Shell-driven Fission across the Nuclear Chart

D.J. Hinde, J. Buete, B.M.A. Swinton-Bland, K.J. Cook, M. Dasgupta, A.C. Berriman, D.Y. Jeung, K. Banerjee, L.T. Bezzina, I.P. Carter, C. Sengupta, C. Simenel, E.C. Simpson

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What controls the Fission mass distribution?

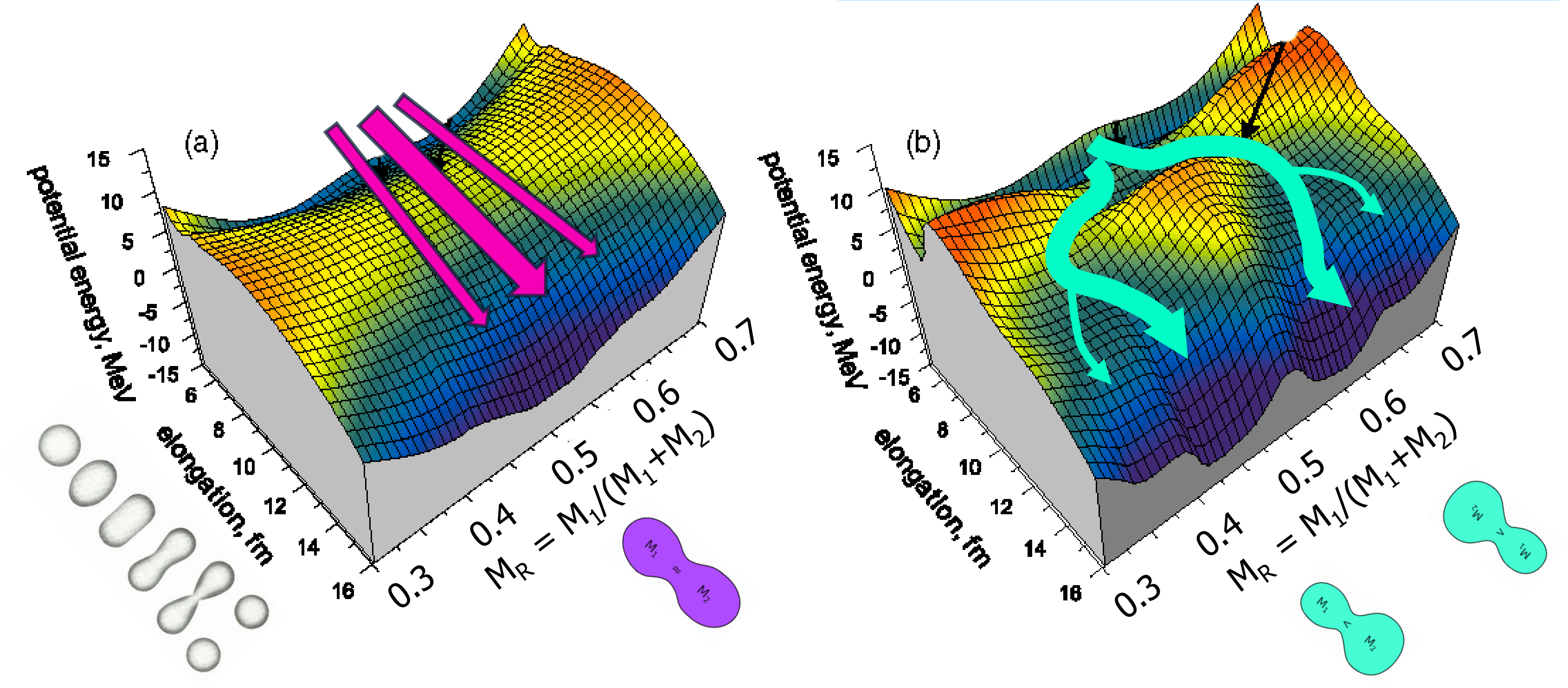
Dominantly the Potential Energy Surface (PES)

Trajectories traverse the PES, leading to scission

J. Phys. G: Nucl. Part. Phys. **35** (2008) 035104 A V Karpov *et al*

Classical Liquid Drop PES

Including quantum shell gaps



Smooth surface, single Gaussian mass-symmetric fission peak; M_R=0.5

Irregular surface ⟹ mass - asymmetric fission peaks

What controls the Fission mass distribution?

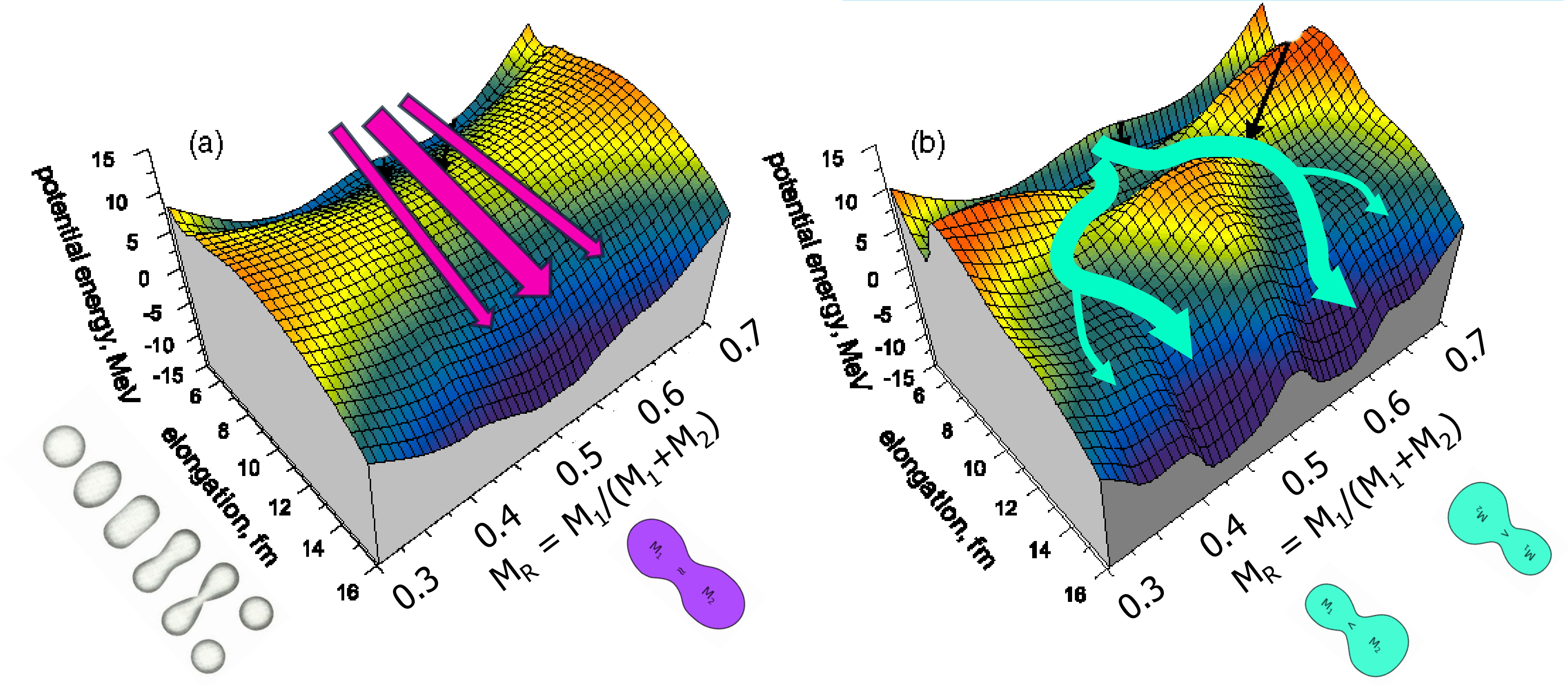
J. Phys. G: Nucl. Part. Phys. **35** (2008) 035104 A V Karpov *et al*

Classical Liquid Drop PES

Including quantum shell gaps

Effects of quantum shells attenuate ("melt") with increasing Ex

⟹ transition towards Liquid Drop PES



Smooth surface, single (Gaussian) mass-symmetric fission peak; M_R=0.5

Irregular surface ⟹ mass - asymmetric fission peaks

Experimental fission fragment characterization (2V)

In c.m. frame:

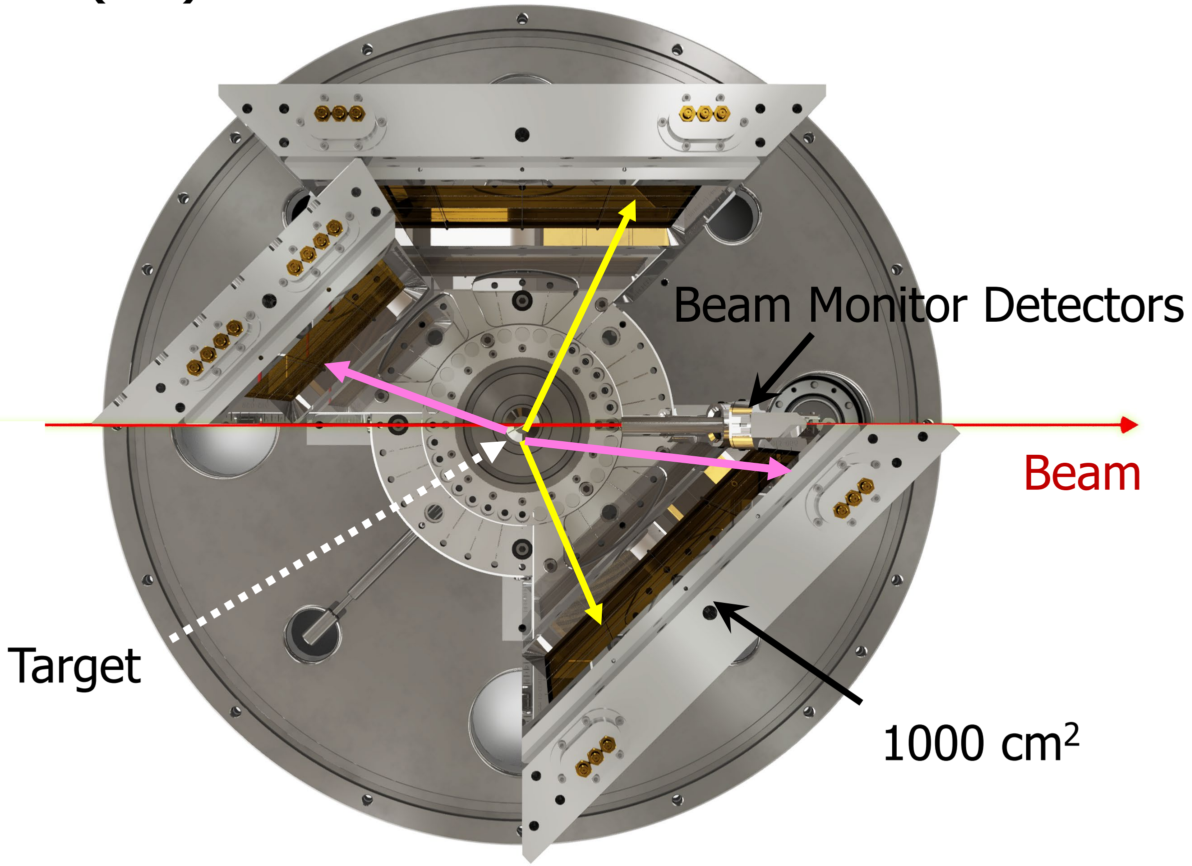
Conservation of momentum $M_1V_1=M_2V_2$

$M_R = M_1/(M_1+M_2) = V_2/(V_1+V_2)$

$M_1 + M_2 = M_{CN}$ ⇒ M_1, M_2, TKE (= E_1+E_2)

$(N/Z)_{FF} \sim (N/Z)_{CN}$ ⇒ Z_1,N_1; Z_2,N_2 (UCD approx.)

Mass resolution limited by velocity perturbations due to momentum carried by neutrons emitted from the fragments



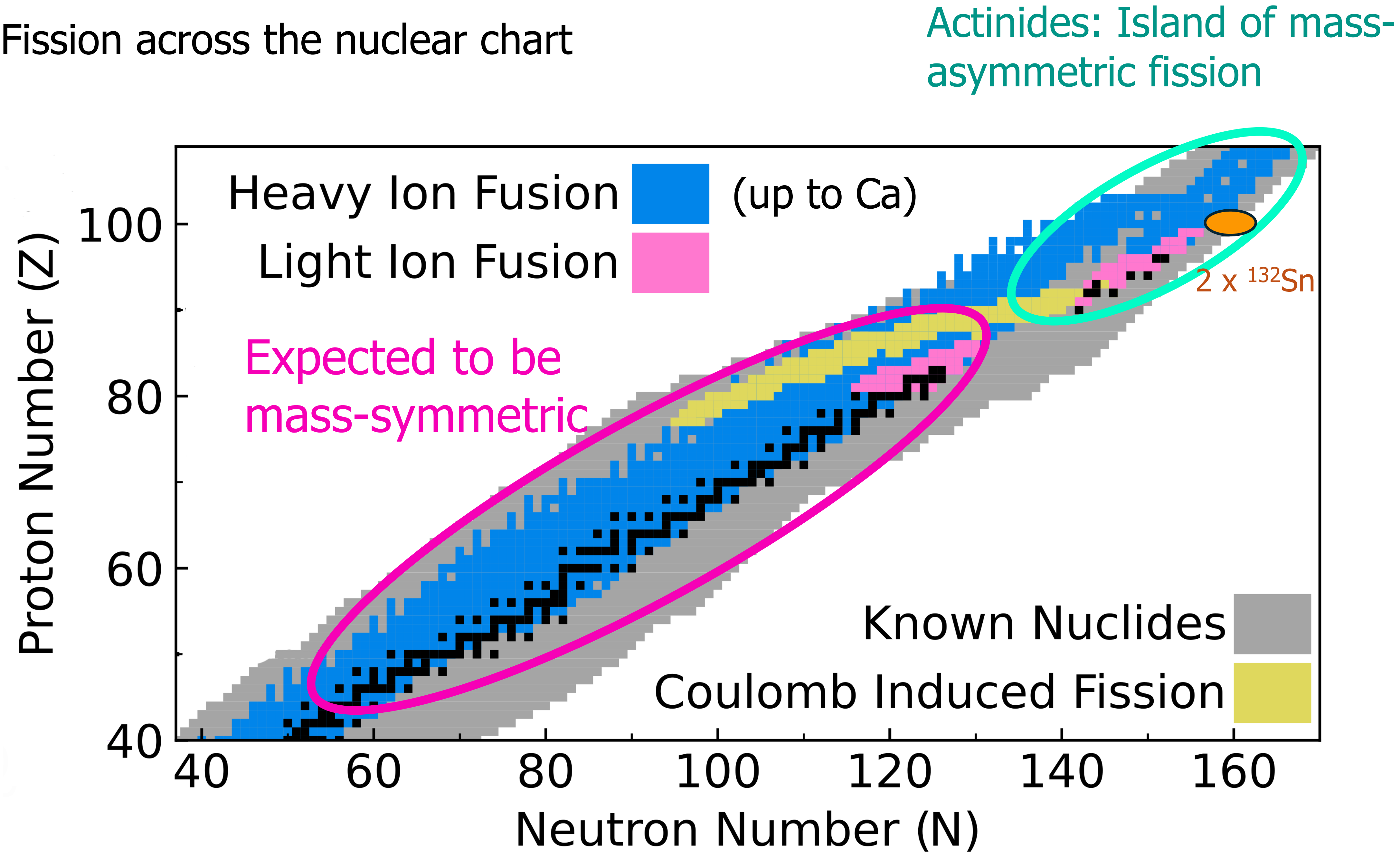
ANU CUBE Spectrometer

18 to 30 cm flight path, ~250 ps FWHM

< 0.3 degrees angular resolution

Measures ~25% of all fission events

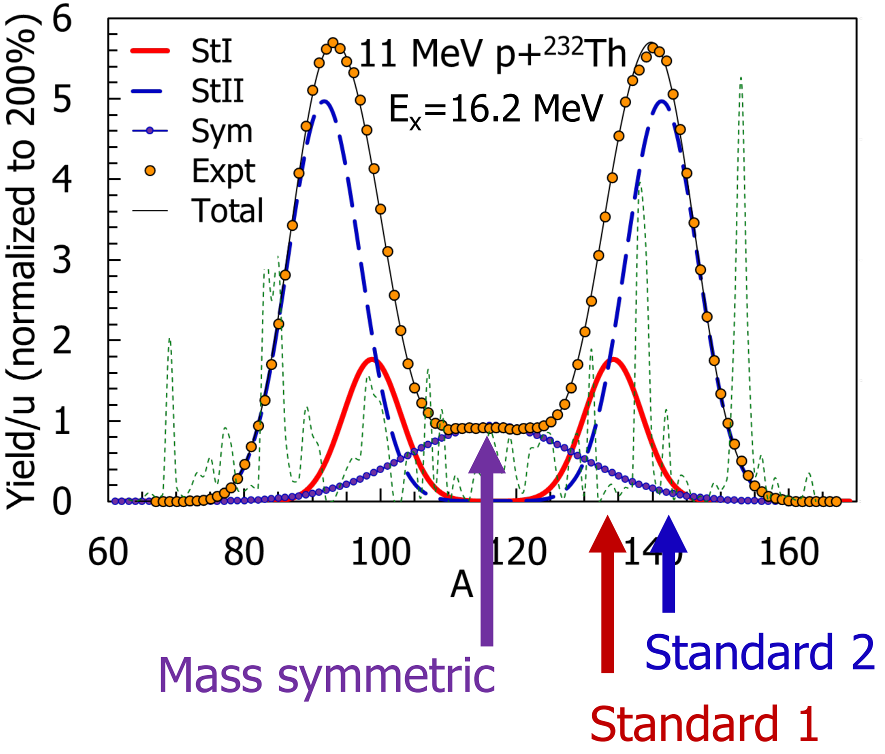
Fission across the nuclear chart



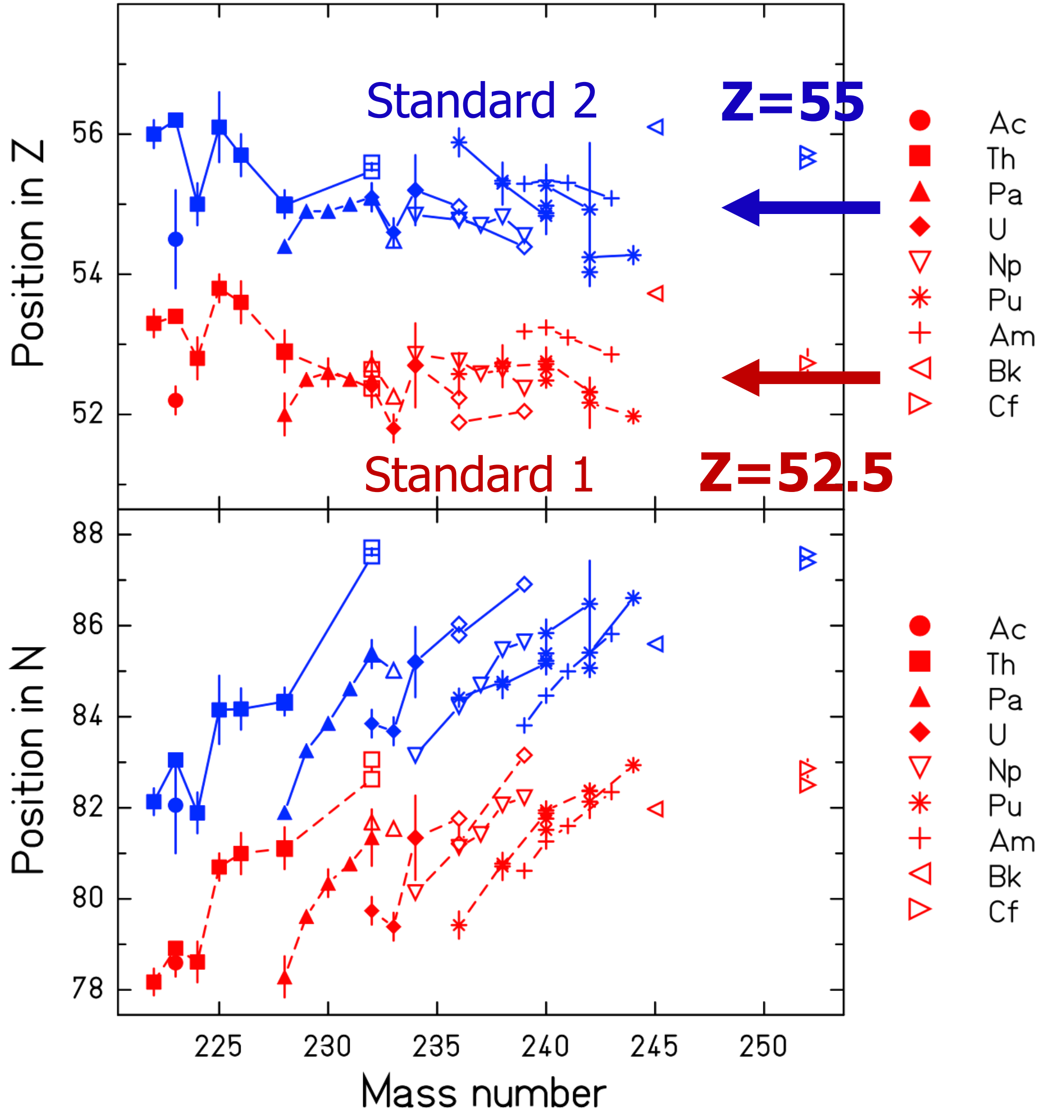
Actinide systematics ⇨ dominance of proton shell gaps in heavy fragment

Main actinide fission modes

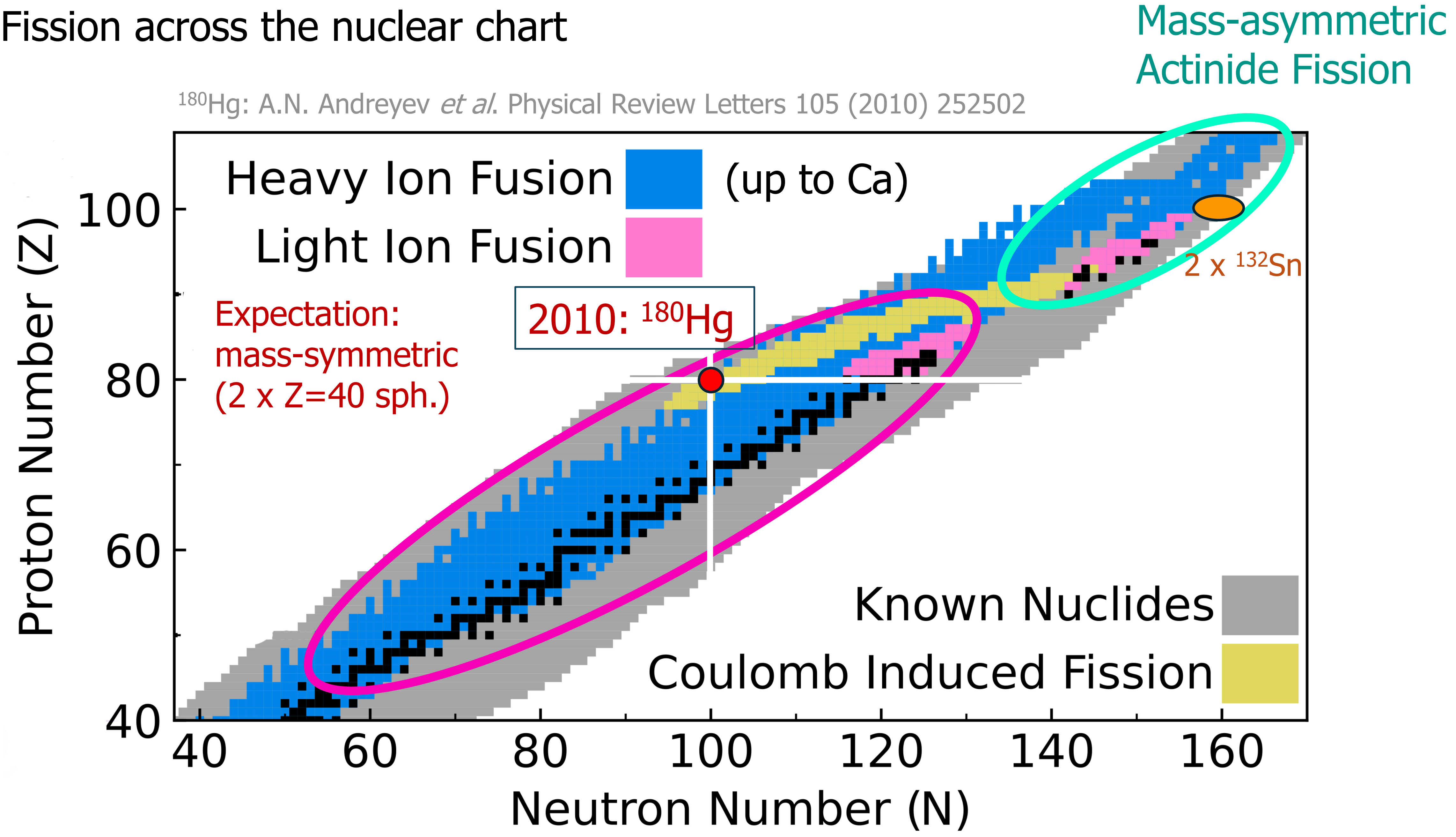
A.C. Berriman *et al.*, Phys. Rev. C106(2022)064614



Böckstiegel *et al.* Nucl Phys A802(2008)12



Fission across the nuclear chart

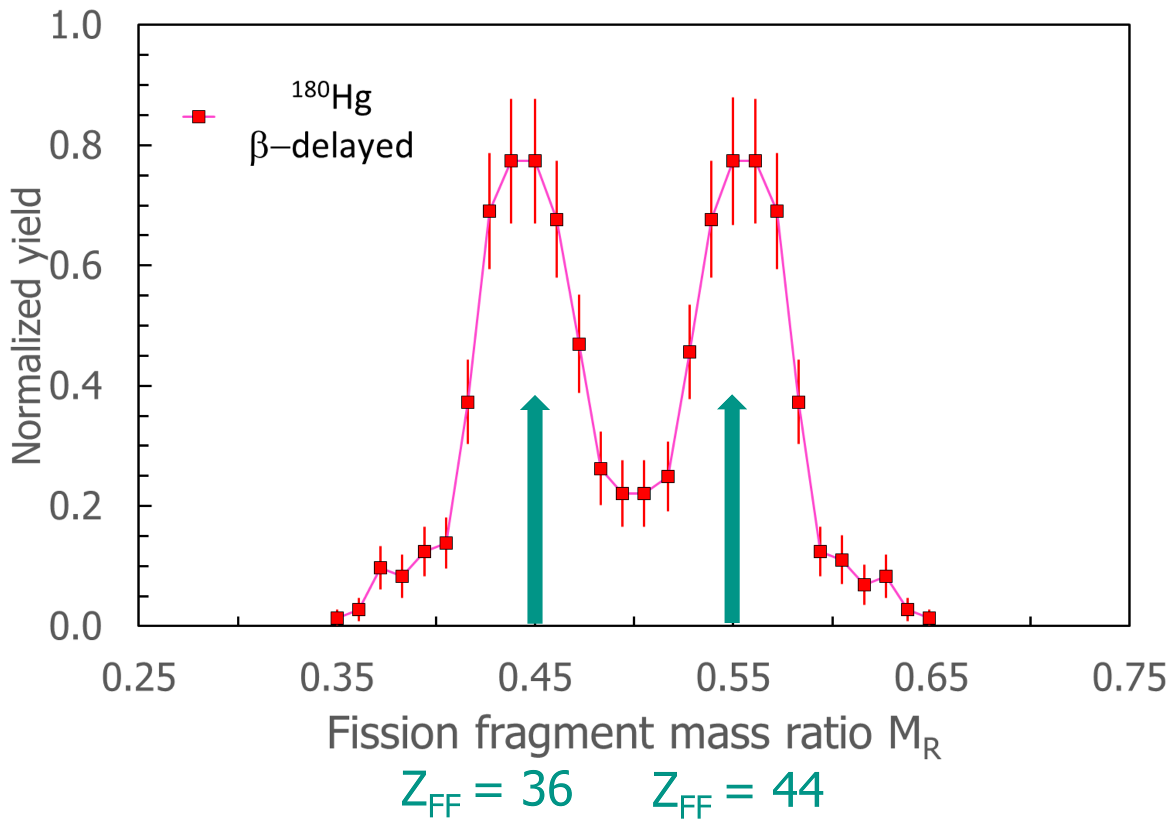


Discovery of mass-asymmetric fission of Hg nuclei – breakthrough!

Fission following β-decay of ^{180}Tl
^{180}Hg fission; E_x~10 MeV

A.N. Andreyev *et al*. Physical Review Letters 105 (2010) 252502.

First strong mass-asymmetric fission outside actinides
Different shell origin:
(Close to Z~36 or 44)



Discovery of mass-asymmetric fission of Hg nuclei – breakthrough!

Fission following β-decay of ^{181}Tl
^{180}Hg fission; E_x~10 MeV

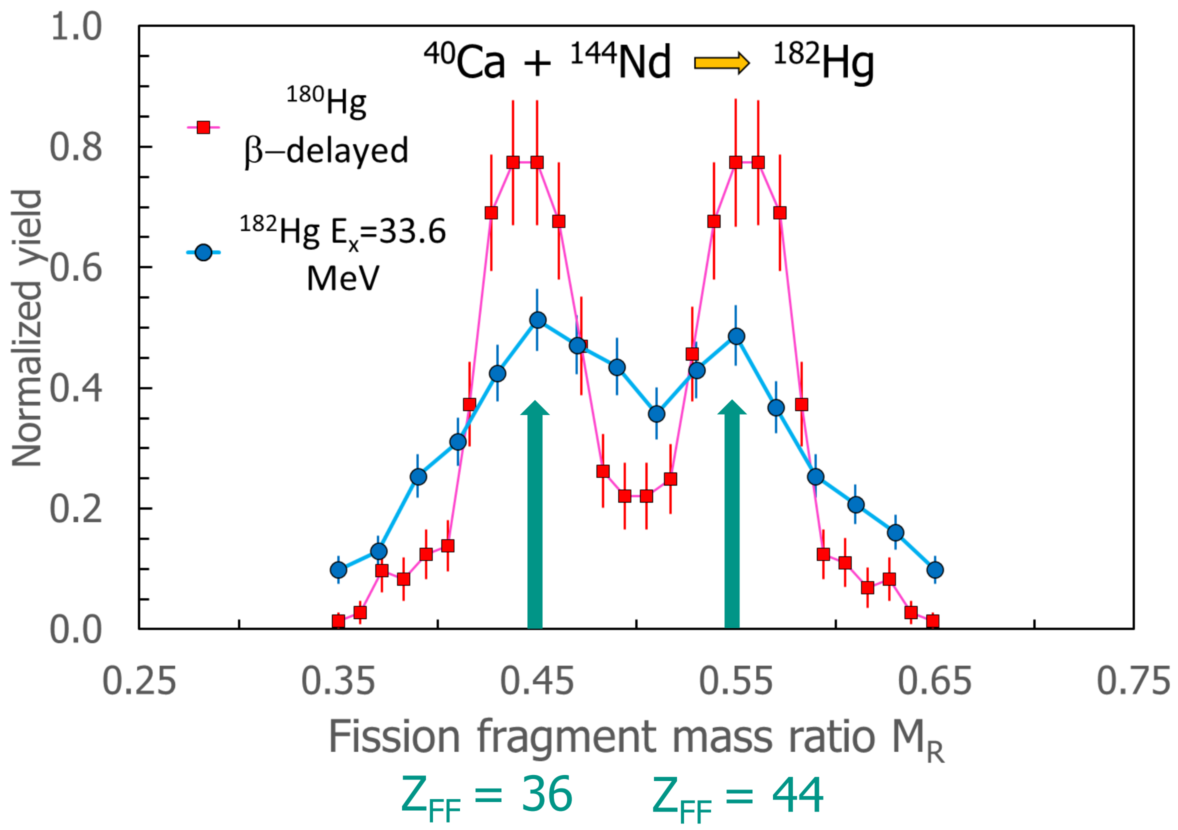
A.N. Andreyev *et al*. Physical Review Letters 105 (2010) 252502.

First strong mass-asymmetric fission outside actinides
Different shell origin:
(Close to Z~36 or 44)

Fission following heavy-ion fusion
^{40}Ca + ^{142}Nd ⟹ ^{182}Hg; E_x=34 MeV)

E. Prasad *et al*., Physical Review C91(2015)064605.

Contemporaneous: K. Nishio *et al*., Physics Letters B748(2015)89.

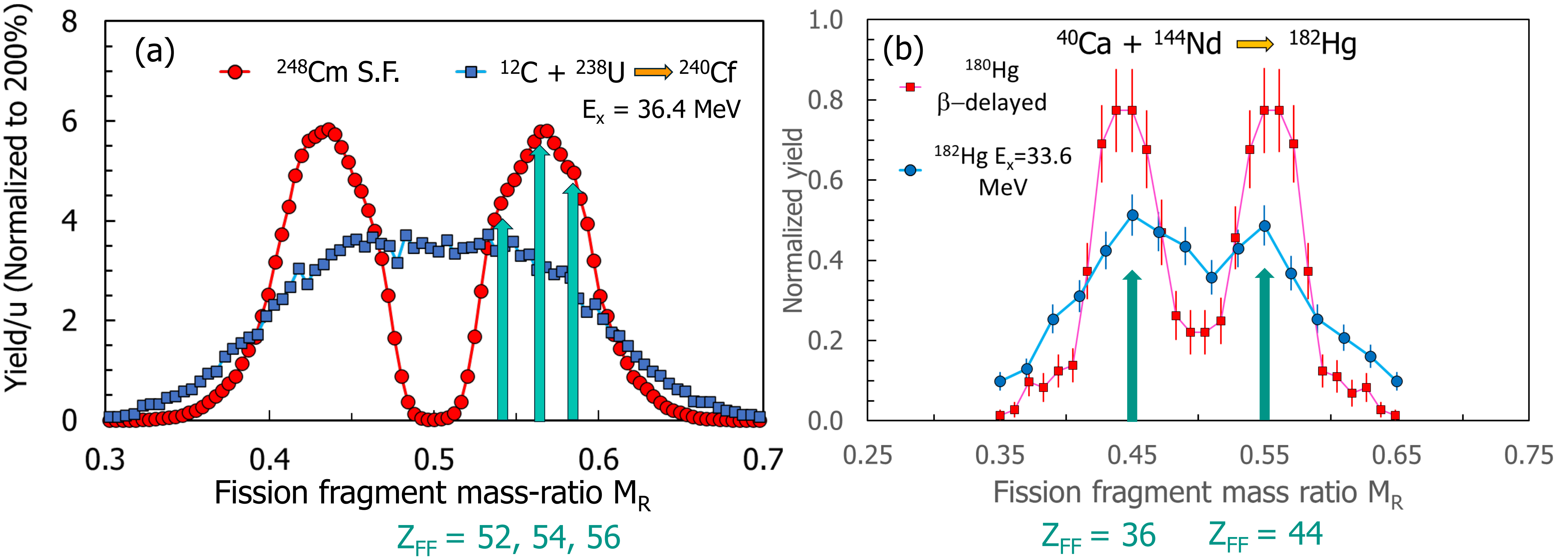


Shell-driven structure in H.I. fission, despite Ex

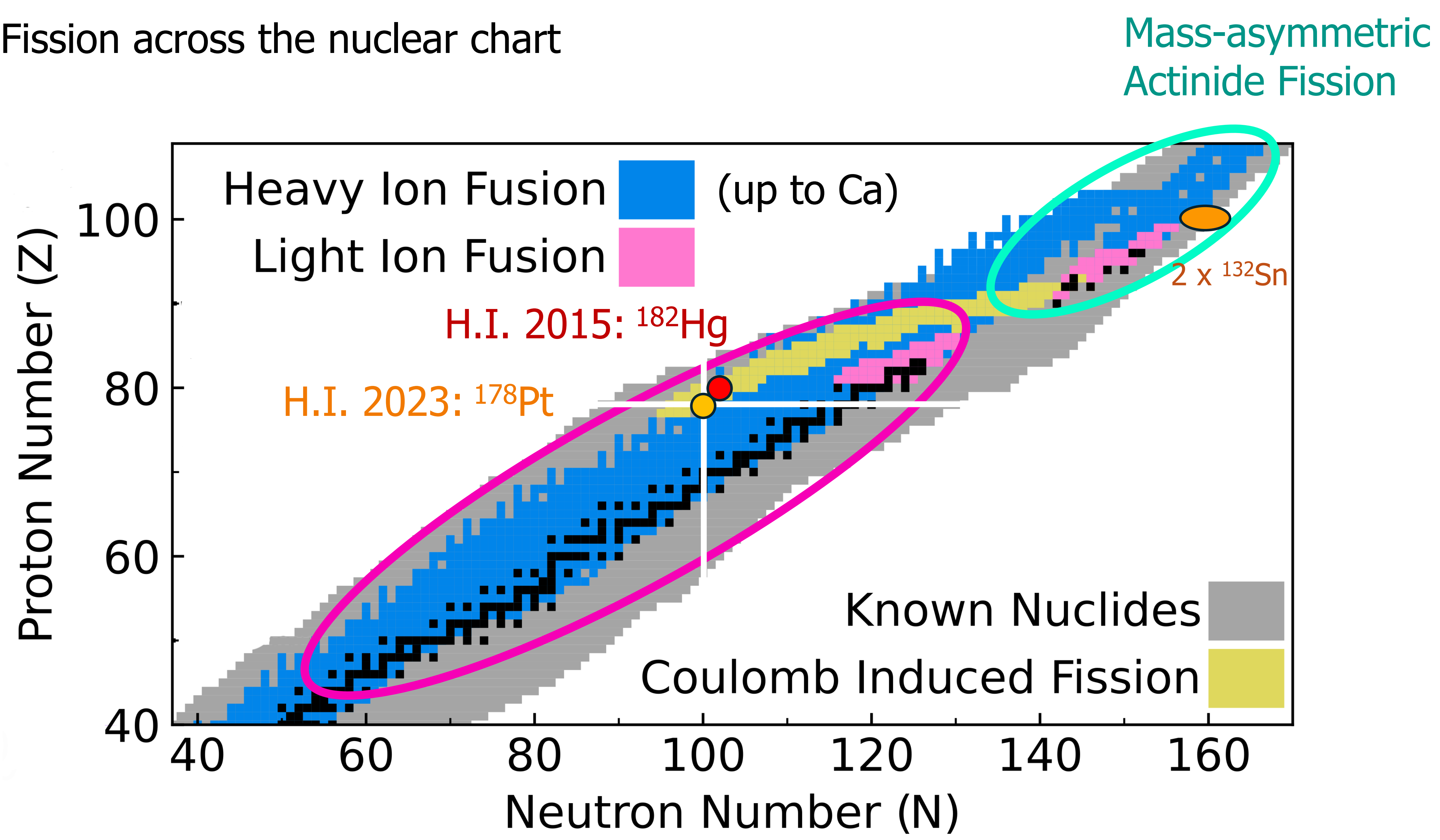
Effect attenuates with Ex (as in actinide fission)

^{248}Cm: A.C. Berriman *et al.*, Phys. Rev. C106(2022)064614

^{182}Hg: E. Prasad *et al.*, Physical Review C91(2015)064605.



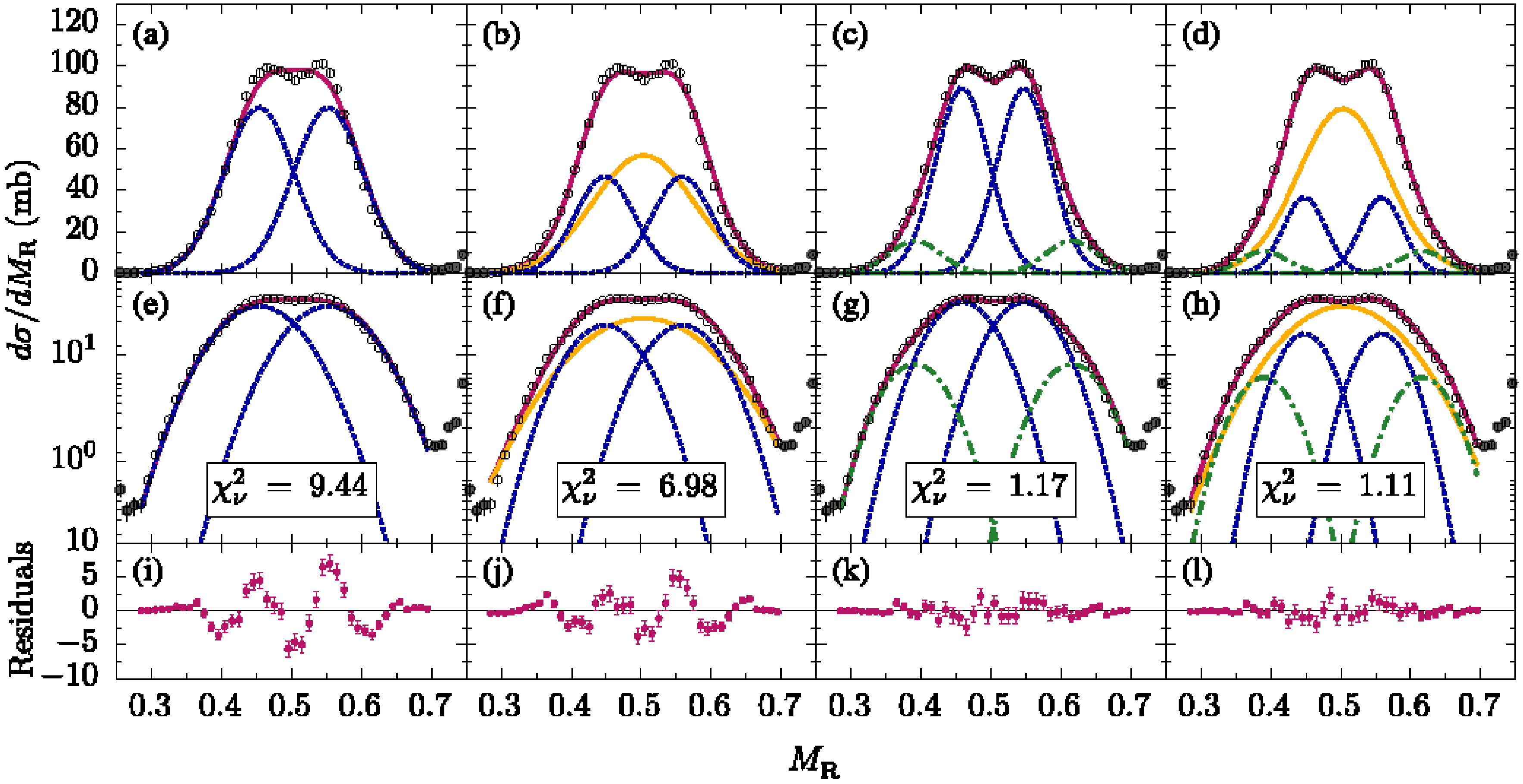
Fission across the nuclear chart



Fits to high statistics fission mass distributions (~10^5 fission events)

$^{34}S+^{144}Sm$ ➡ ^{178}Pt fusion-fission M_R-TKE distribution (expt. 4/2018, then COVID)

E_x = 37.7 MeV

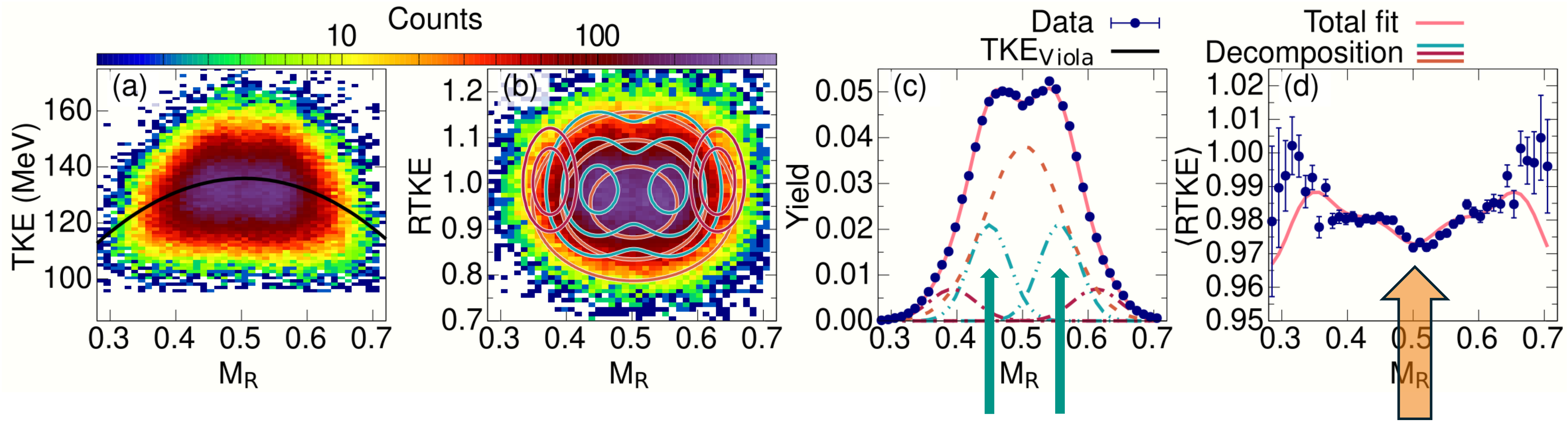


Inner asymmetric peak positions always the same

Residuals give visualization of fit quality

B.M.A. Swinton-Bland, J. Buete *et al.*, Phys. Lett. B837(2023)137655

Additional constraints from simultaneous fits to mass and TKE



$$TKE_{Viola} \sim \frac{Z_1 Z_2}{r_0(A_1^{1/3} + A_2^{1/3})}$$

Linearize: $RTKE = \frac{TKE}{TKE_{Viola}}$

$Z_{FF} = 35$ $Z_{FF} = 43$

$Z_{FF} = M_R * Z_{CN}$

Need low RTKE mass-symmetric fission

$^{34}S + ^{144}Sm$ ⇨ ^{178}Pt $E_x = 37.7$ MeV

B.M.A. Swinton-Bland, J. Buete *et al.*, Phys. Lett. B837(2023)137655

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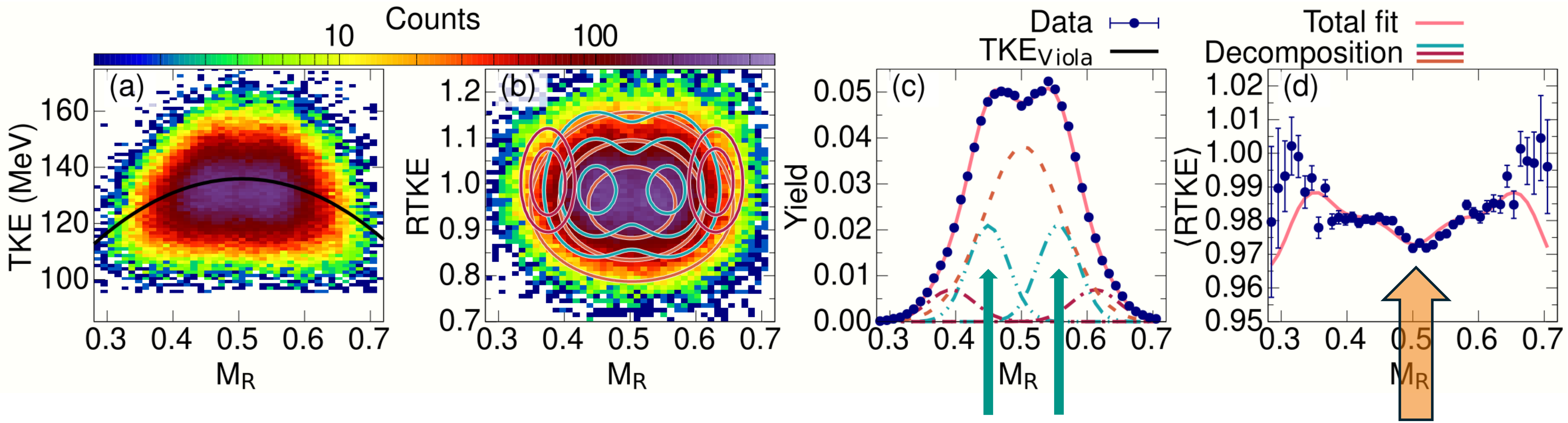


Z_{FF} = 35 Z_{FF} = 43

$$TKE_{Viola} \sim \frac{Z_1 Z_2}{r_0(A_1^{1/3} + A_2^{1/3})}$$

Linearize: $RTKE = \frac{TKE}{TKE_{Viola}}$

$Z_{FF} = M_R * Z_{CN}$

Need for a low RTKE mass-symmetric mode

Agrees with ^{180}Hg fission: for ^{178}Pt dominant asymmetric fission is associated with Z_{FF} ~ 35 or 43

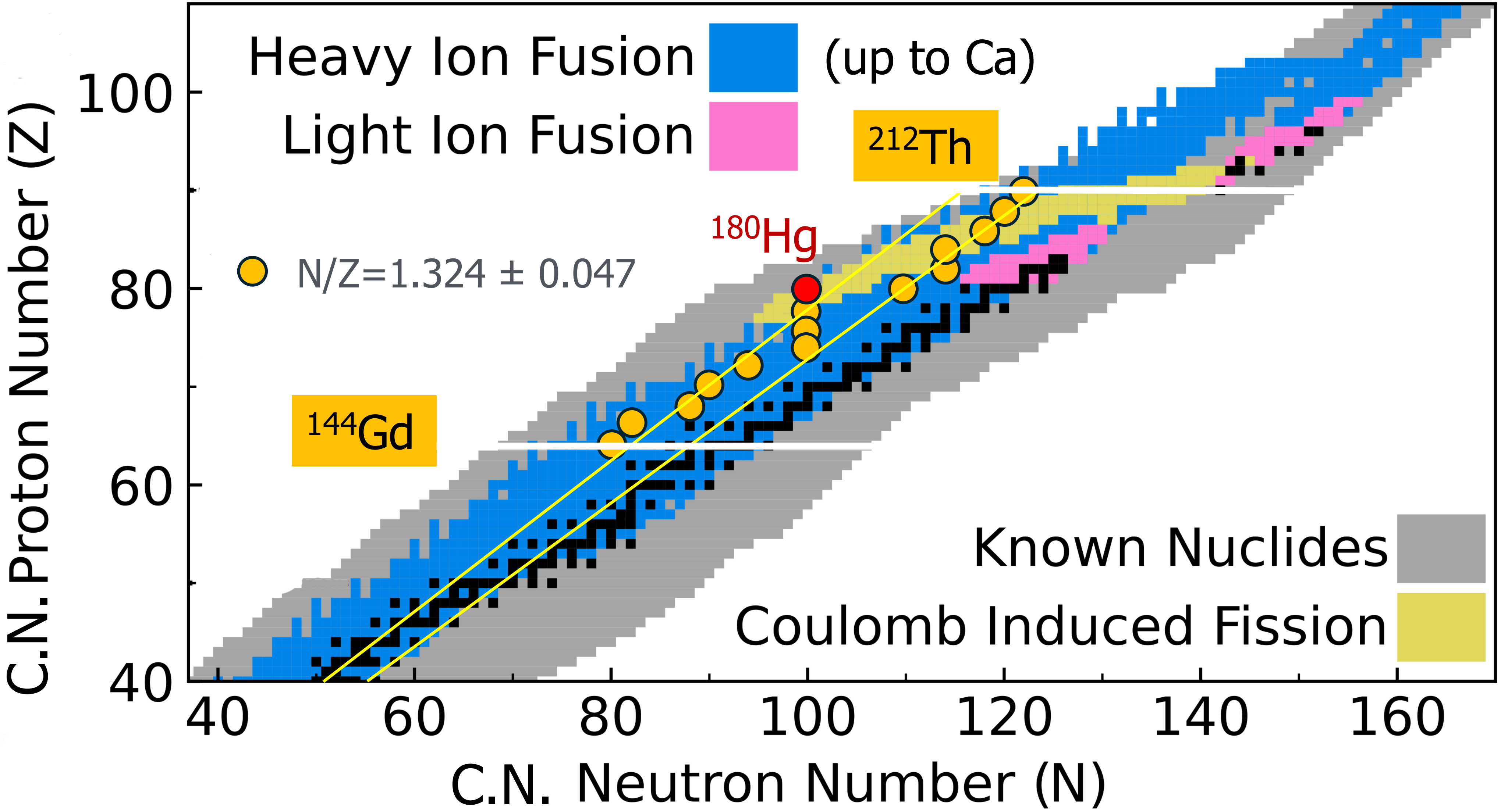
Which one? Systematic measurements should provide the answer:

B.M.A. Swinton-Bland, J. Buete *et al.*, Phys. Lett. B837(2023)137655

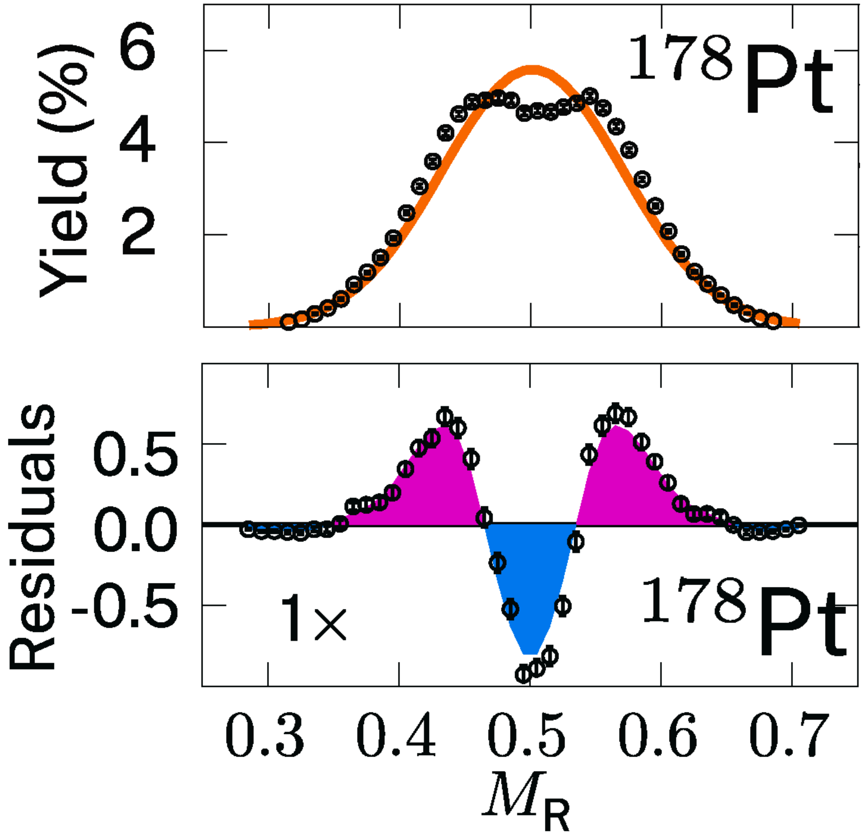
Systematics using S beams from HIAF + CUBE spectrometer (expt 4/2018)

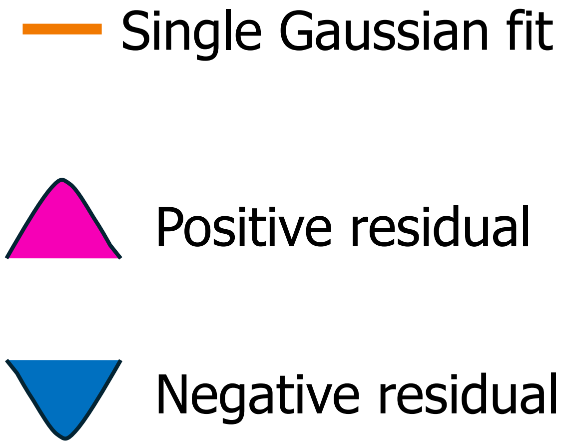
J. Buete, B.M.A. Swinton-Bland *et al.*, Phys. Lett. B 865 (2025) 139459

Ex above g.s. from 25 to 70 MeV



Model-independent systematics of all the mass distributions: Residuals from single-Gaussian fits





Residual structure symmetric about M_R=0.5

J. Buete *et al.*, Phys. Lett. B 865 (2025) 139459

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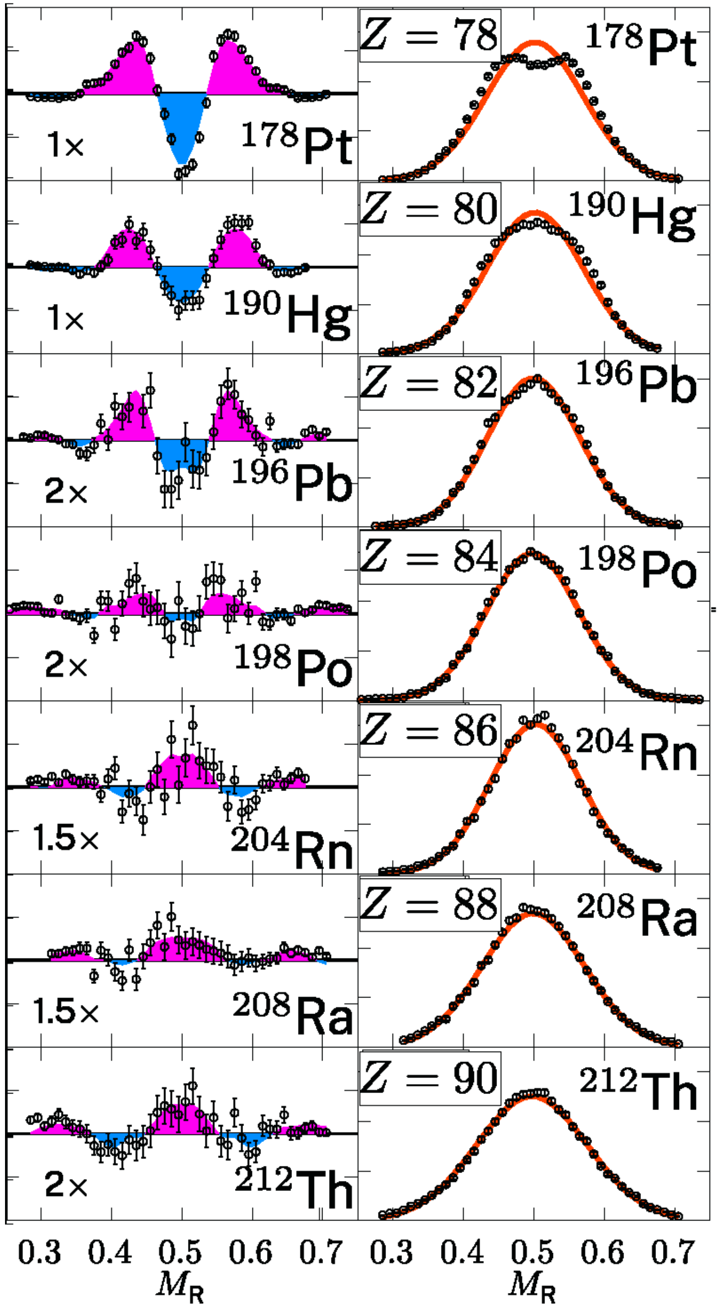


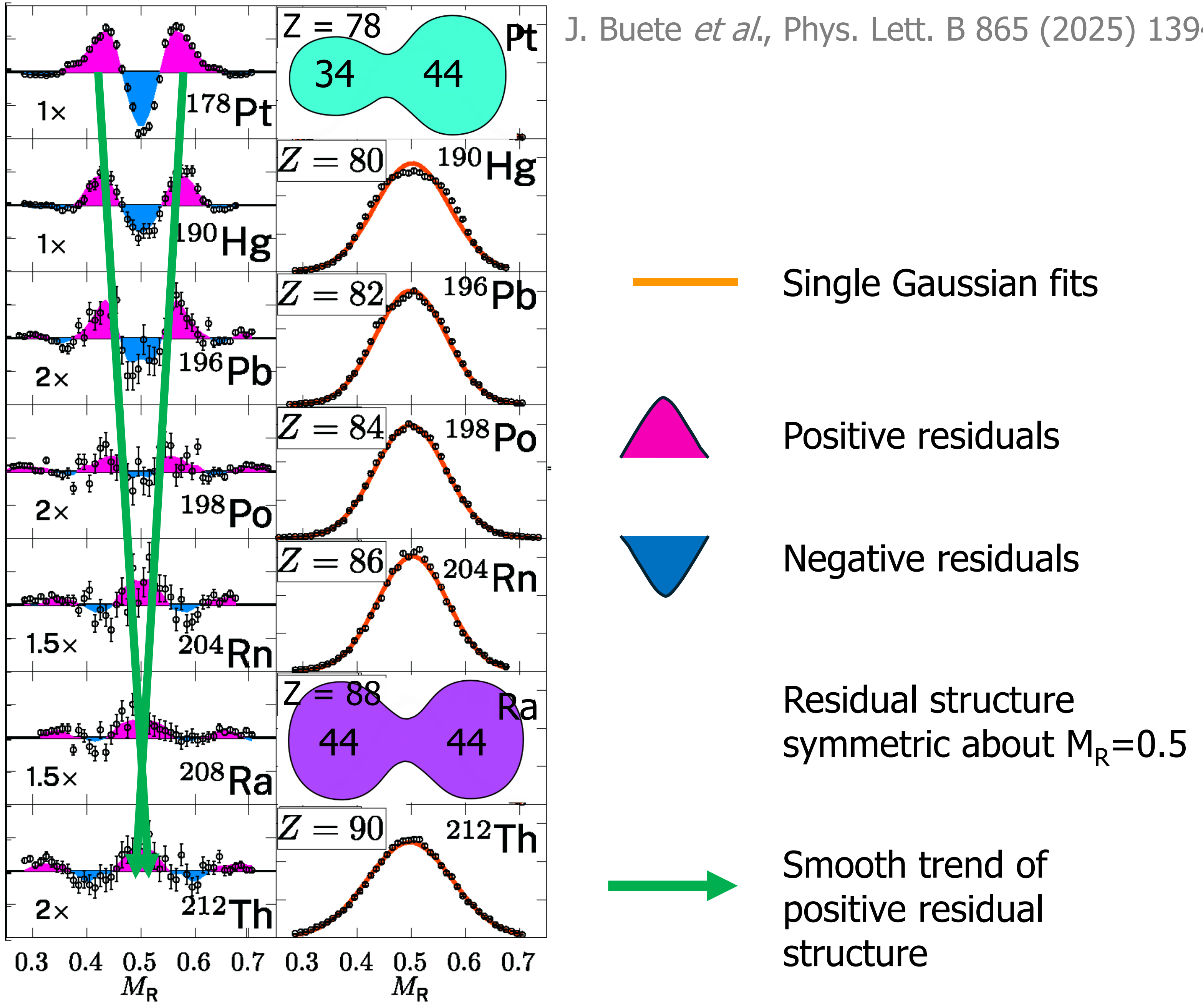
Single Gaussian fits

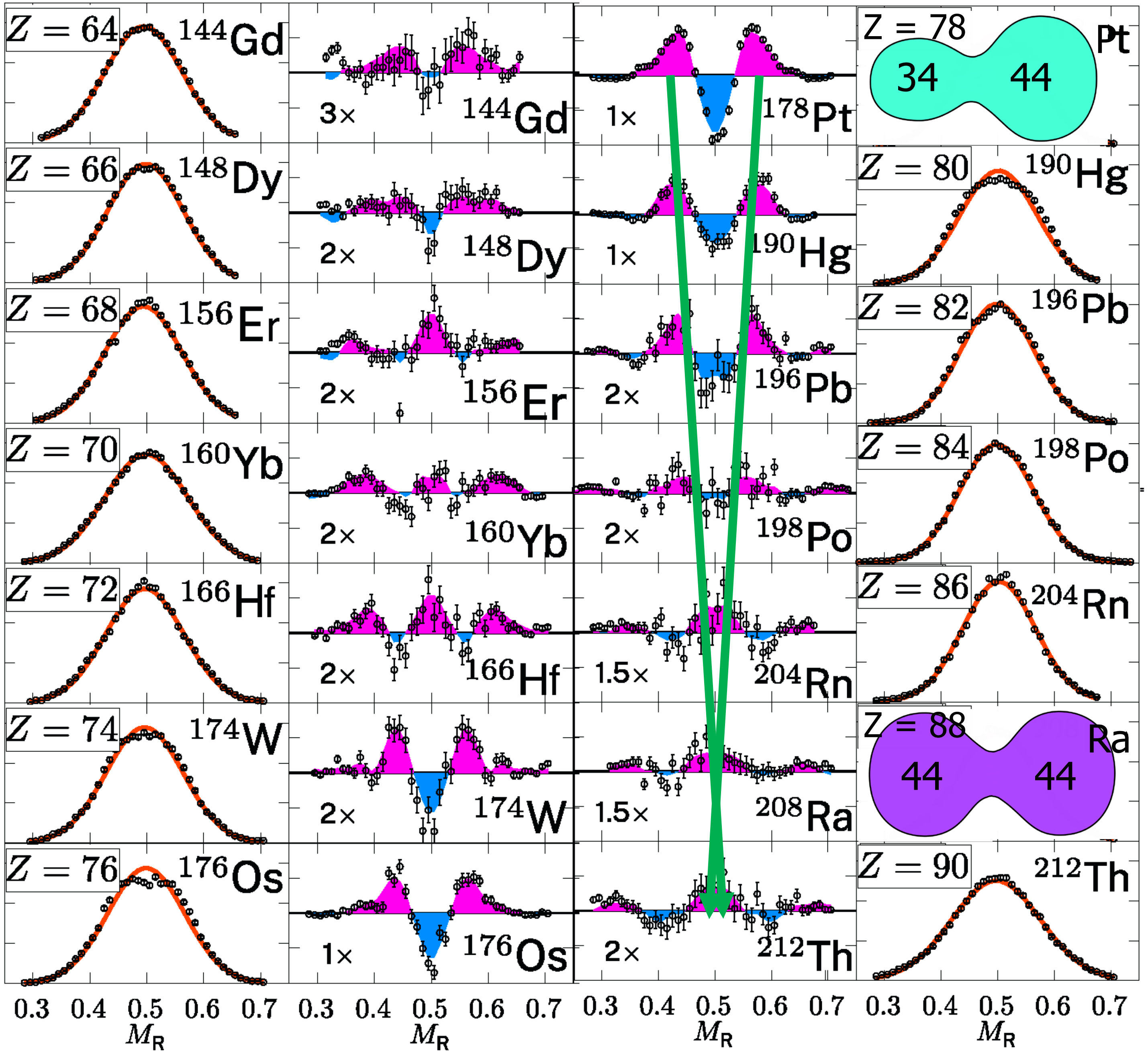
Positive residuals

Negative residuals

Residual structure symmetric about M_R=0.5

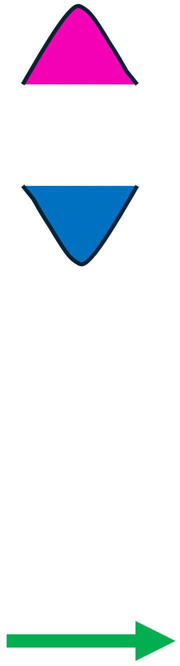
J. Buete *et al.*, Phys. Lett. B 865 (2025) 139459





J. Buete *et al.*, Phys. Lett. B 865 (2025) 139459

Broadest survey below actinide nuclei



Single Gaussian fits

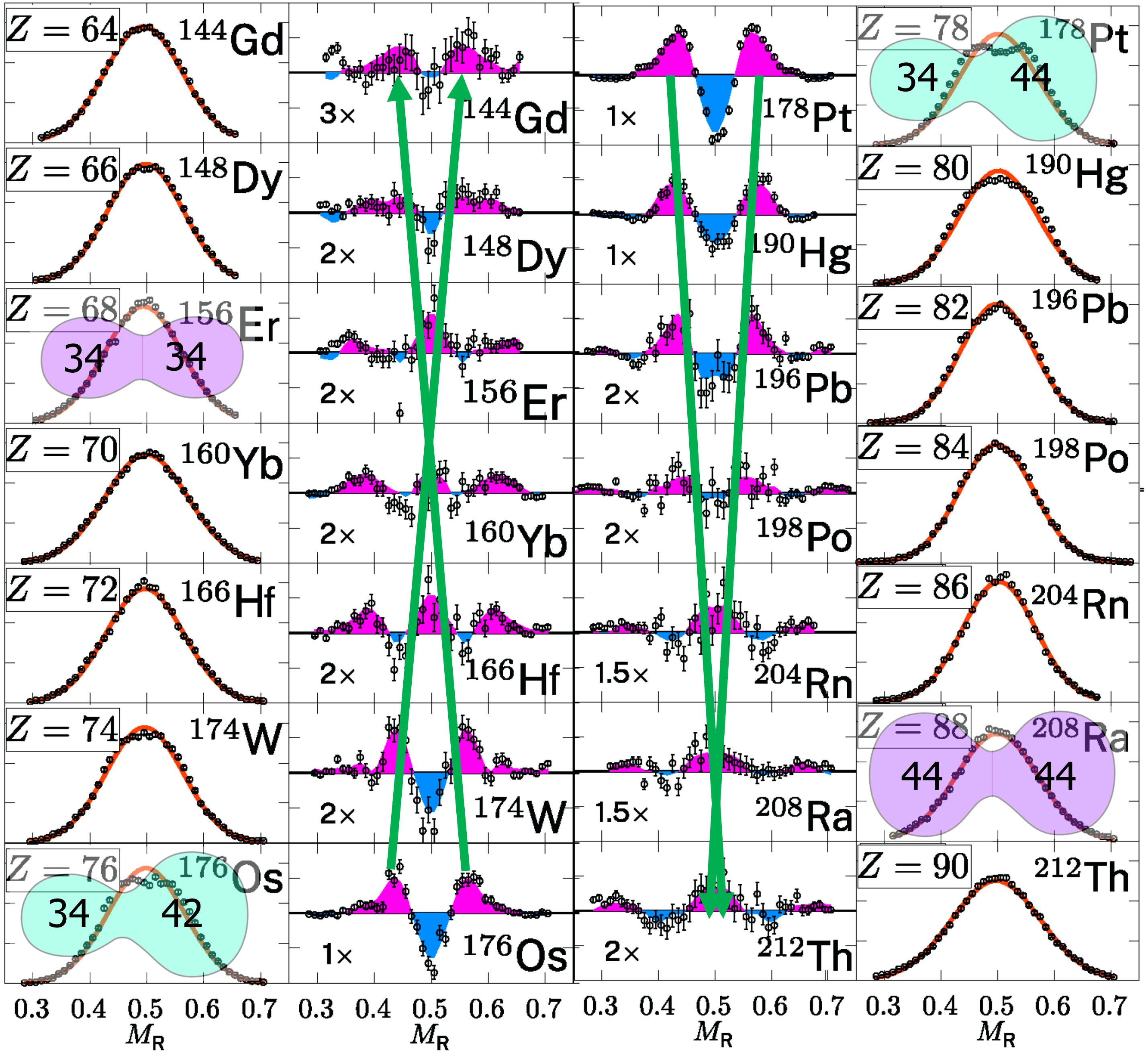
Positive residuals

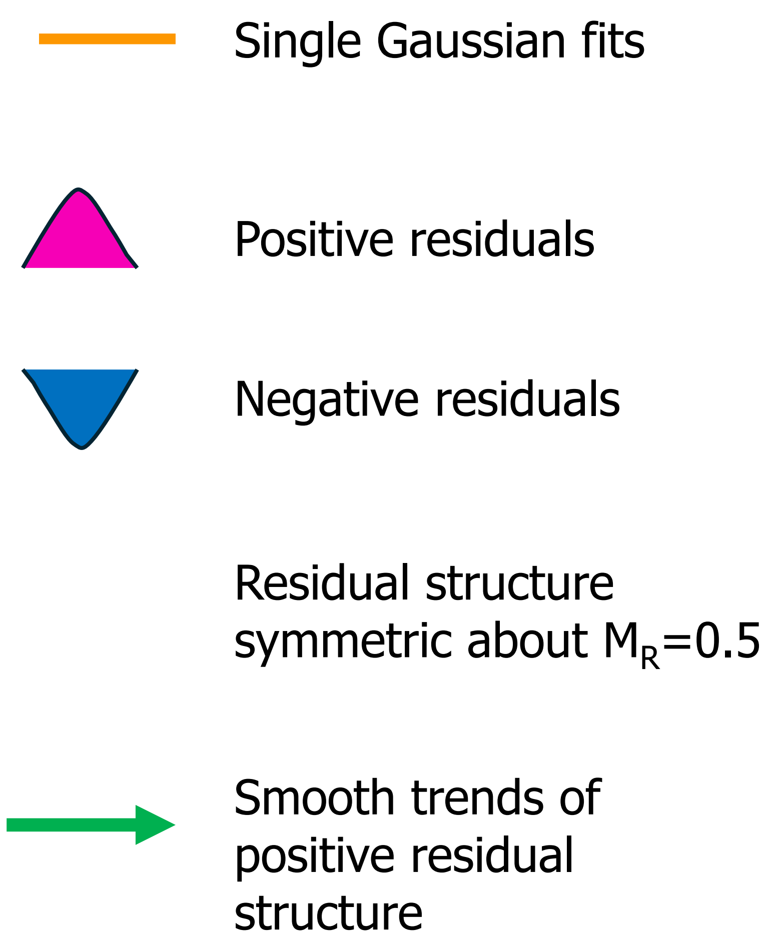
Negative residuals

Residual structure symmetric about M_R=0.5

Smooth trends of positive residual structure

J. Buete *et al.*, Phys. Lett. B 865 (2025) 139459

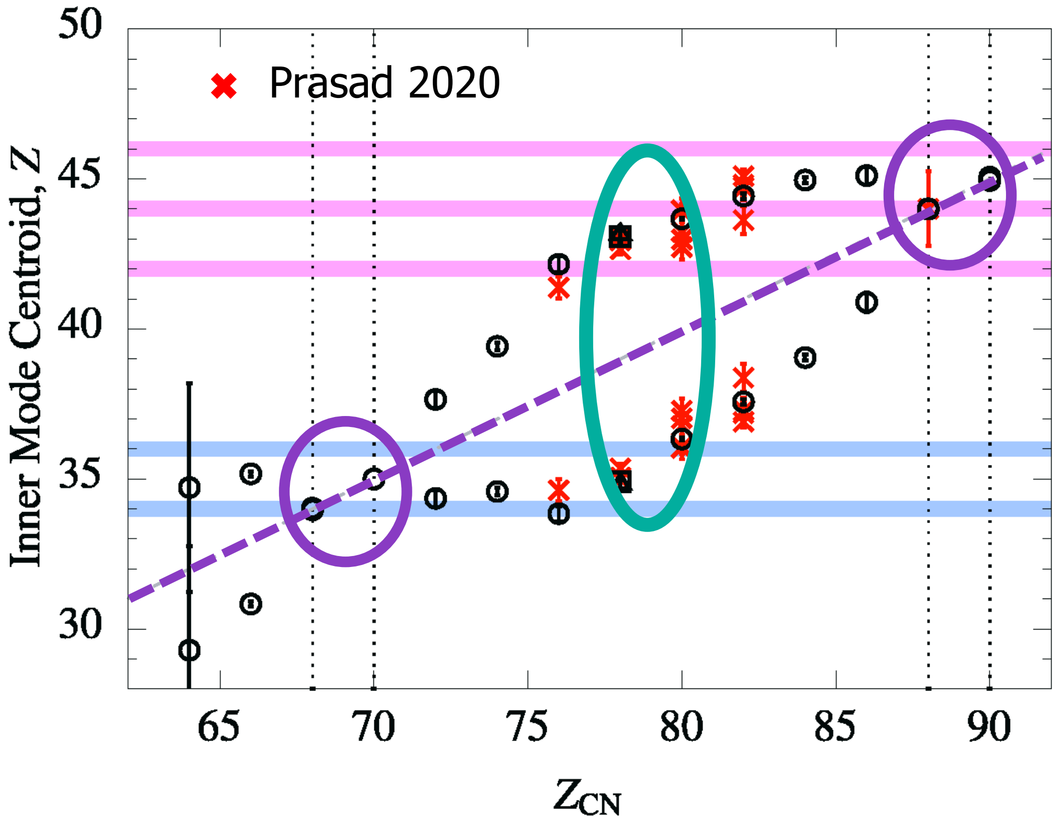


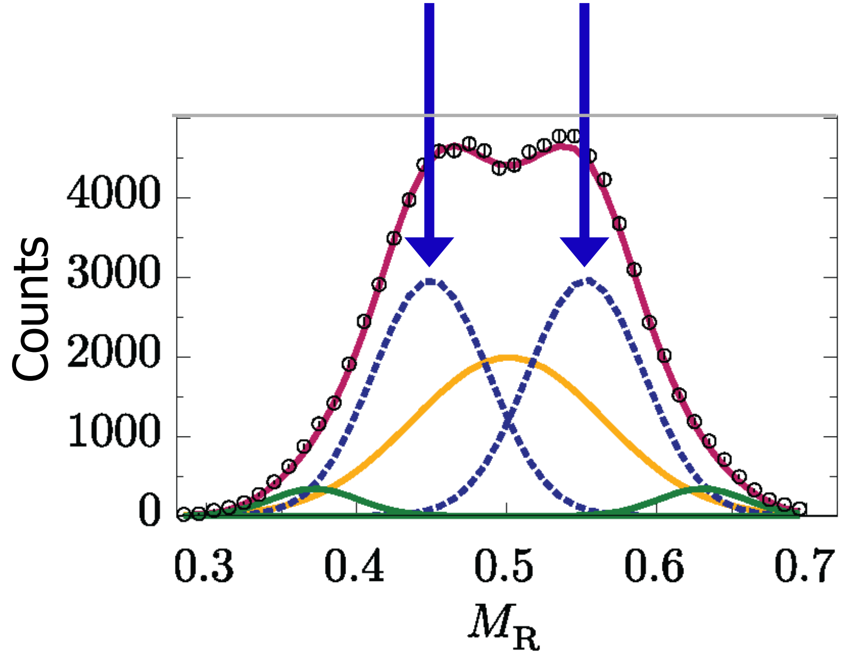


Quantitative: 2-D unconstrained multi-mode fitting - (i) inner asymmetric mode

J. Buete, B.M.A. Swinton-Bland *et al.*, Phys. Lett. B 865 (2025) 139459

✖ E. Prasad *et al.* Physics Letters B811(2020)135941
(Low statistics: one asymmetric mode)





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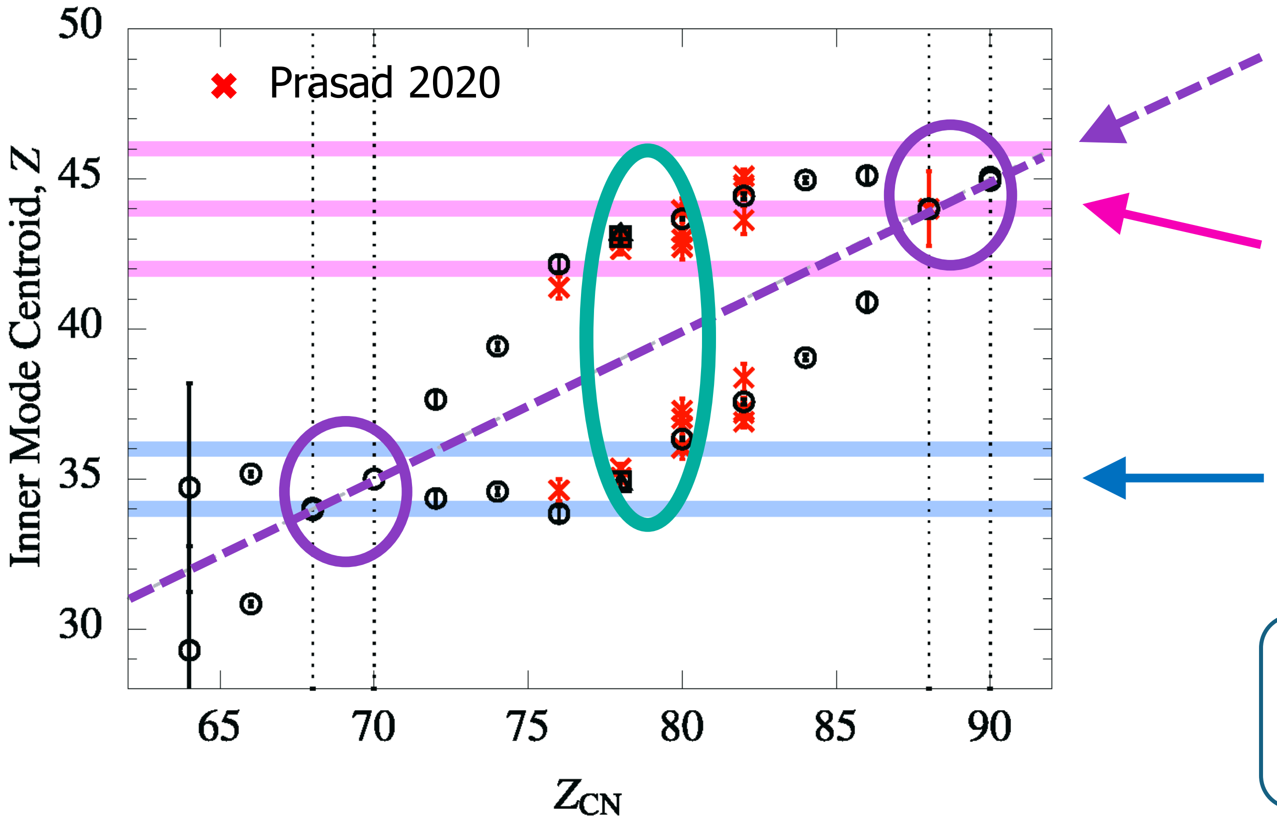


G. Scamps and C. Simenel Phys. Rev. C 100(2019)041602.

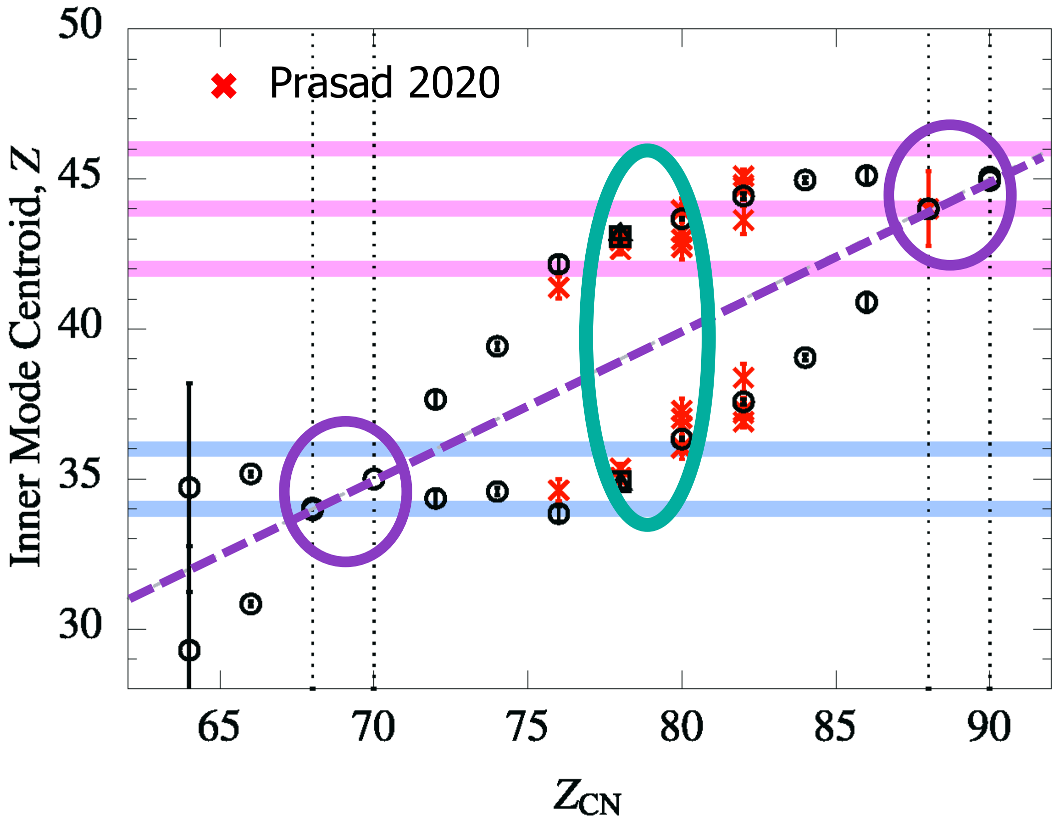
Use UCD approximation: $(N/Z)_{FF} \sim (N/Z)_{CN}$

OK to ± 0.5 protons

Quantitative: 2-D unconstrained multi-mode fitting - (i) inner asymmetric mode

J. Buete, B.M.A. Swinton-Bland *et al.*, Phys. Lett. B 865 (2025) 139459

✖ E. Prasad *et al*. Physics Letters B811(2020)135941



Line of mass-symmetry

Expected quadrupole shell gaps

G. Scamps and C. Simenel Phys. Rev. C 100(2019)041602.

Expected octupole shell gaps

UCD approximation: $N/Z_{FF} \sim N/Z_{CN}$

OK to ± 0.5 protons

Near-symmetric at Z_{CN}=68,70: 2x34

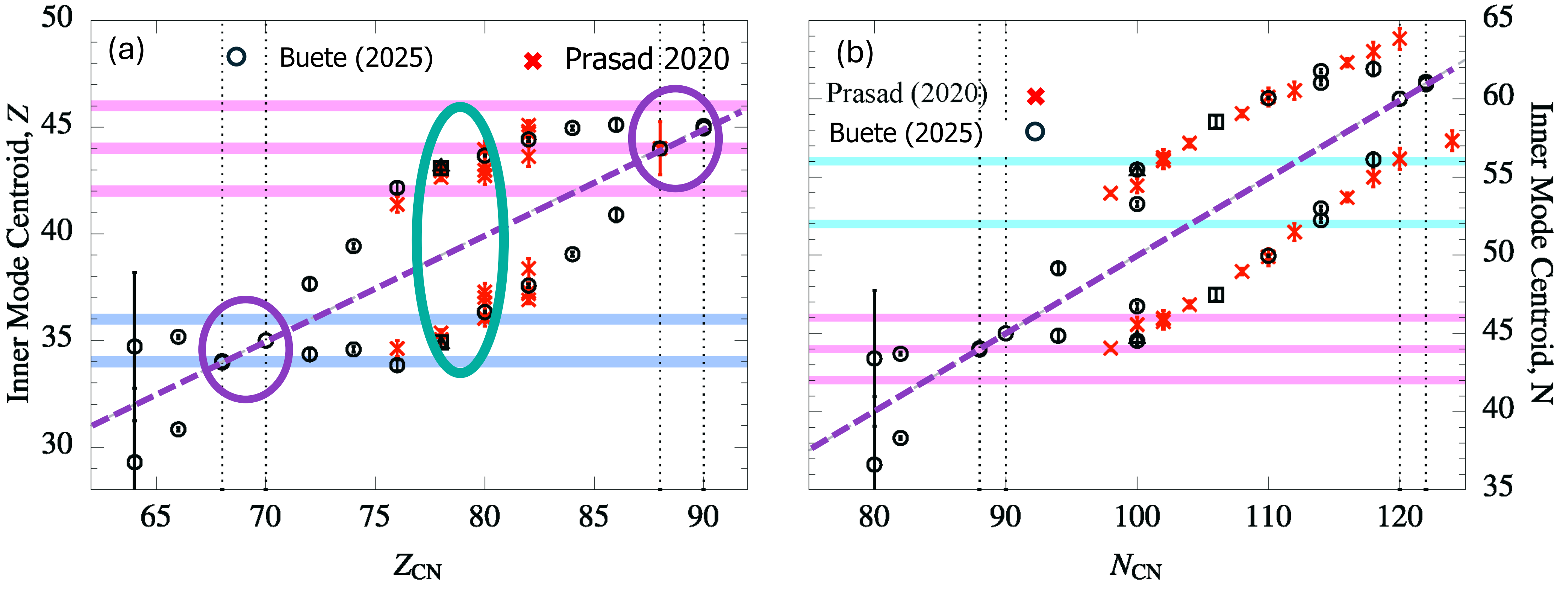
Near-symmetric at Z_{CN}=88,90: 2x44

Strongest asymmetry at Z_{CN}=78 = 34+44

Both Z_{FF}~34, Z_{FF}~44 important

Quantitative: 2-D unconstrained multi-mode fitting - (i) inner asymmetric mode

J. Buete, B.M.A. Swinton-Bland *et al.*, Phys. Lett. B 865 (2025) 139459 ✖ E. Prasad *et al*. Physics Letters B811(2020)135941



Near-symmetric at Z_{CN}=68,70: 2x34

Near-symmetric at Z_{CN}=88,90: 2x44

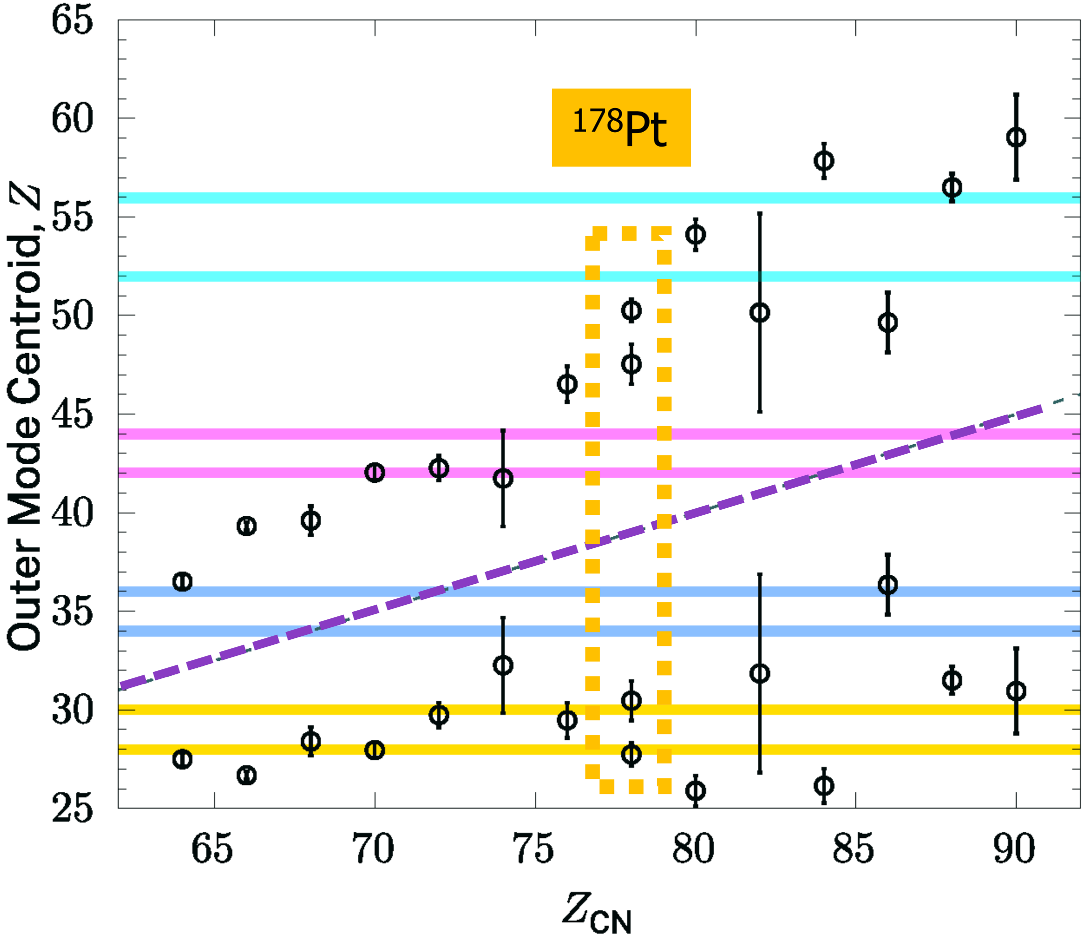
Strongest asymmetry at Z_{CN}=78 = 34+44

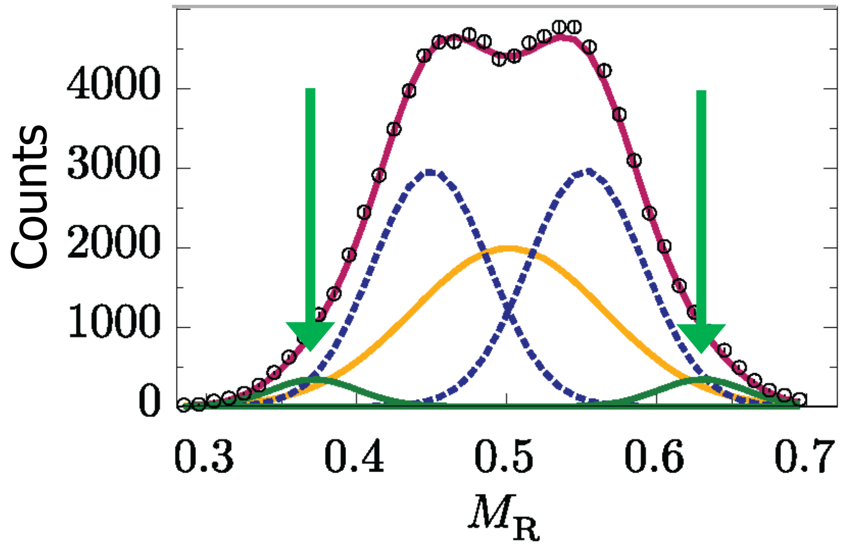
Correlation with N_{FF} seems weak, as in Actinides

Existing data cannot exclude N_{FF}~44 playing a role

2-D multi-mode fitting: (ii) outer asymmetric mode

J. Buete, B.M.A. Swinton-Bland *et al.*, Phys. Lett. B 865 (2025) 139459





2-D multi-mode fitting: (ii) outer asymmetric mode

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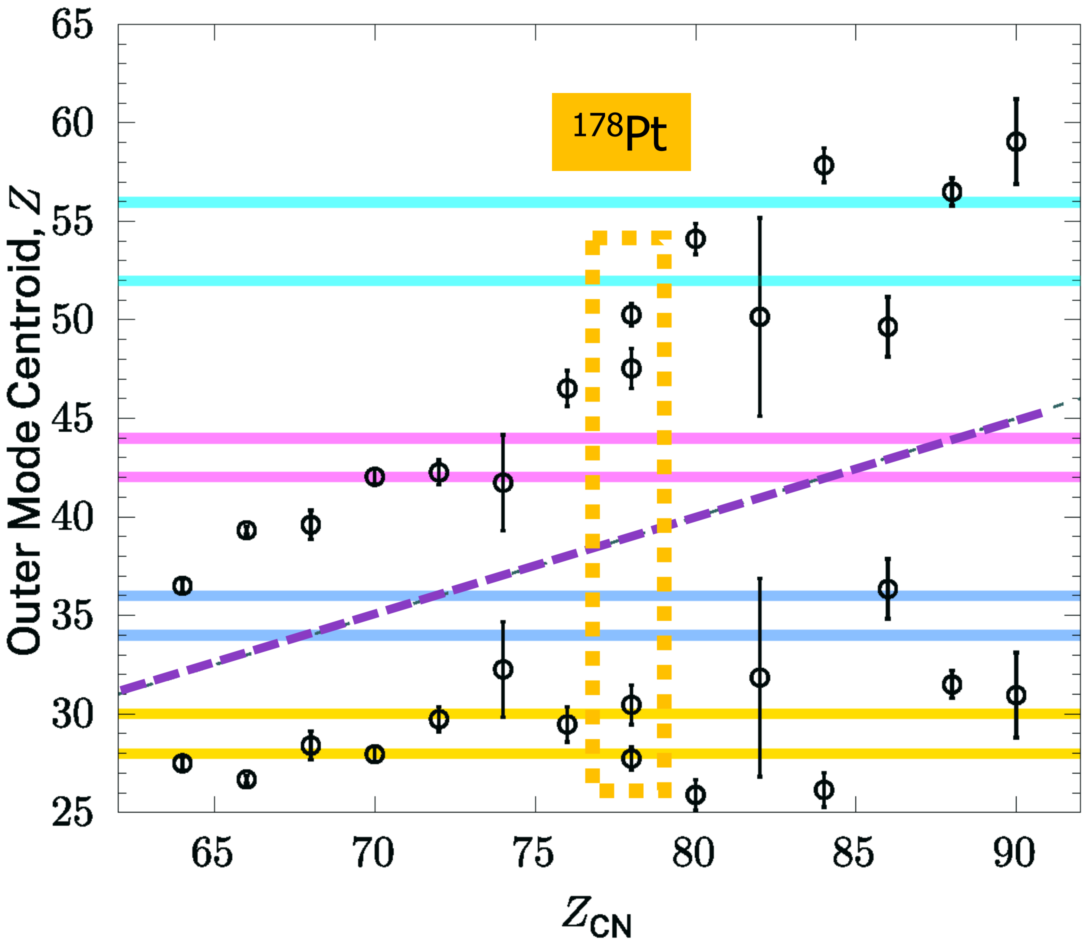


Correlated with light fragment:
Z_{FF} ~ 28?
More than one shell gap?

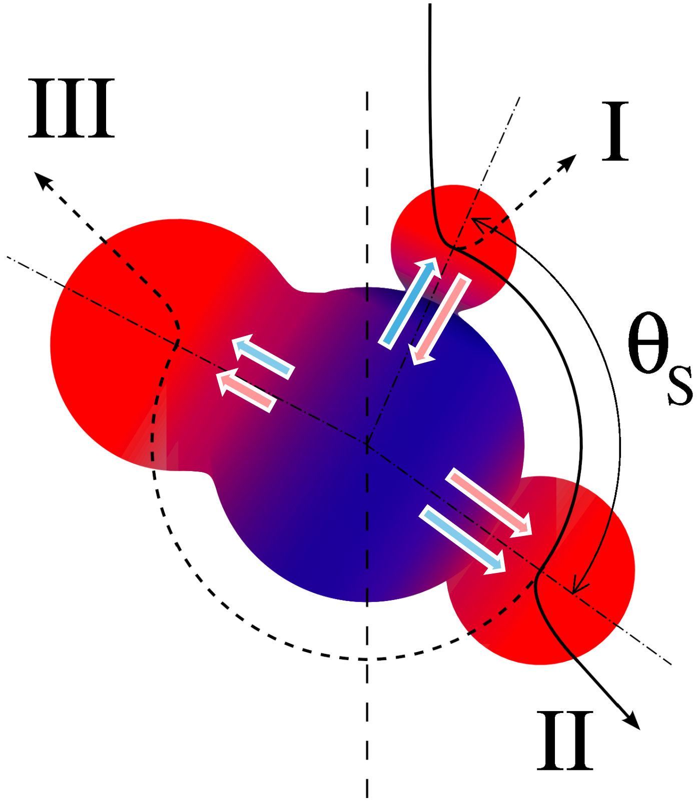
Want higher statistics and lower Ex

Difficult whilst also avoiding significant contributions from quasifission!

Evidence for effects of shells in quasifission mass distributions?

Slow quasifission

$t_s > 10^{-20}$ s



$$\theta_s = \omega t_s$$

Quasi-elastic Collision

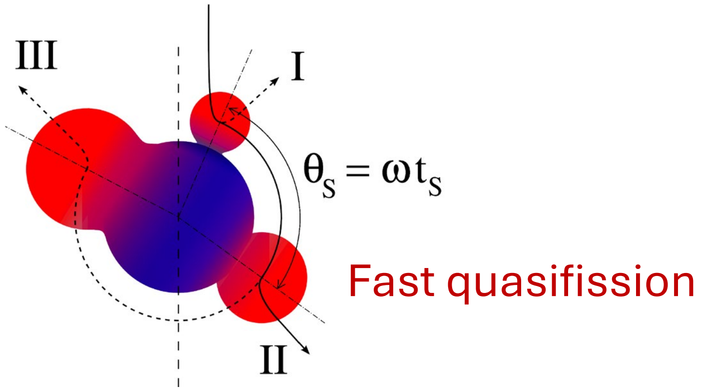
Deep Inelastic Collision

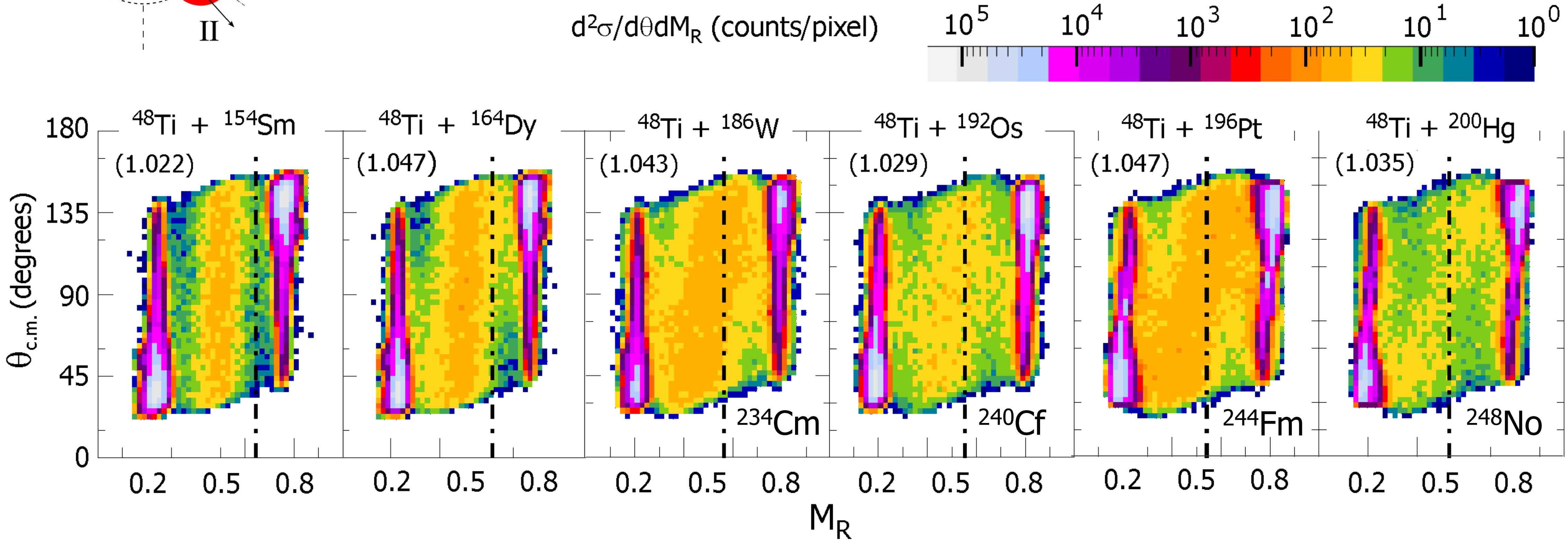
Fast quasifission

$t_s = (5 – 10) \times 10^{-21}$ s

Evidence for effects of shells in quasifission mass distributions?

D.J. Hinde *et al.*, Phys. Rev. C106(2022)064614



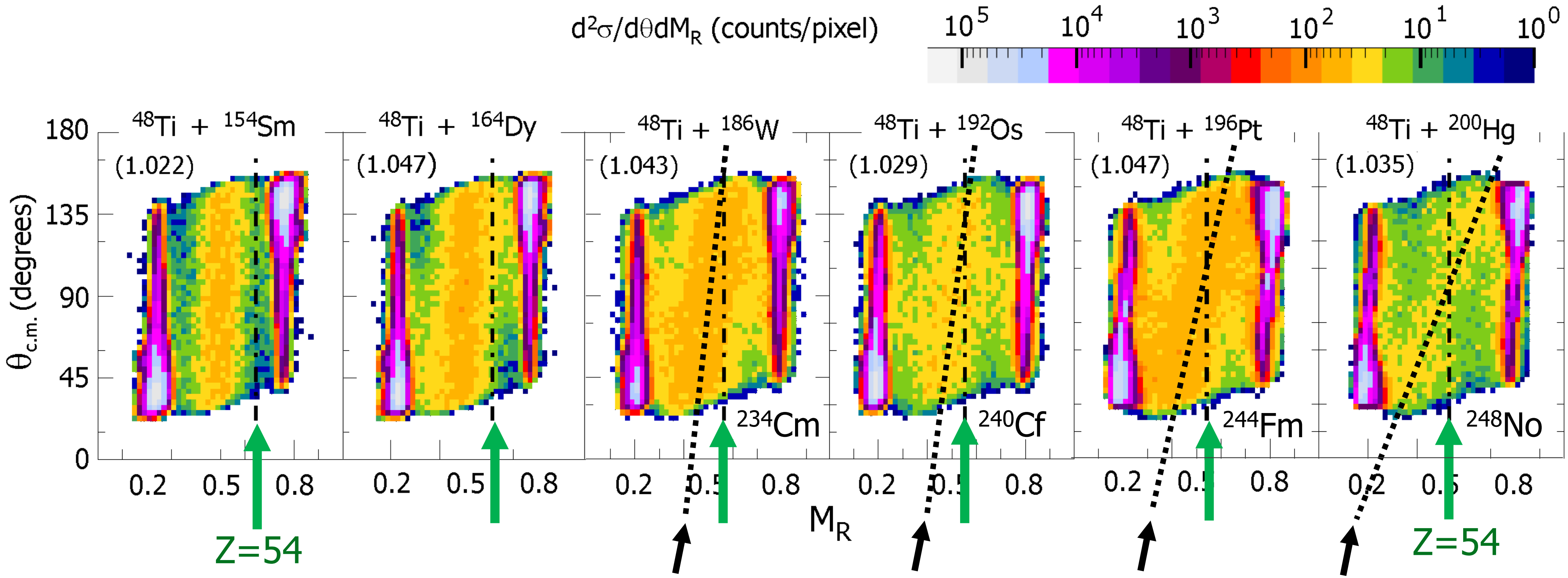


Evidence for effects of shells in quasifission mass distributions?

D.J. Hinde *et al.*, Phys. Rev. C106(2022)064614

The strongest effect of shells seen in fission mass distributions:

Standard I + Standard II mass asymmetric fission in actinide nuclides Z ~ 54

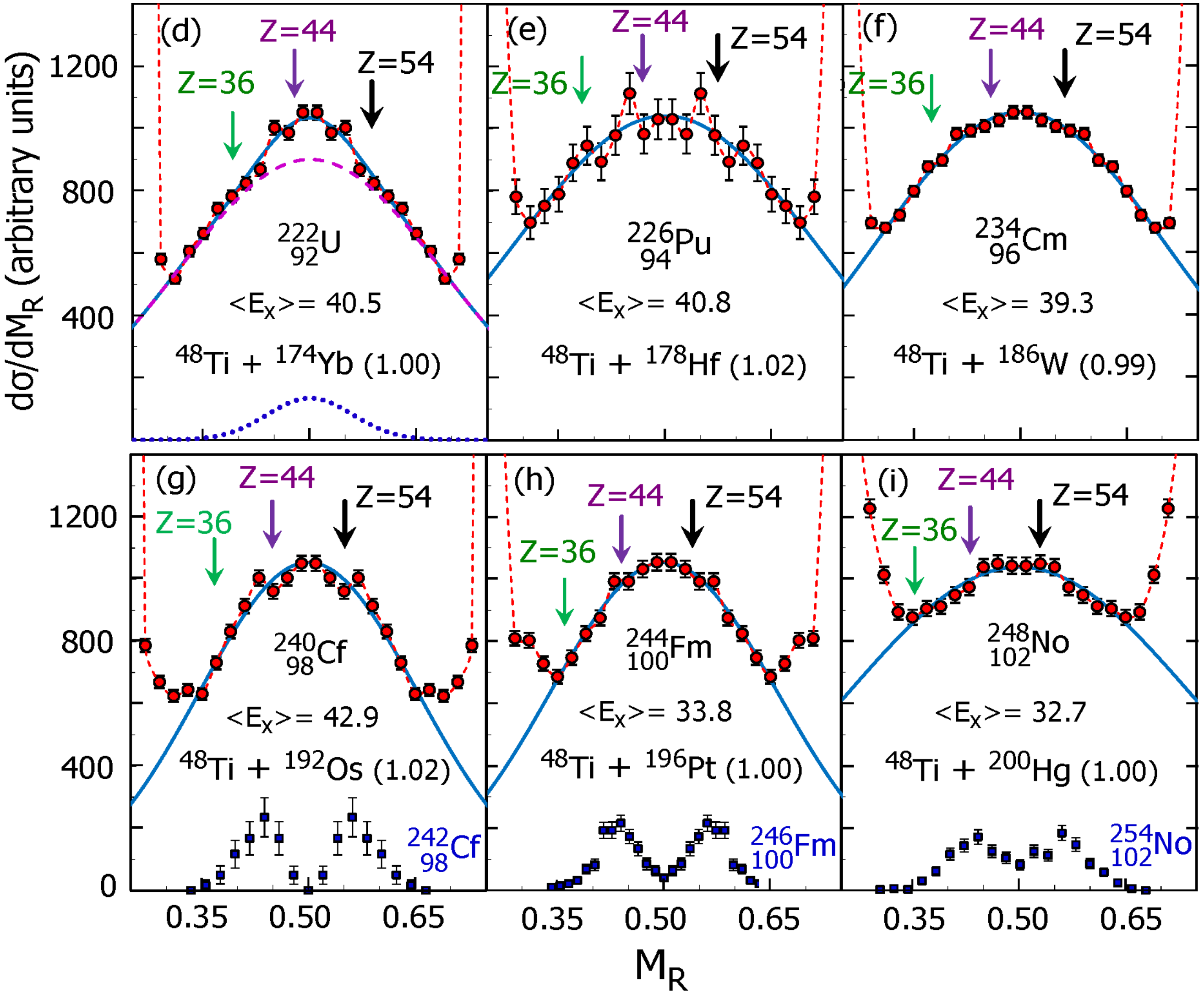


Strong mass angle correlation → fast quasifission dominant

Weak effect on quasifission of the shells important in actinide fission

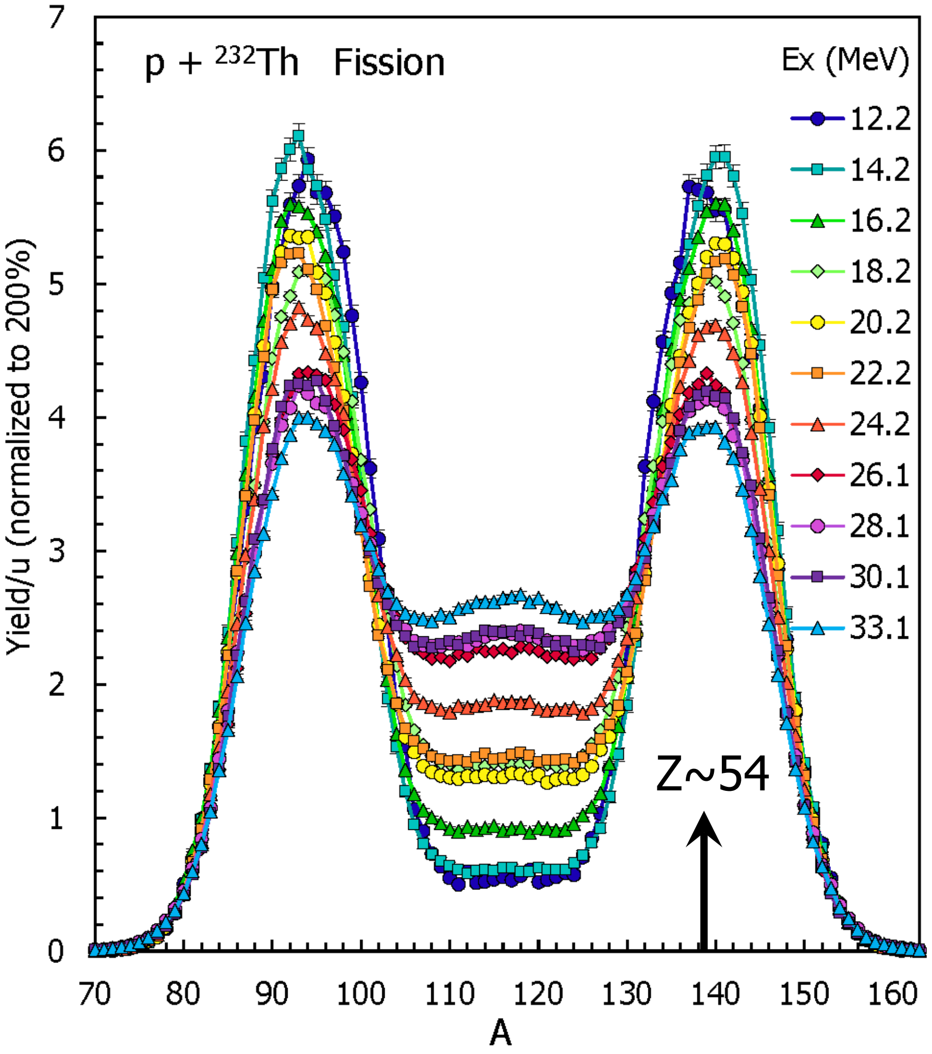
No significant features aligned with St I + St II (Z~54)

D.J. Hinde *et al.*, Phys. Rev. C106(2022)064614

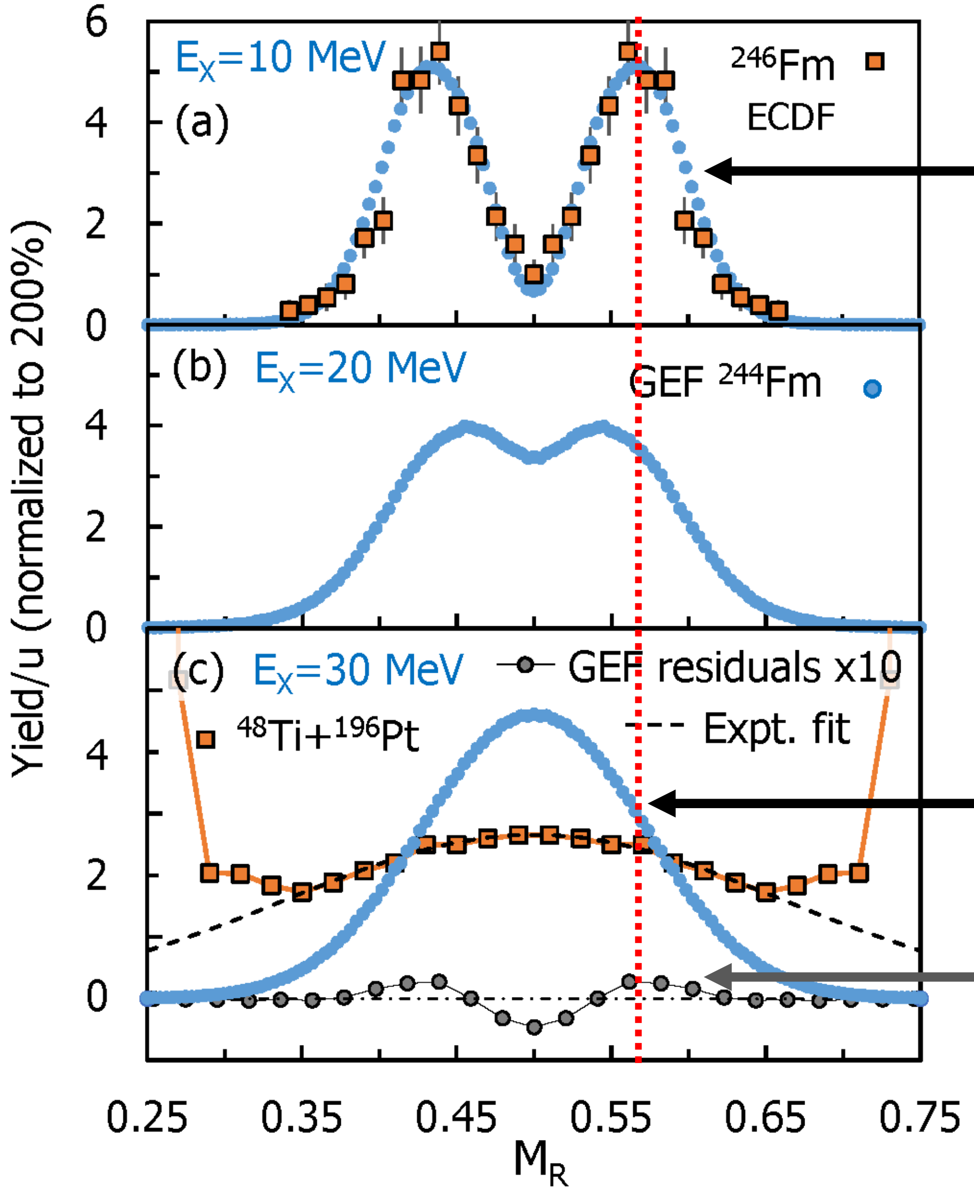


CUBE detector system "sees" correct shell effects

A.C. Berriman *et al.*, Phys. Rev. C105(2022)064614



Expected attenuation with E_X of shell effects



D.J. Hinde *et al.*, Phys. Rev. C106(2022)064614

GEF reproduces low E_X mass distribution

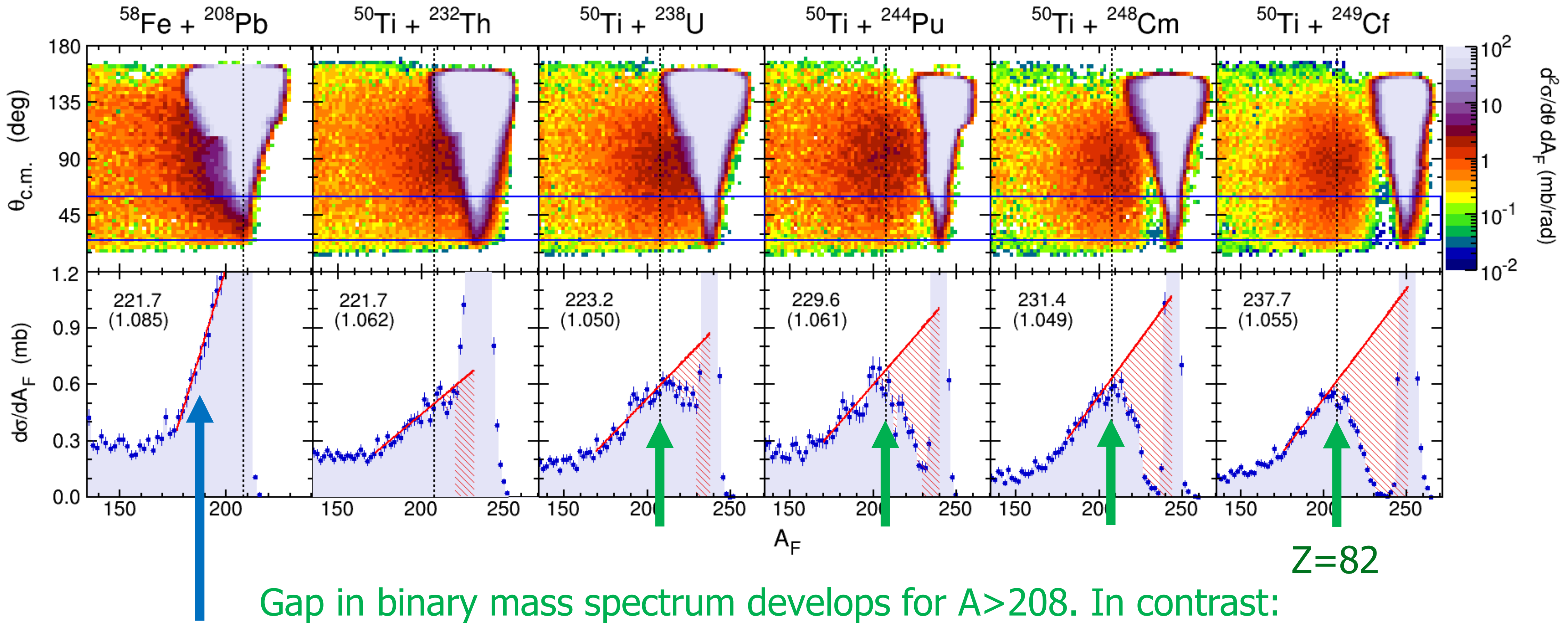
GEF code of K.-H. Schmidt et al.

First-chance fission calculations vs. E_X

Shell effects invisible at E_X = 30 MeV

Residuals from a single Gaussian fit to GEF show faint evidence of the shell structure

Do ^{208}Pb spherical shells gaps affect quasifission mass distributions?



Gap in binary mass spectrum develops for A>208. In contrast:

^{58}Fe+^{208}Pb mass distribution increases linearly towards target mass

Sequential fission of heavy (fissile) binary quasifission products with A>208 could occur (estimate: red hatched areas)

D.Y. Jeung *et al.*, Phys. Lett. B837(2023)137641

Sequential fission of heavy quasifission fragment

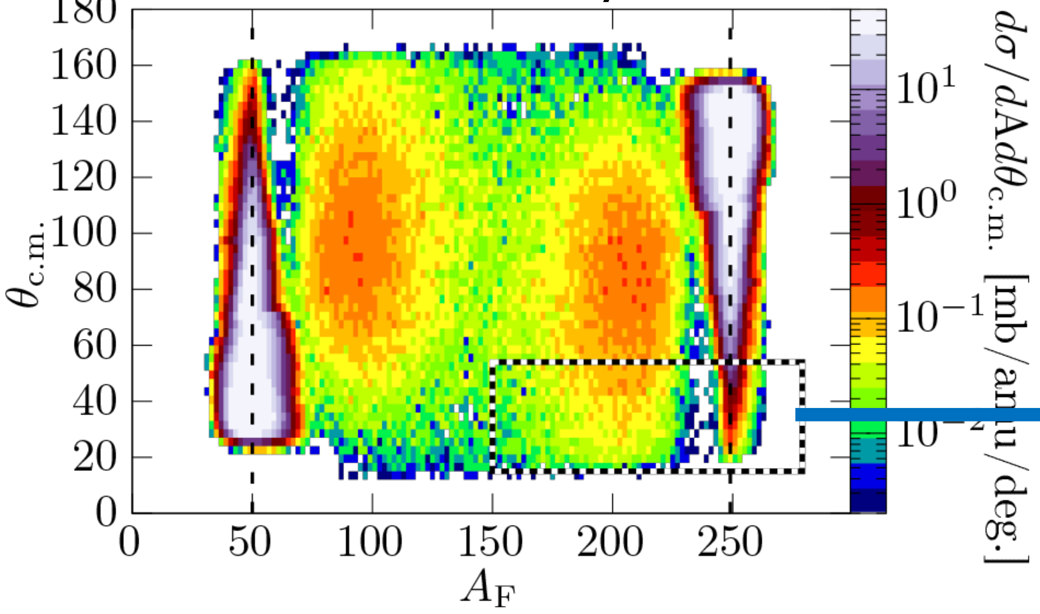
Three-body events:

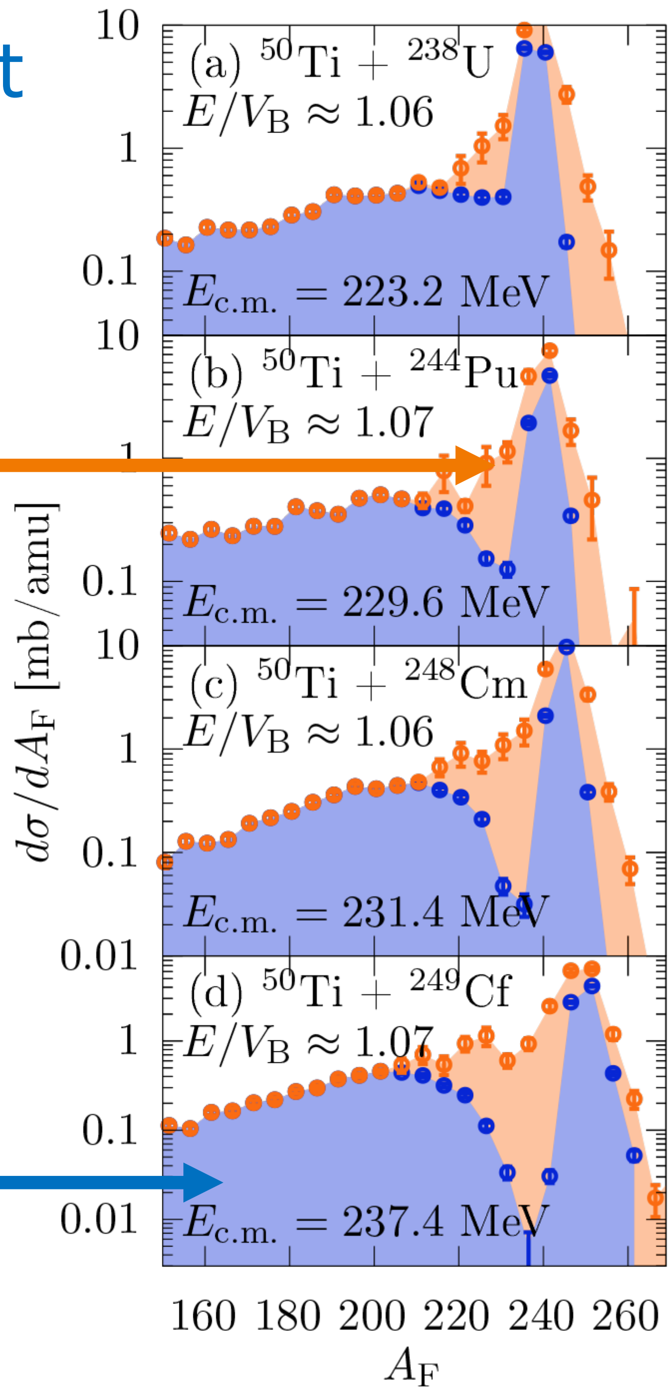
- Reconstruct primary quasifission mass-split
- Correct for geometrical efficiency
- Add to measured binary outcomes

Fills gap above ^{208}Pb! Sequential fission dominant, not ^{208}Pb shells

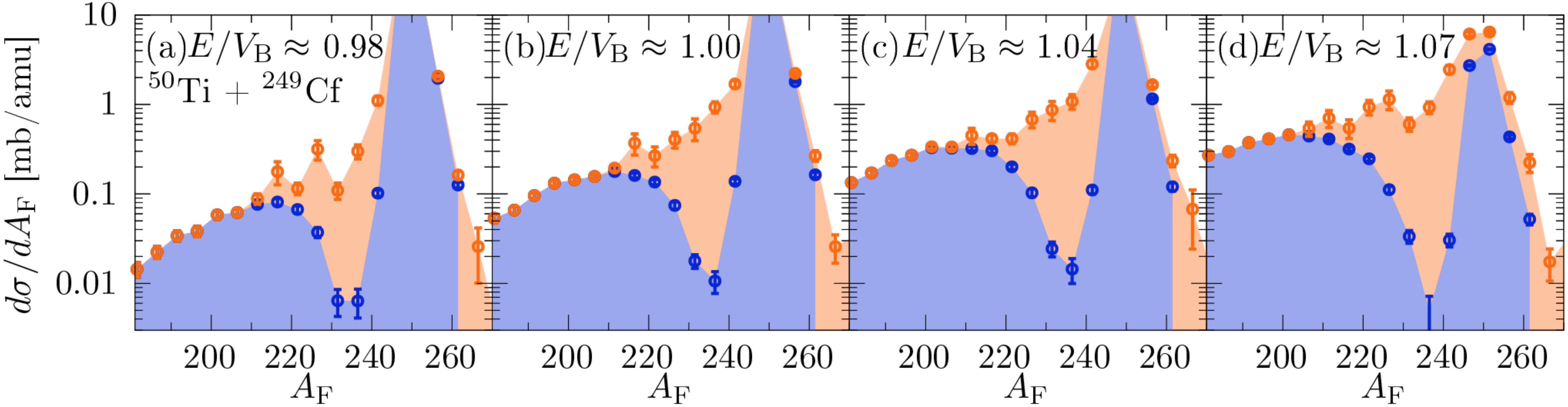
Jacob Buete *et al.*, (ANU) Letter in preparation

$^{50}Ti + ^{249}Cf$ Binary events





$^{50}Ti + ^{249}Cf$



Gaps above ^{208}Pb filled by sequential fission at all energies (E/V_B) measured.

Primary quasifission mass-splits look like $^{58}Fe+^{208}Pb$, increasing monotonically to the target mass.

For $^{58}Fe+^{208}Pb$ sequential fission of primary fragments lighter than ^{208}Pb will not distort the 2-body spectrum.

Conclusions

- Effects of shell gaps (attenuated by E_X) are seen in heavy-ion induced fission
- Shell gaps drive structure in fission mass distributions "everywhere":
  - across the nuclear chart
  - at low initial E_X and higher E_X (importance of multi-chance fission?)
  - at mass-symmetry as well as for asymmetric mass-splits
- Two independent mass-asymmetric features (modes) in sub-Pb fission
- Shell-effects weak in quasifission (no multi-chance low E_X component)