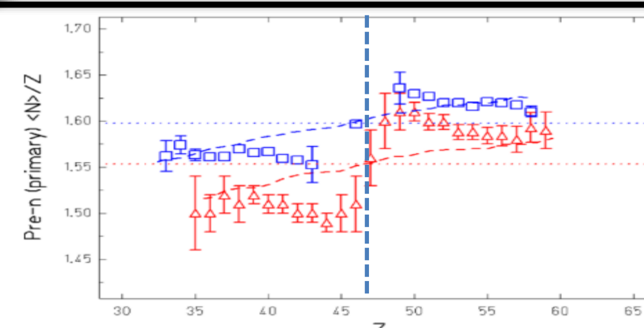
^{239}U

^{240}Pu

^{252}Cf



Actinides



^{239}U

^{240}Pu

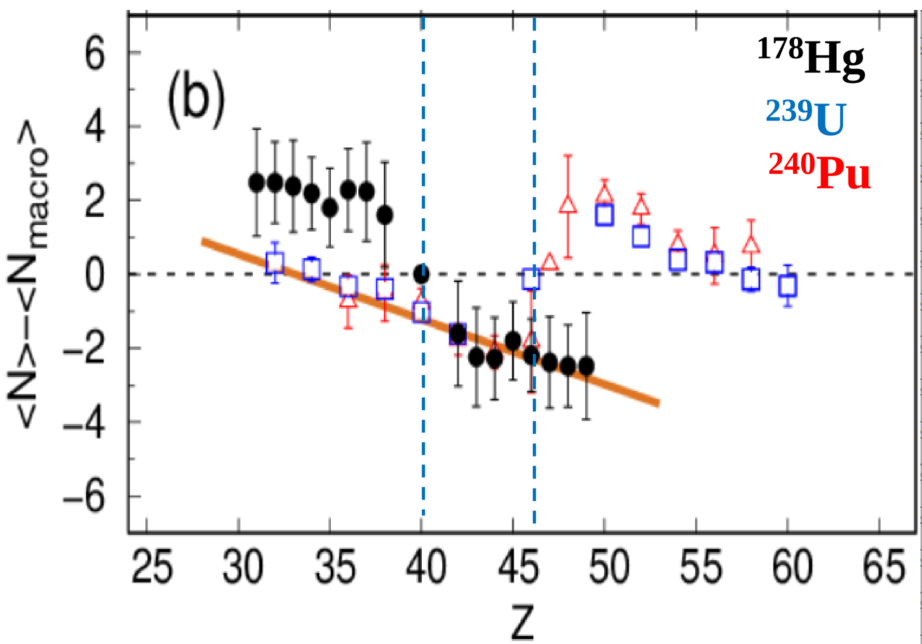
⇨ Famous M_n sawtooth

⇨ 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?

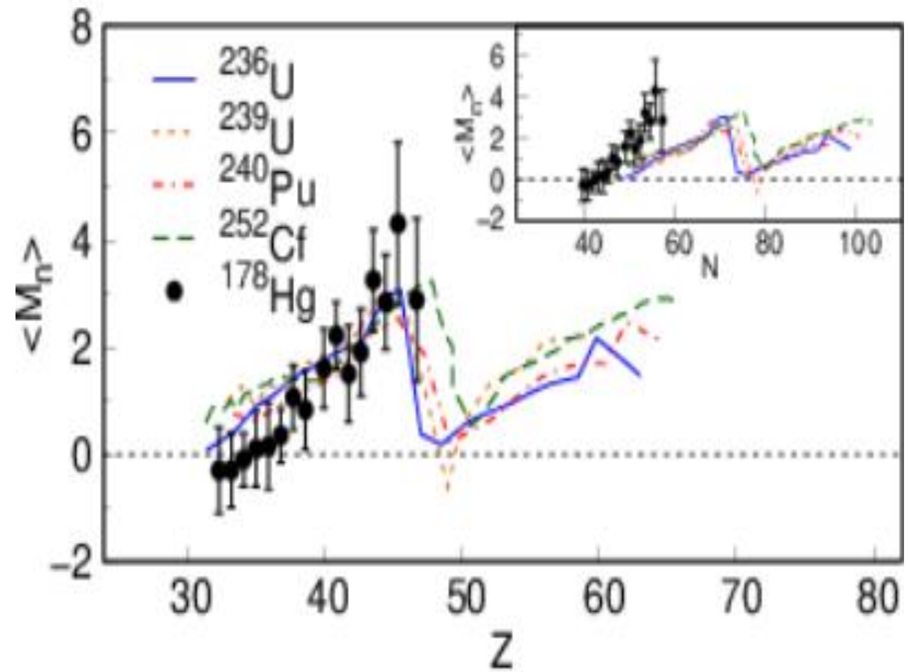
Microscopic contribution to n-richness



➩ **Same microscopic contribution to *N/Z* at given *Z* for different *N*'s**

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

Shape relaxation after scission



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

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

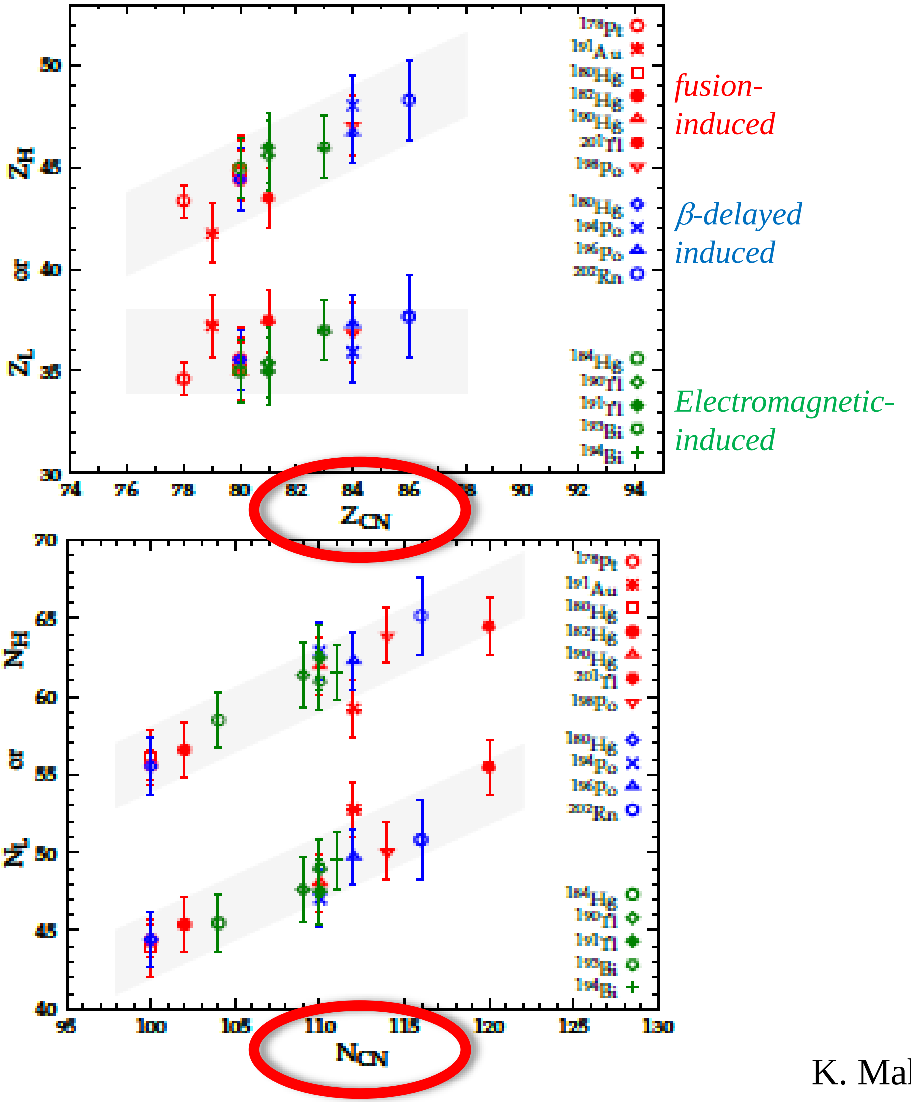
Protons as key drivers in fission

Shape relaxation governed by the proton sub-system for *Z* between 30 and 50
⇨ **The scission configuration is driven by up to highly-deformed shapes due to <u>proton</u> nuclear structure effects**

Neutron-deficient pre-actinides mandatory
to discriminate between
proton and neutron drivers

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 TDHF

(Scamps and Simenel, *PRC100,041602*)

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**

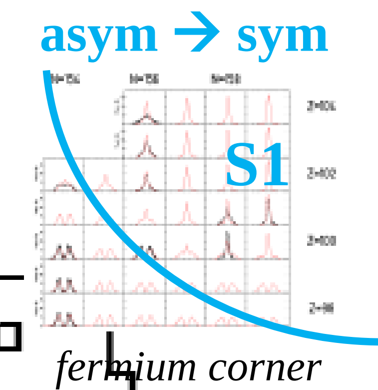
2. Due to the fissioning system macroscopic potential energy ~ N/Z

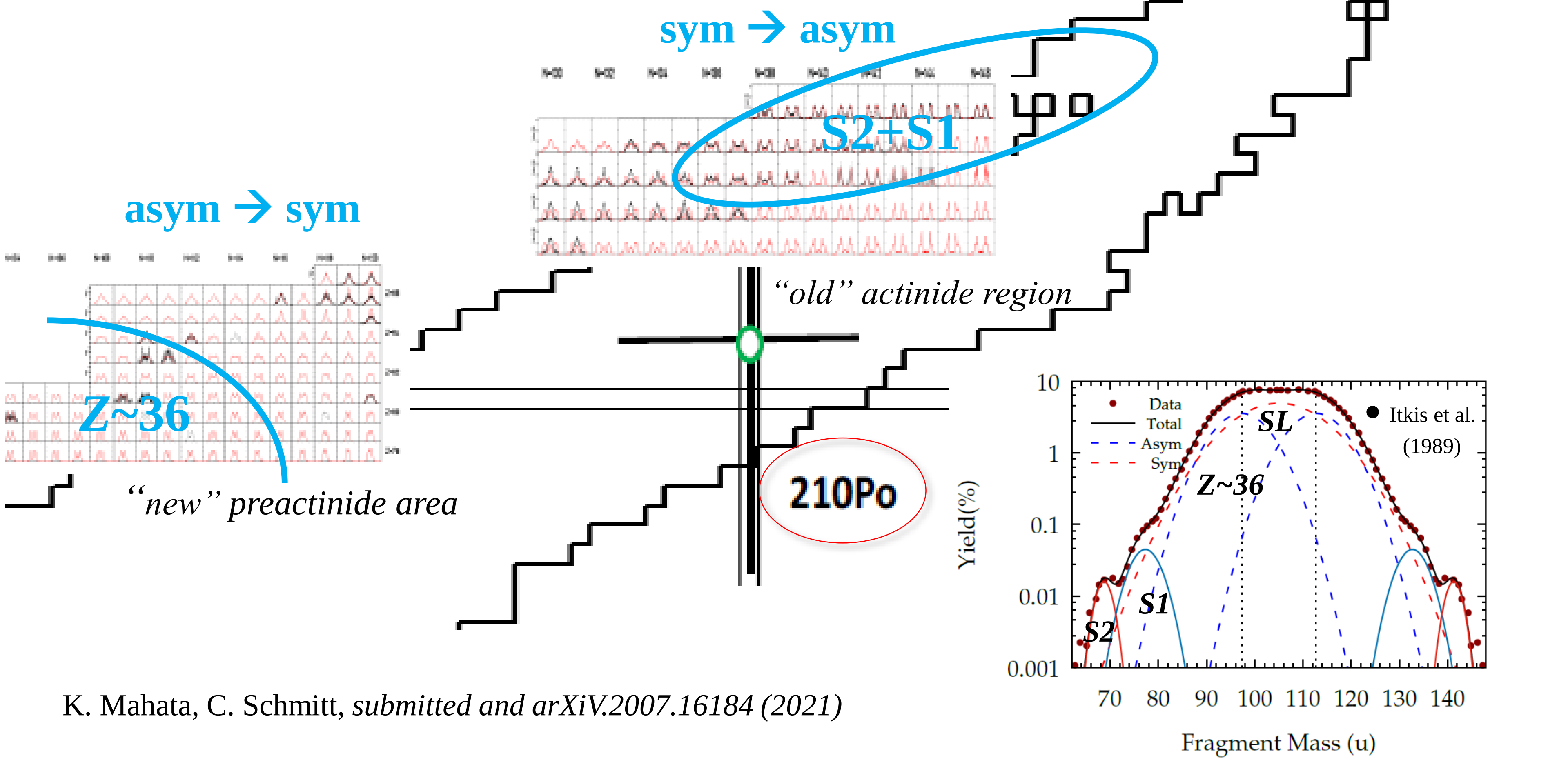
⇨ Competition = $f\,(A_{fiss}, Z_{fiss})$

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***

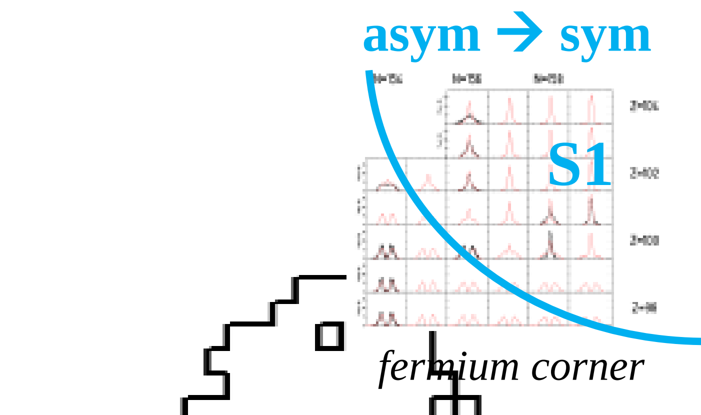


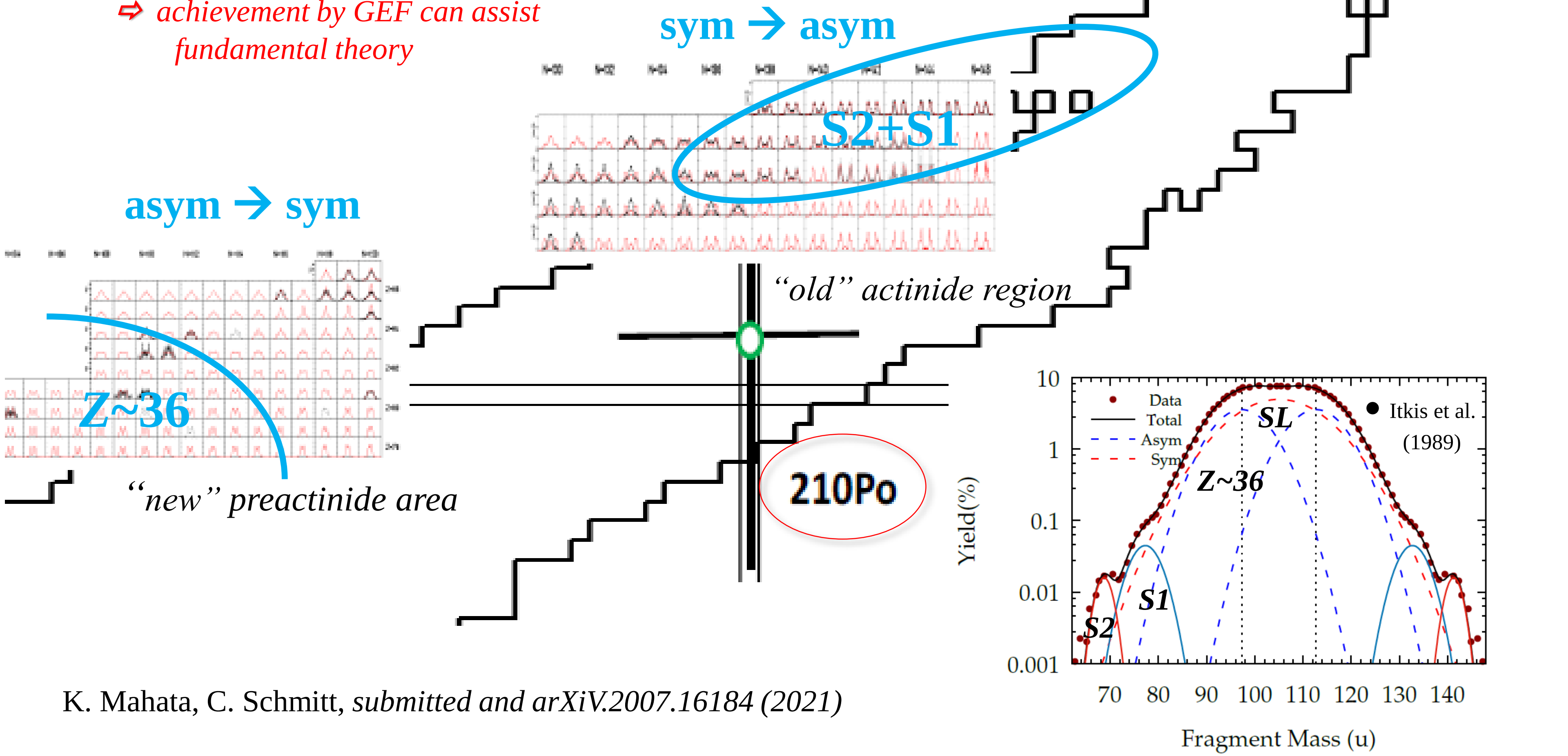


K. Mahata, C. Schmitt, *submitted and arXiV.2007.16184 (2021)*

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*

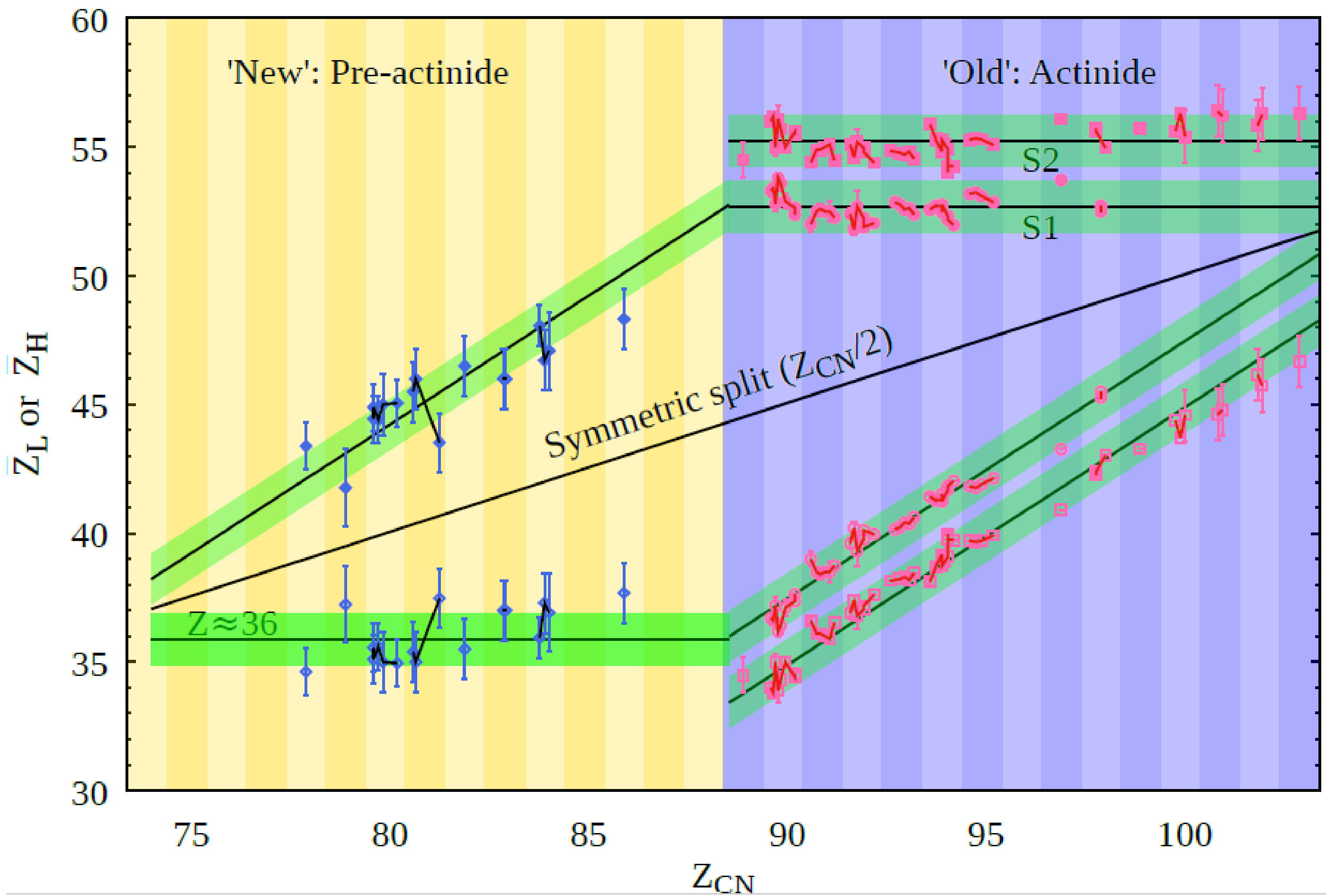




K. Mahata, C. Schmitt, *submitted and arXiV.2007.16184 (2021)*

… 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*

Thank you for your attention

Special thanks to:

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