原子核でつむぐrプロセス
2019.05.22−24
京都大学・基礎物理学研究所
（パナソニック国際ホール）

Nuclear fission: its relation to and impacts on r-process nucleosynthesis and formation/properties of super-heavy elements

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International workshop on nuclear physics for astrophysical phenomena

Date: Oct. 23rd–25th, 2019

Confirmed invited speakers: Stéphane Goriely(ULB), Gabriel Martínez–Pinedo (IKP)

Topics: Nuclear physics relating to astrophysical phenomena

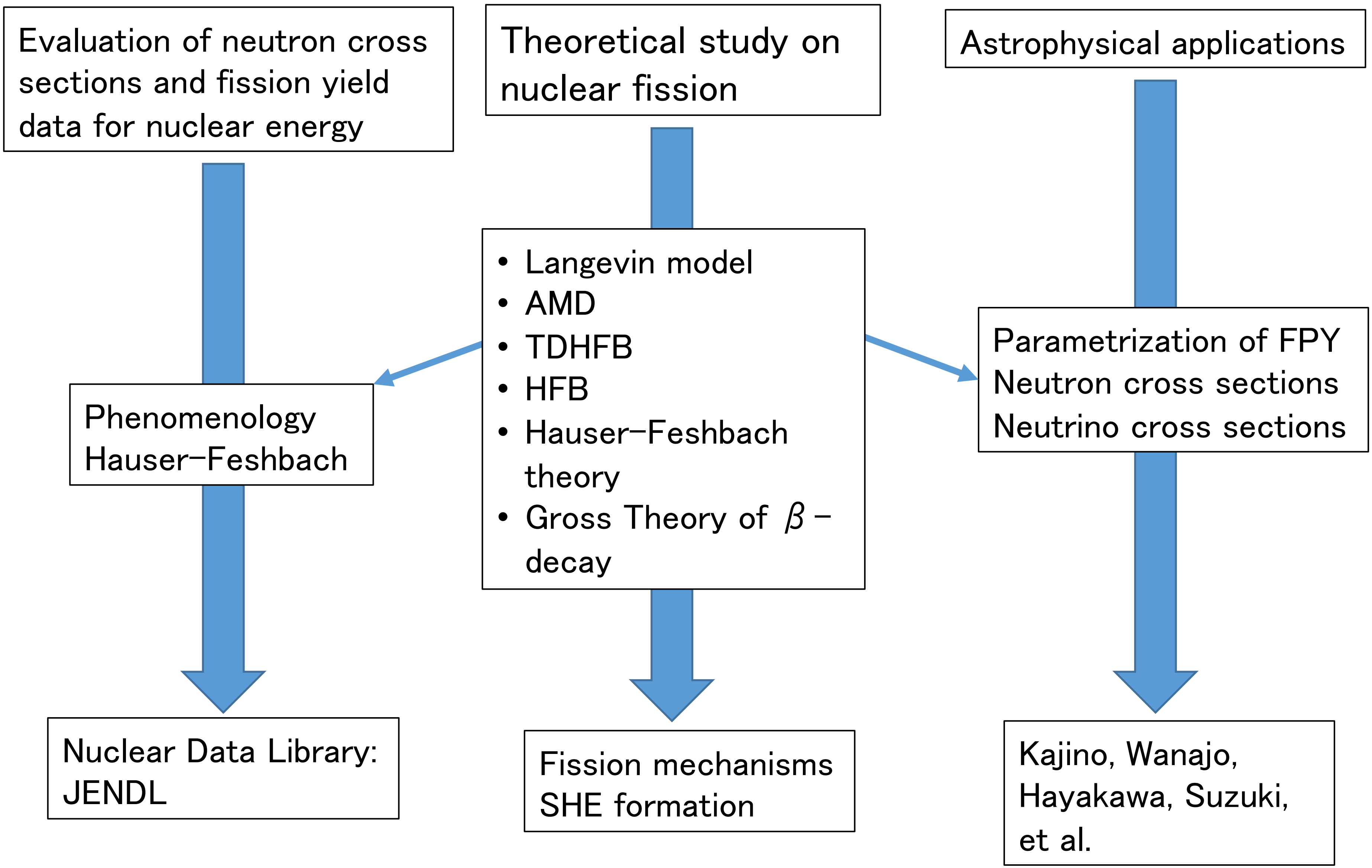
Key topics: Nucleosyntheisis, nuclear EOS, fission, mass table, beta decay etc.

Venue: Tokyo Institute of Technology, Tokyo, Japan

Workshop registration and the website will be announced soon (in early July)

Contact: chikako@lane.iir.titech.ac.jp

Fission study at Tokyo Tech.

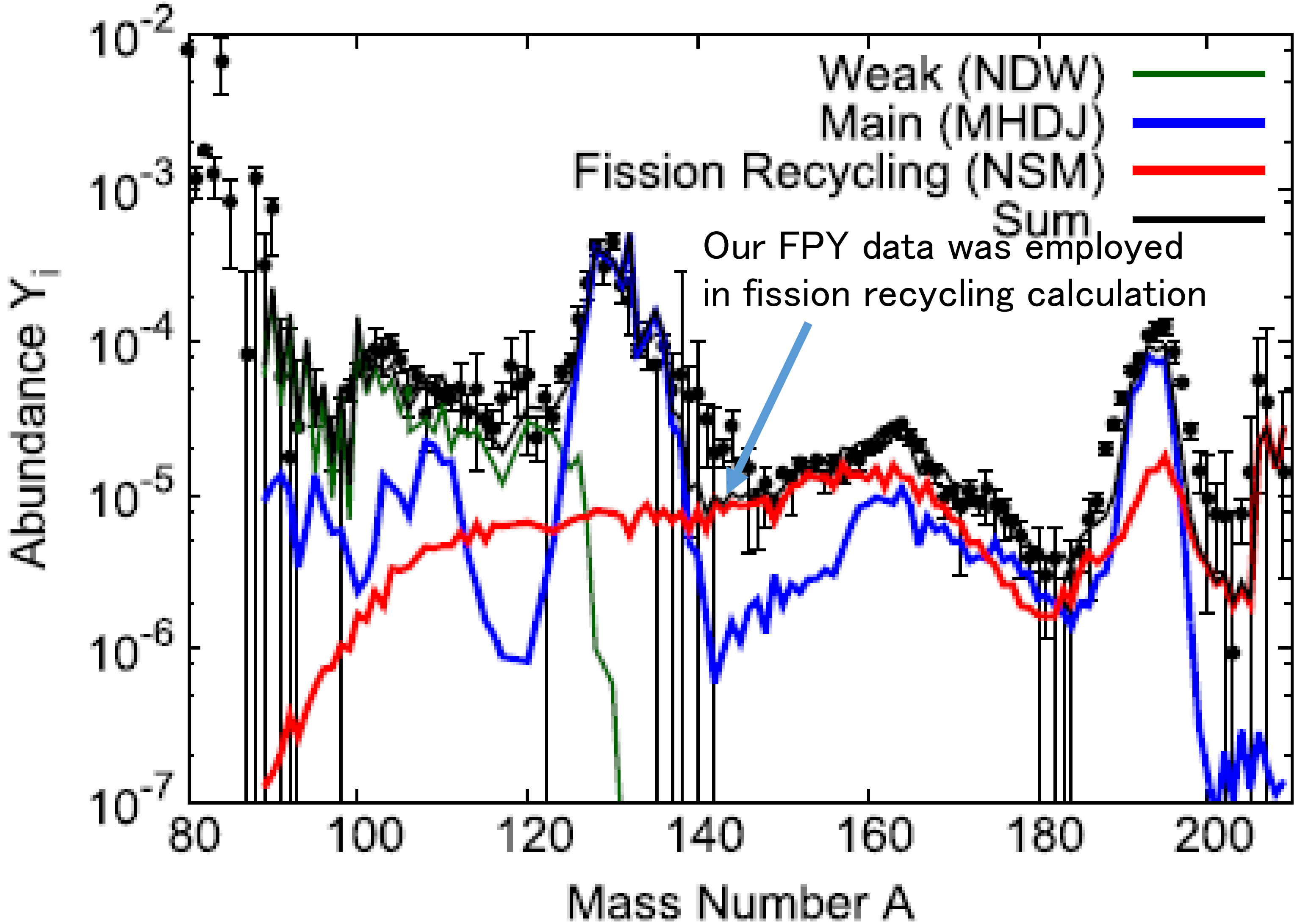


THE ASTROPHYSICAL JOURNAL, 816:79 (9pp), 2016 January 10

doi:10.3847/0004-637X/816/2/79

RELATIVE CONTRIBUTIONS OF THE WEAK, MAIN, AND FISSION-RECYCLING *r*-PROCESS

S. SHIBAGAKI[1,2], T. KAJINO[1,2], G. J. MATHEWS[2,3], S. CHIBA[4], S. NISHIMURA[2,5], AND G. LORUSSO[5,6,7]



International

日本経済新聞

2019年5月24日（金）

ニュートリノのエネルギー、量子機構など、評価手法開発

2018/9/4 5:00

量子科学技術研究開発機構や国立天文台などの共同研究グループは超新星爆発（星の大爆発）で放出される素粒子ニュートリノのエネルギーを精度よく評価する有力な手法を発見した。各種元素が合成される場となる超新星爆発のメカニズム解明に役立つ成果。4日付のフィジカル・レビュー・レターズ誌オンライン版に発表した。

超新星爆発のエネルギーの99%はニュートリノが持ち去るので、爆発の詳細を知るにはニュートリノのエネルギーの見積もりが重要。ニュートリノは6種類あるが、反電子型というタイプについてはエネルギーの評価手法がなかった。

今回、研究グループは超新星爆発で生じる放射性同位体テクネチウム98の約2割が反電子型ニュートリノの反応に由来することを理論的に突き止めた。

テクネチウム98は短期間でルテニウム98という安定同位体になる一方、いん石は太古の超新星爆発に由来する物質を多く含む。そこで今回得られた知見を使えば、いん石中のルテニウム98を測定することで、超新星爆発で生じる反電子型ニュートリノのエネルギーを評価できる。今後はルテニウム98が、いん石研究の重要テーマになる。

将来、スーパーカミオカンデなどの観測装置で超新星爆発の反電子型ニュートリノがキャッチされた場合、どのような星の爆発が起きたのか、より詳しく推定できるようになる。

Our branching ratio data for neutrino cross sections was employed

Background: Nuclear fission and SHE

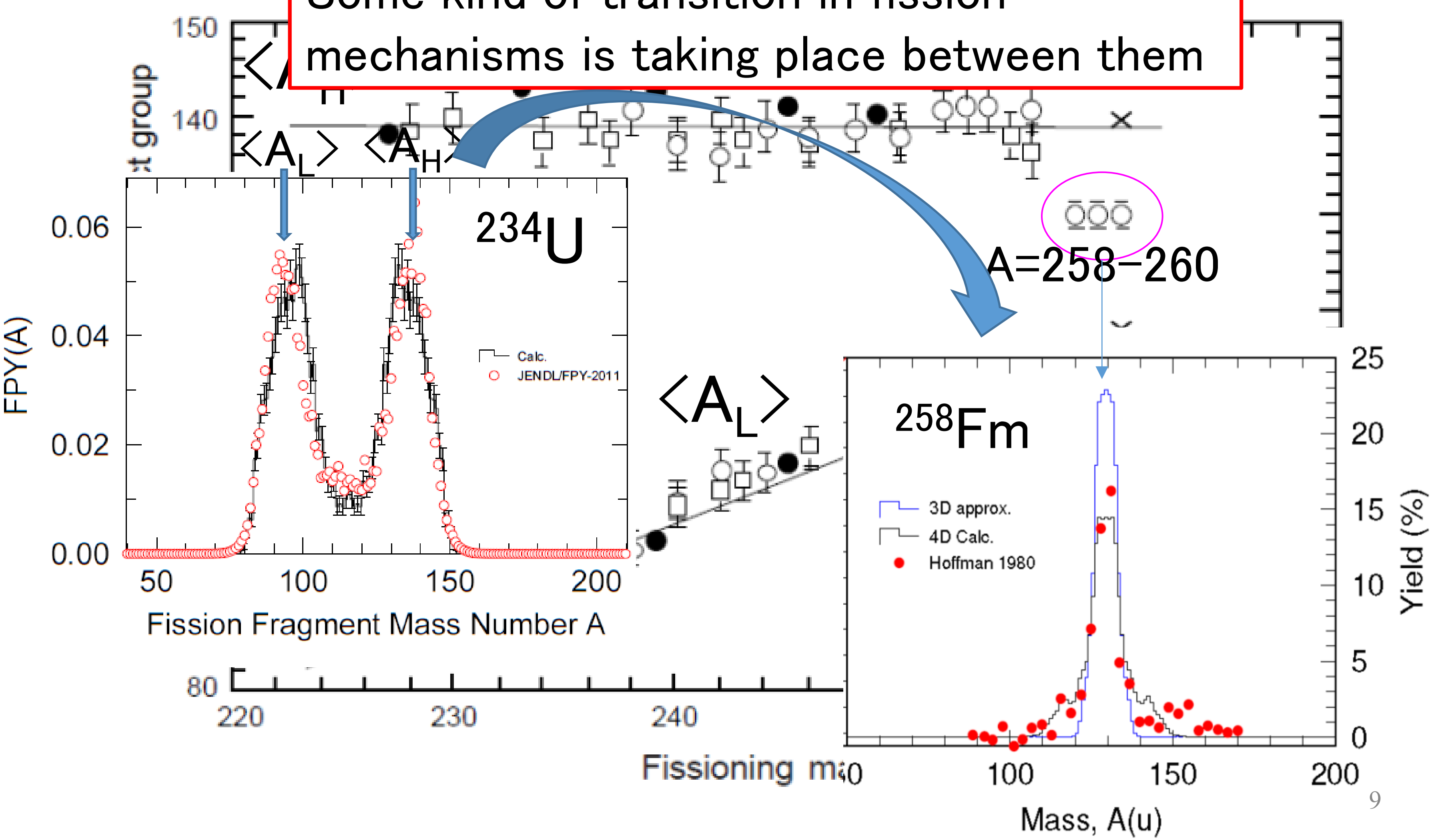
1. Nuclear fission is the key physics process as a base in nuclear technologies, especially for estimation of reactor kinetics, inventory of radioactive nuclei in spent nuclear fuel, material damage, and so on, so accurate data is necessary
2. Nuclear fission is also important in understanding origin of elements in r-process nucleosynthesis in the cosmos, since fission recycling is believed to occur in binary NS merger scenario, gravitational wave and signature of heavy elements from which have been observed and now are important parts of "multimessenger astronomy". Here, not only isotope distribution but also kinetic energy of FF is important as a source of local heating
3. Understanding of nuclear fission is essential in the synthesis of superheavy elements (SHE), since fission prevents formation of SHE as a major competing process

Background: Nuclear fission and SHE

6. Due to complexity of the process as a large-amplitude collective motion, however, nuclear fission still offers a field of big challenges to nuclear physics, especially, the process from formation of excited compound nucleus to scission is still a mysterious process
7. Many observables arise as a result of fission, e.g., fission fragment yield, TKE, population of prompt neutrons and gammas which is followed by a series of β-decay, and their correlations must be comprehended in a consistent manner, which is still a difficult subject
8. We have been treating the process before scission by several theories, such as Langevin equation, Antisymmetrized Molecular Dynamics (AMD) and Time-Dependent Hartree-Fock (TDHF), and their outcomes are to be connected to statistical decay model and theory of β-decay
9. These methodologies can be applied also to study of fission and formation of Super Heavy Element (SHE), later part of my talk is devoted to this subject

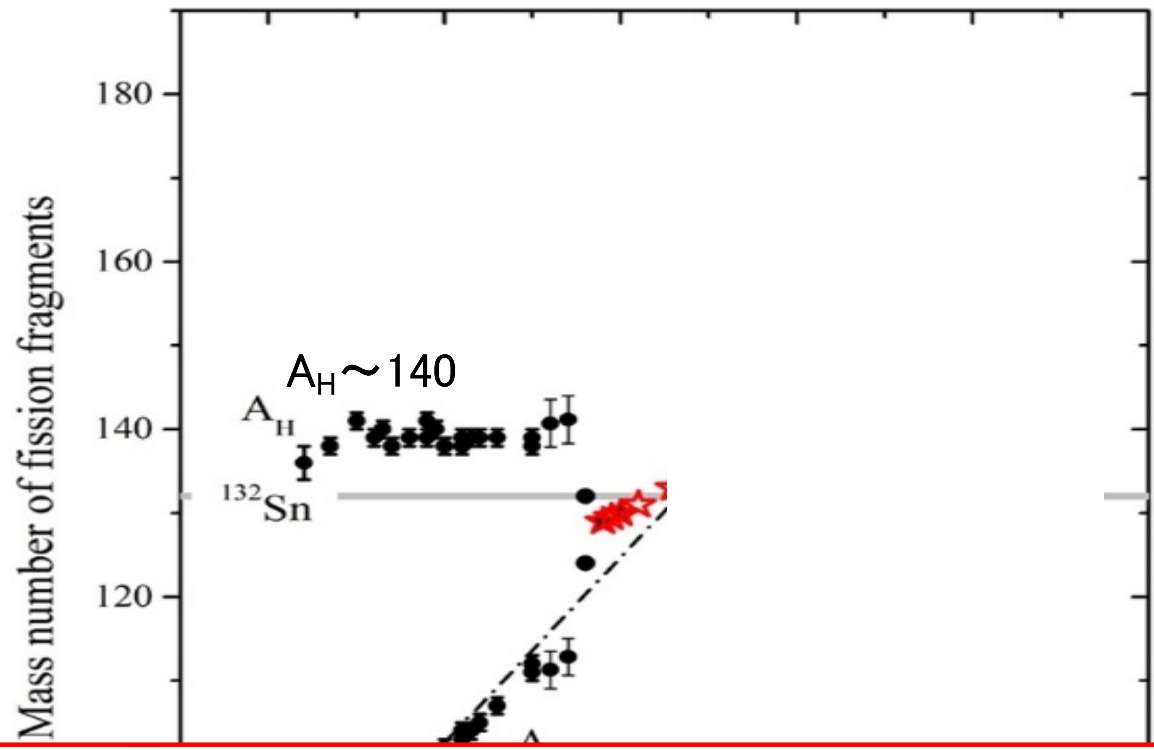
Systematics of average peak position of light (L) and heavy (H) fragments

Some kind of transition in fission mechanisms is taking place between them



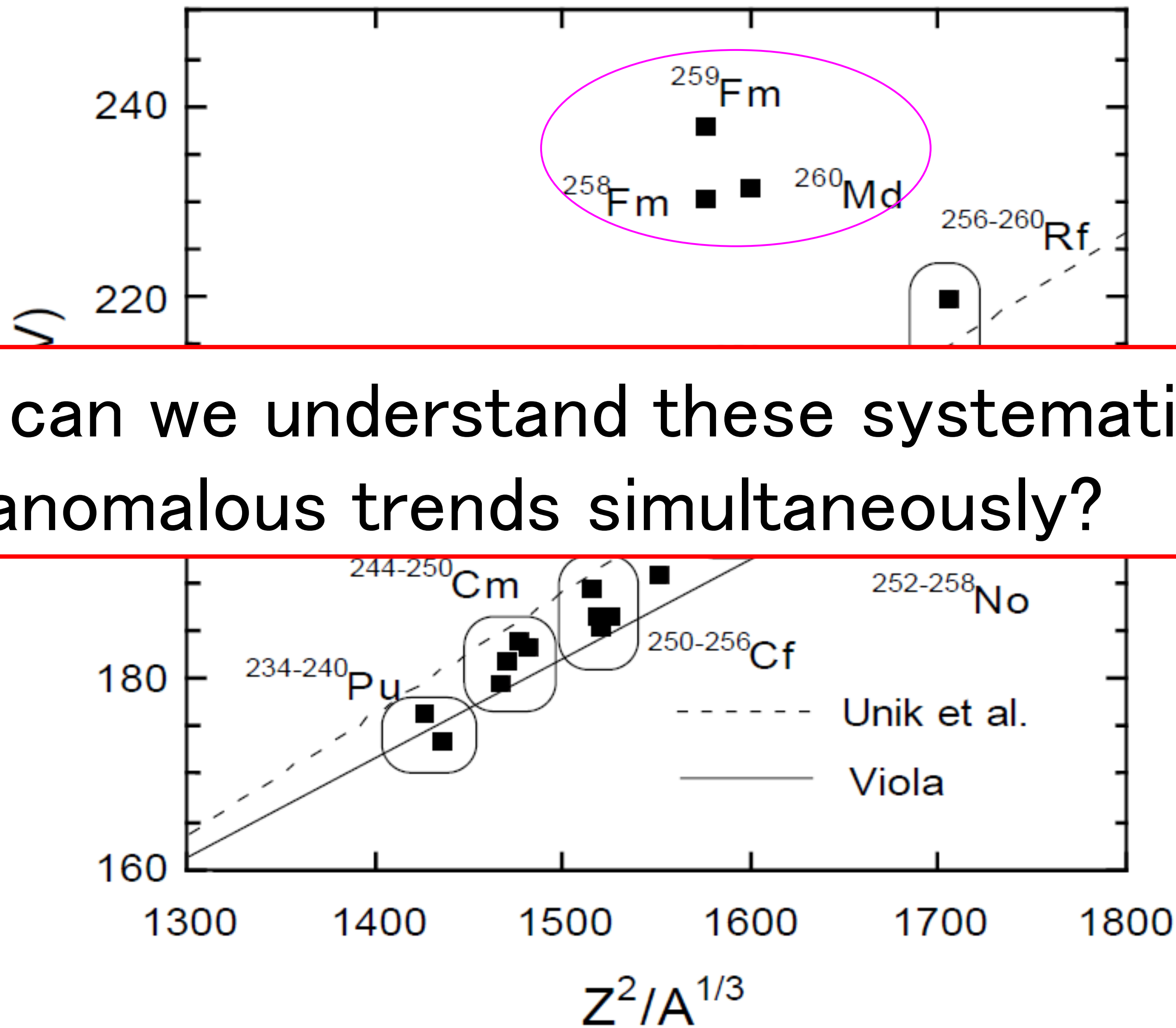
Peak position at broader region of nuclei

Itkis et al., Nucl. Phys. A944(2015)204–237



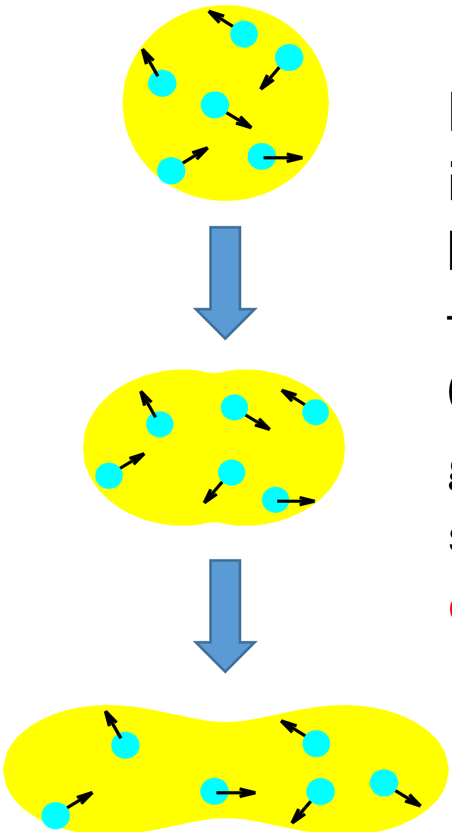
- How these changes in the systematics and anomalies in peak positions can be understood?
- Fission of SHE is important for r-process

Systematics and anomaly in the average Total Kinetic Energy of Fission Fragments



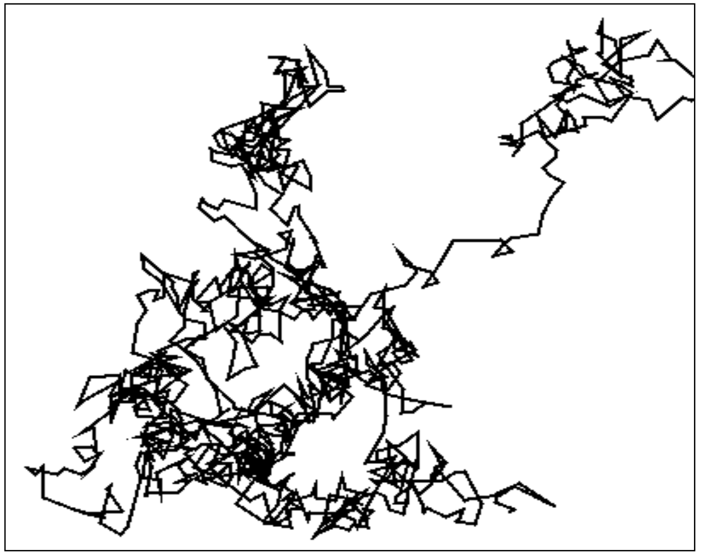
How can we understand these systematical and anomalous trends simultaneously?

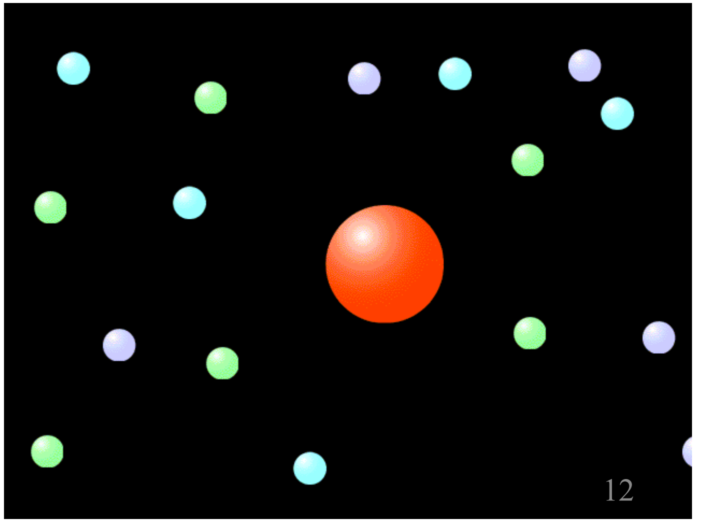
Nuclear fission treated by Langevin equation



Nuclear shape evolution is driven by random kicks by nucleons in thermal equilibrium (microscopic d.o.f.) given to the nuclear surface (macroscopic d.o.f) inside the surface

Brownian motion

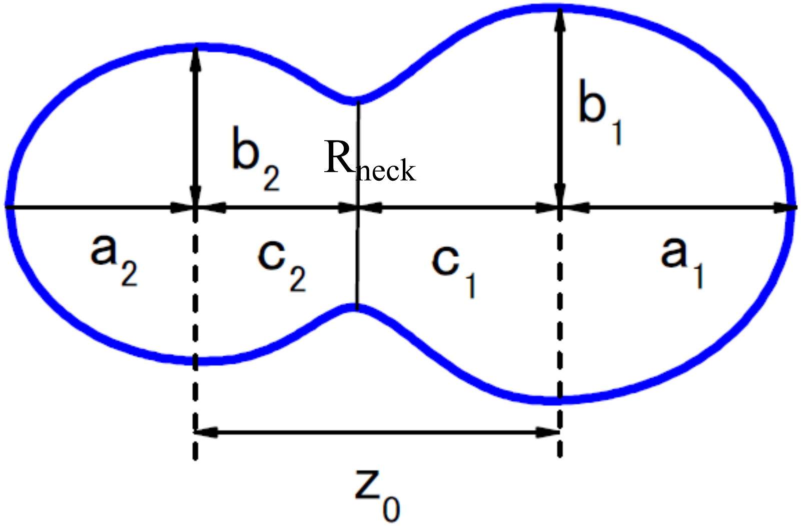




These 2 different d.o.f have different time scales:

- nucleon motion : 1 to 10 fm/c
- shape motion : ～>10,000fm/c

Shape parametrization



Two-center model
(Maruhn and Greiner, Z. Phys. 251(1972) 431)

Collective coordinates (3 or 4 dynamical variables)

$$\{q\}_{4D} = \{ZZ_0, \delta_1, \delta_2, \alpha\}$$

- $ZZ_0 = \dfrac{z_0}{R}$ Elongation

  R : Radius of compound nucleus $= 1.2 A_{CN}^{1/3}$

- $\delta_i = \dfrac{3(a_i - b_i)}{2a_i + b_i}$ Deformation of fragments

- $\alpha = \dfrac{A_1 - A_2}{A_1 + A_2}$ Mass asymmetry

  A_1 : mass of the right fragment

  A_2 : mass of the left fragment

- $\varepsilon = 0.35$ neck parameter : fixed **No free parameter**
- volume conservation condition is applied

4D Langevin model C.Ishizuka et al., PRC 96, 064616 (2017).

$$\begin{cases} \dfrac{dq_i}{dt} = \left(m^{-1}\right)_{ij} p_j \\ \dfrac{dp_i}{dt} = -\dfrac{\partial F}{\partial q_i} - \dfrac{1}{2}\dfrac{\partial}{\partial q_i}(m^{-1})_{jk} p_j p_k - \gamma_{ij}(m^{-1})_{jk} p_k + g_{ij} R_j(t) \end{cases}$$

Drift term — Friction term — Wiener term

$\{q_i : i = 1..4\} = \{ZZ_0,\ \alpha\ ,\ \delta_1,\ \delta_2\}$

$$dV = TdS - PdV - \sum_i K_i q_i$$

$$dT = -\sum_i K_i q_i$$

q_i : Nuclear shape motion

p_i: Momentum conjugate to q_i

Nuclear model calculation

F: Helmholtz' free energy, $F = V - TS$: 2-center Woods-Saxon model

m_{ij} : Inertia tensor : Werner-Wheeler model or Linear Response Theory

γ_{ij}: friction tensor: Wall and Window or Linear Response Theory

$g_{ij} g_{ij} = \gamma_{ij} T$: Fluctuation dissipation theorem (+Einstein relation)

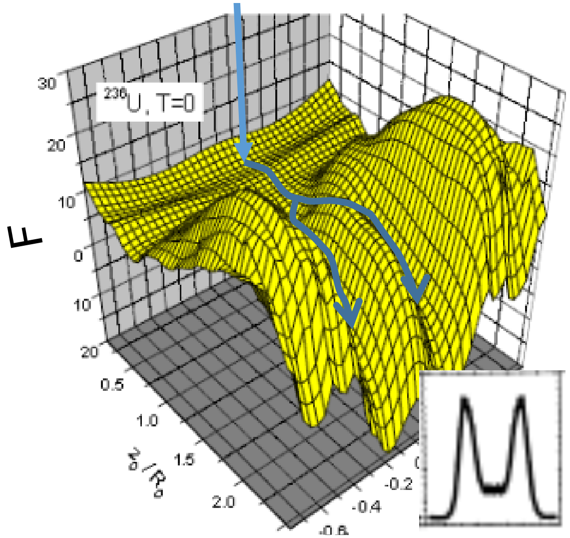
$$T = \sqrt{\frac{E^* - \frac{1}{2} m_{ij} p_i p_j - E_{rot}}{a}}$$

E^* : Total excitation energy of the system

Temperature dependent free energy surface F

F.A.Ivanyuk, C.Ishizuka, M.D.Usang and SC, Phys. Rev. C 97, 054331 (2018)

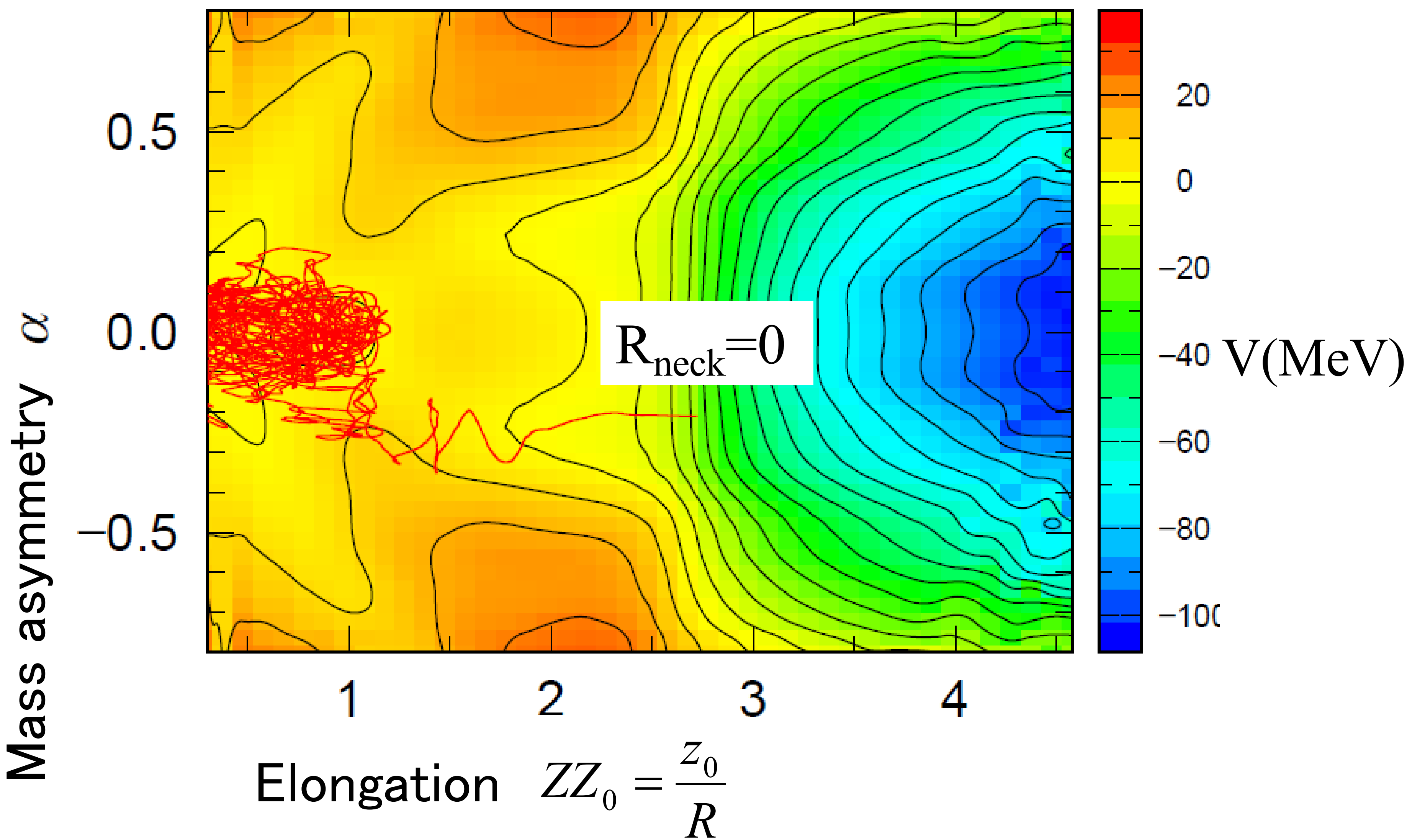
^{236}U



Macro-Micro calculation
- 4D Woods-Saxon
- Strutinsky shell correction
- BCS pair correction

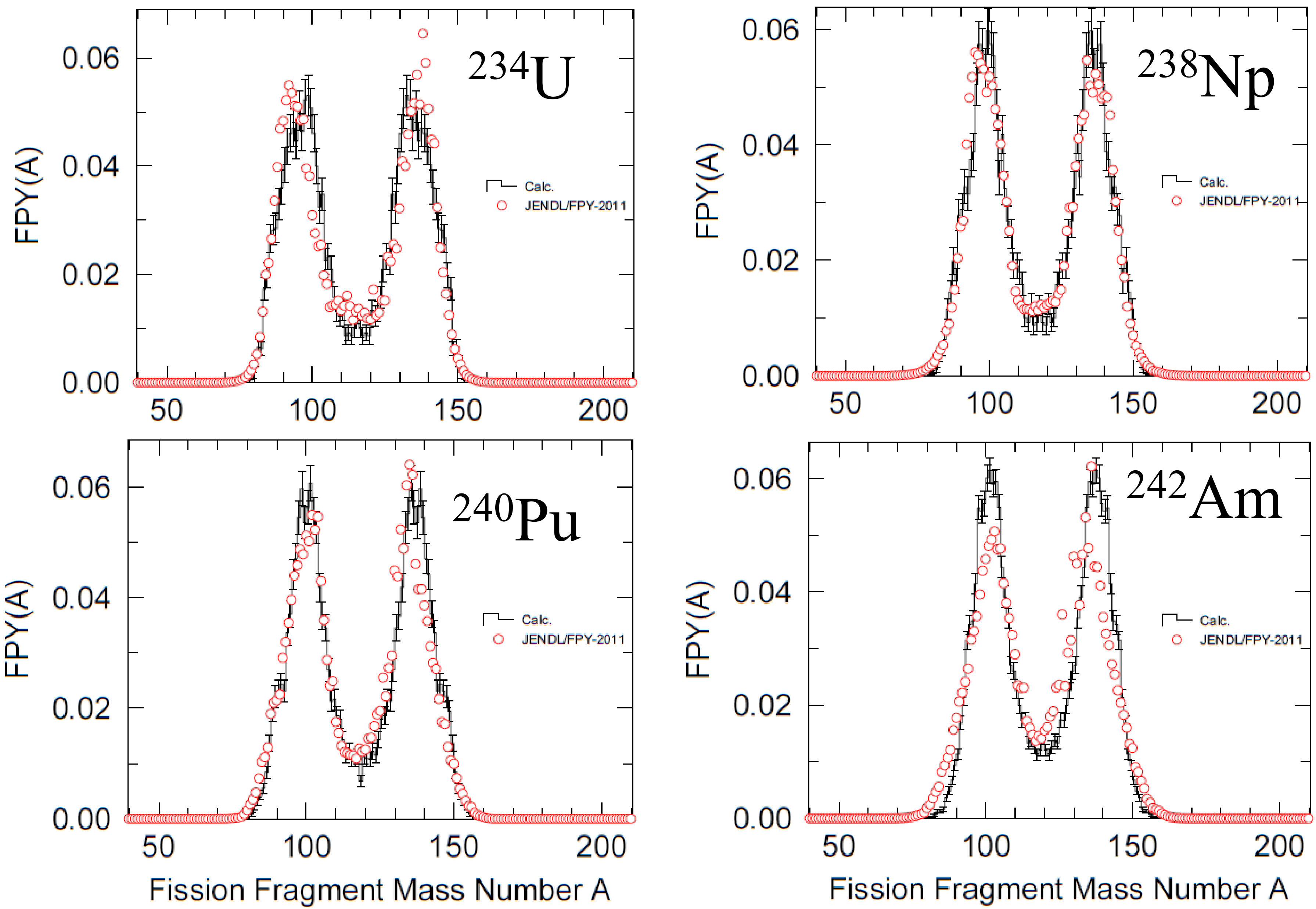
Example of Langevin trajectories (^{236}U, 20MeV)

Not differentiable everywhere
Infinite path length when $\delta t \to 0$



Predictions for mass distributions (Ex=20MeV)

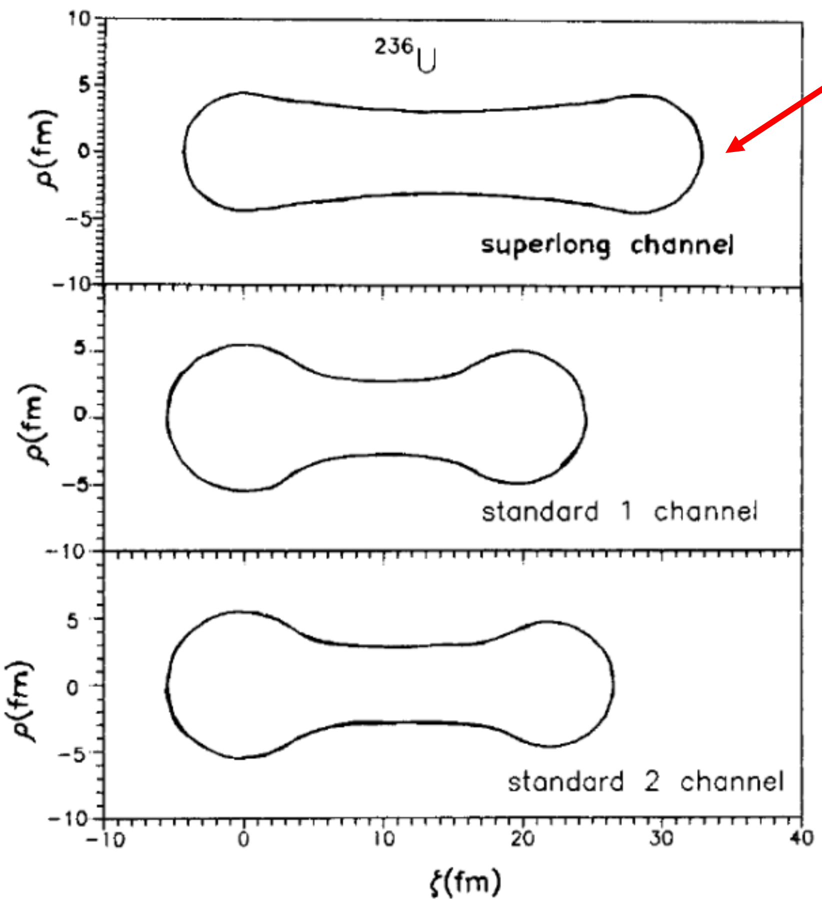
Tokyo Tech

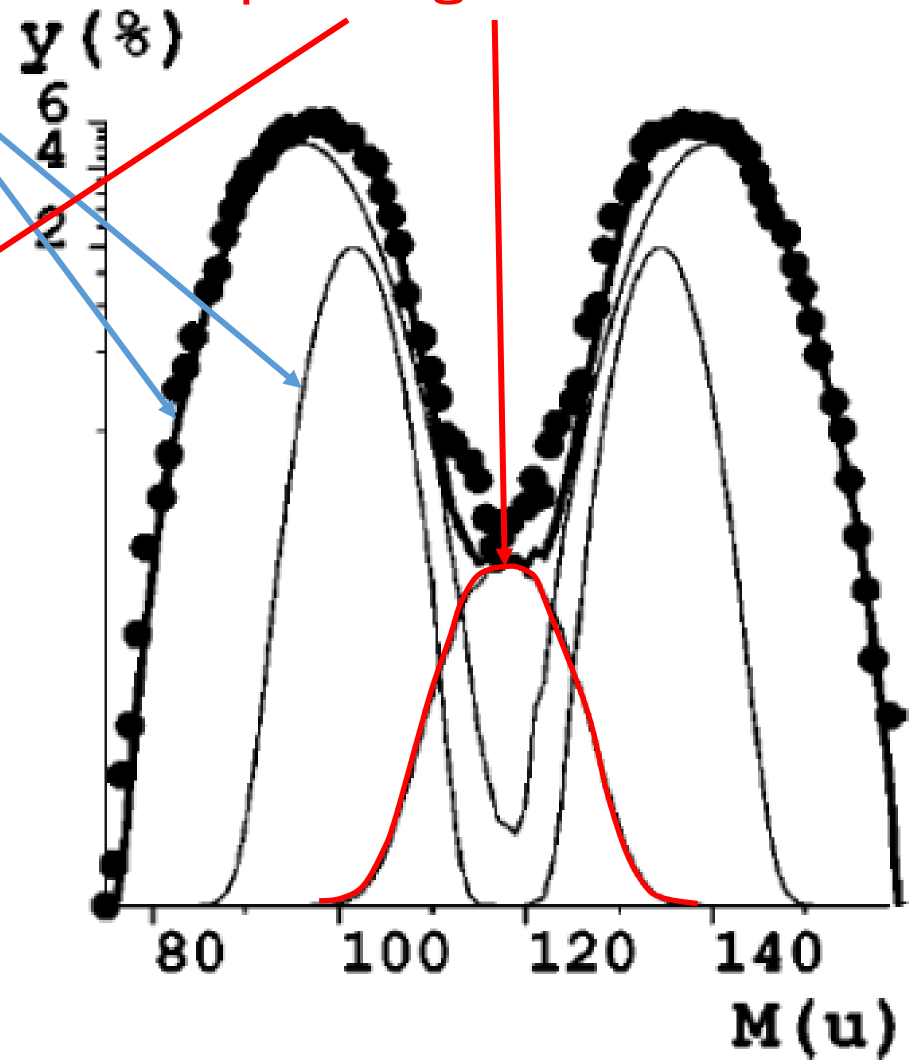


Decomposition of fission modes (Brosa)

Symmetric component:
Superlong mode

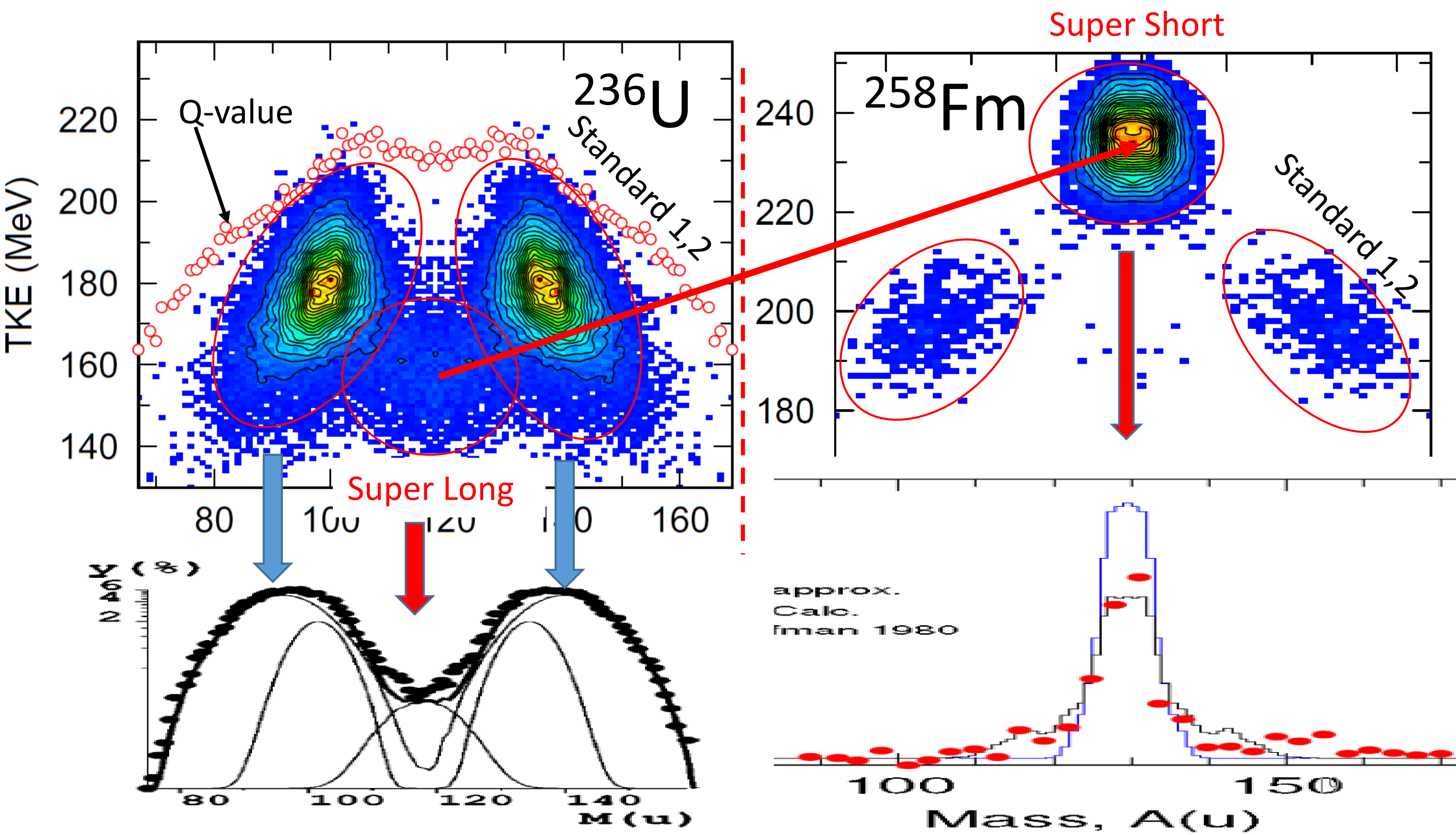
asymmetric components
(Standard 1 & 2 modes)





Mass-TKE correlation and its decomposition

Clear transition of fission mechanisms, symmetric mode begin super long for ^{236}U, while it is super short for ^{258}Fm



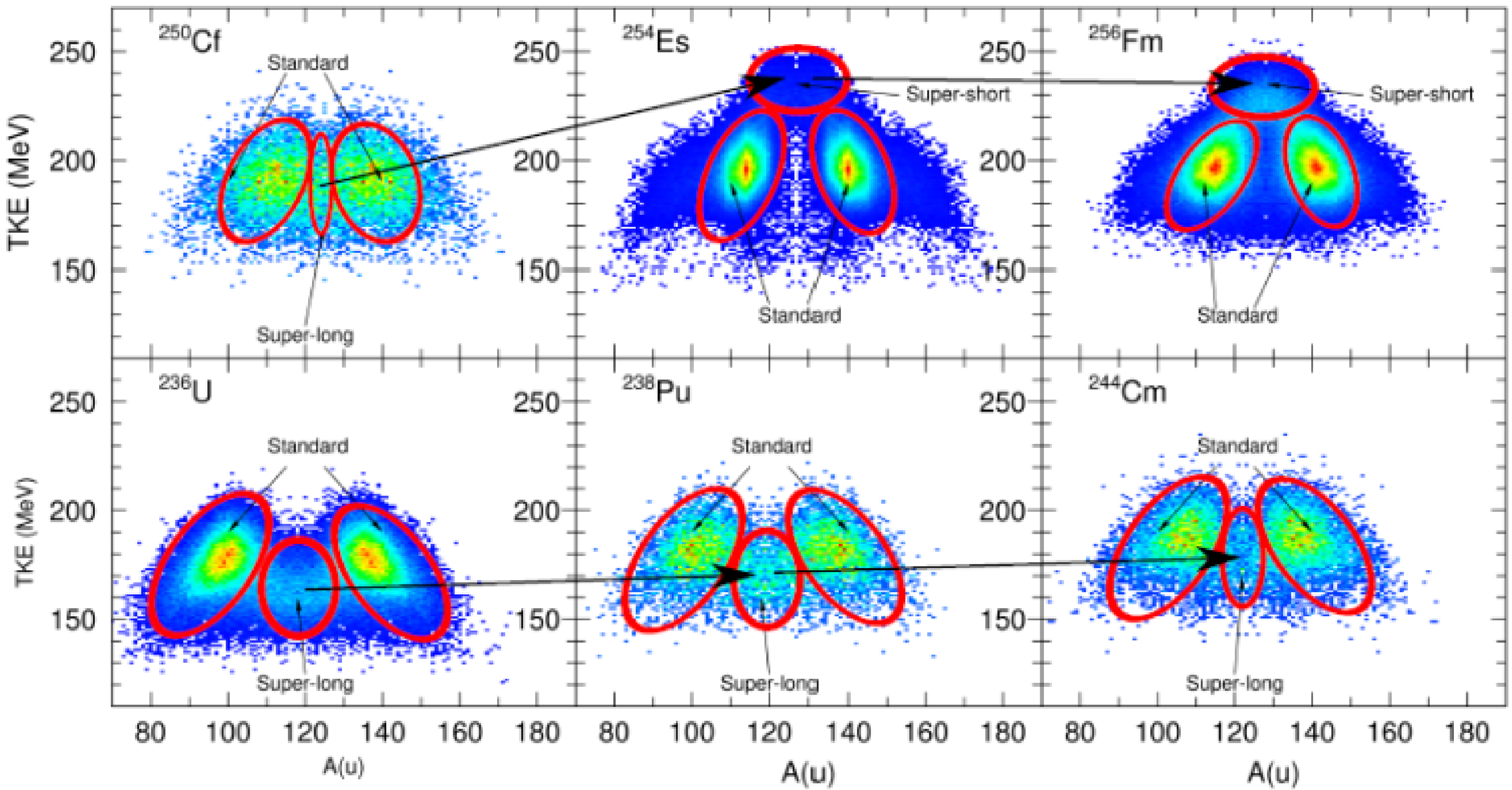
Systematics in Mass–TKE correlations

Tokyo Tech

U236 to Fm256

Neck parameter, $\epsilon = 0.35$

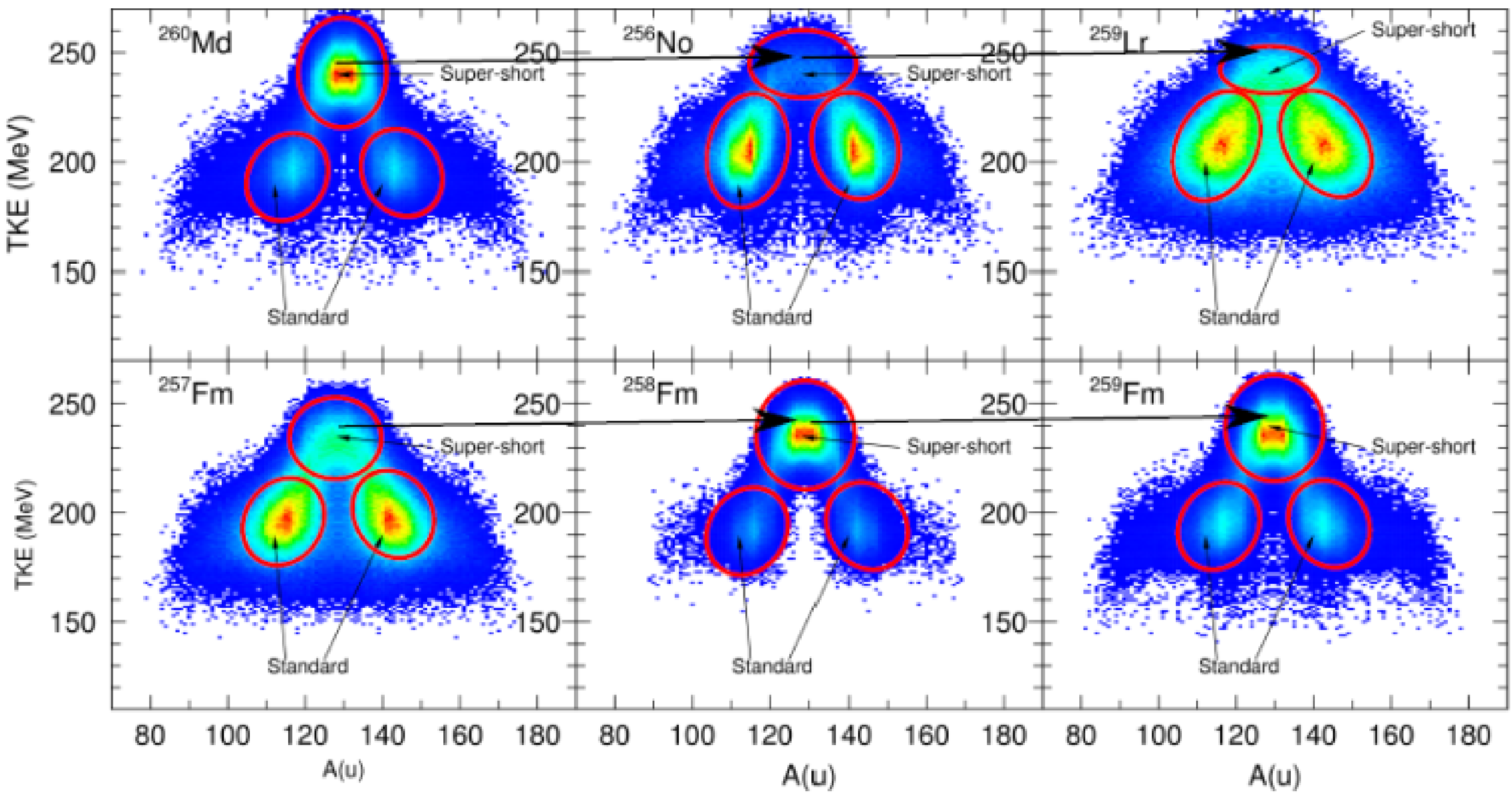
Look carefully how the symmetric component behaves. Look also how the dominant mode (red contour part) changes



Systematics in Mass-TKE correlations

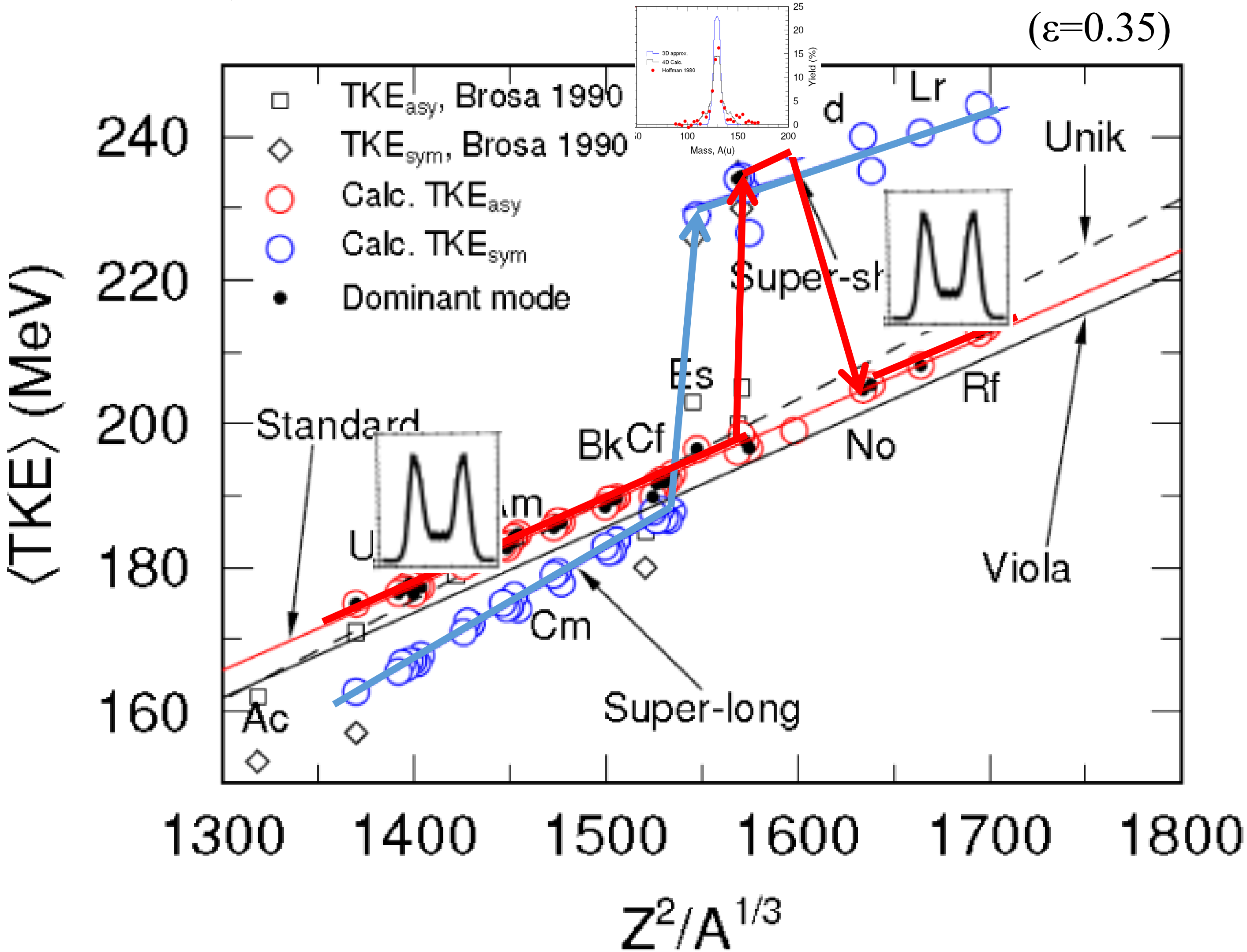
From Fm257 to Lr259

Neck parameter, $\epsilon = 0.35$



Results of mass–TKE correlations

Let us look how the symmetric component and dominant mode behave as a function of the $Z^2/A^{1/3}$



Results of mass-TKE correlations

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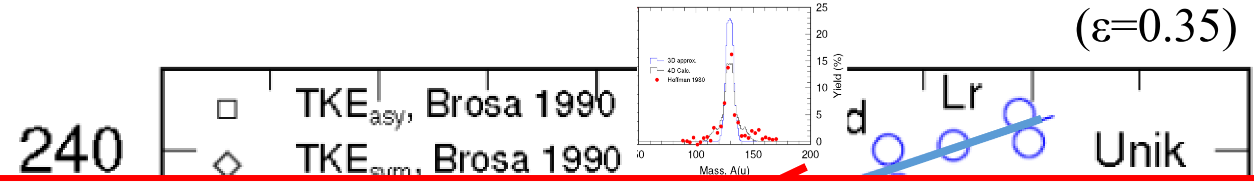
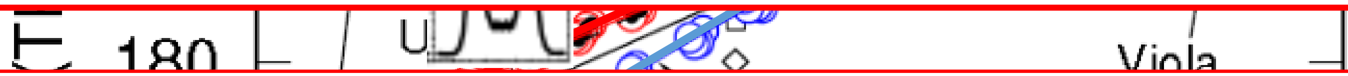
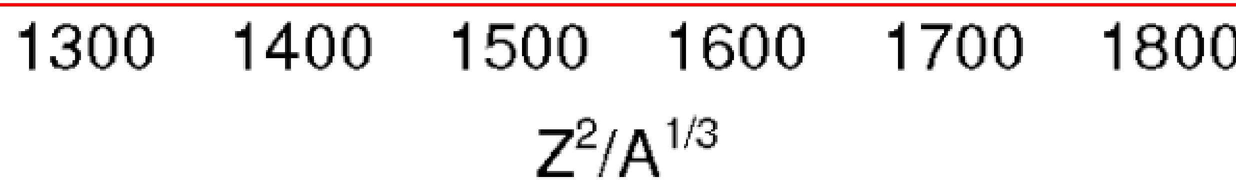


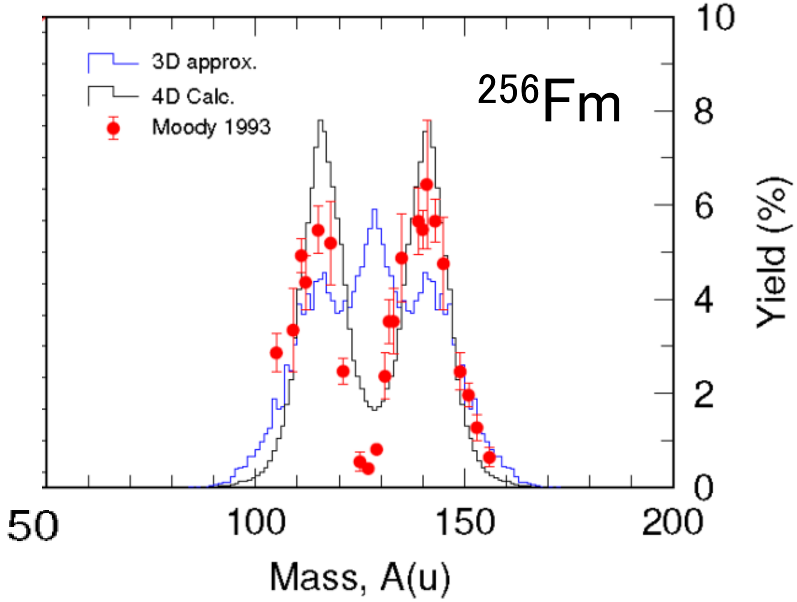
We can understand the systematical and anomalous trends in mass and TKE distributions of these nuclei in terms of correlated transition of the symmetric mode and that of dominant mode:
Usang, Ishizuka, Ivanyuk and SC "Correlated transitions in TKE and mass distributions of fission fragments described by 4-D Langevin equation", Scientific Reports 9, 1525(2019).

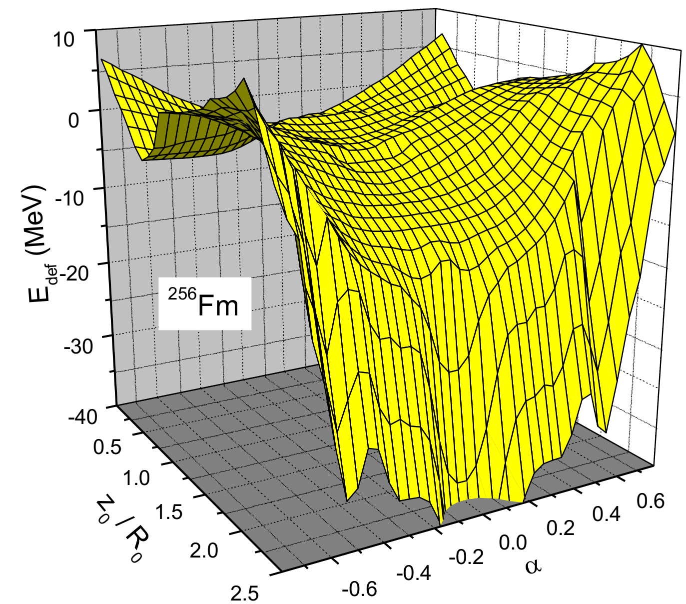


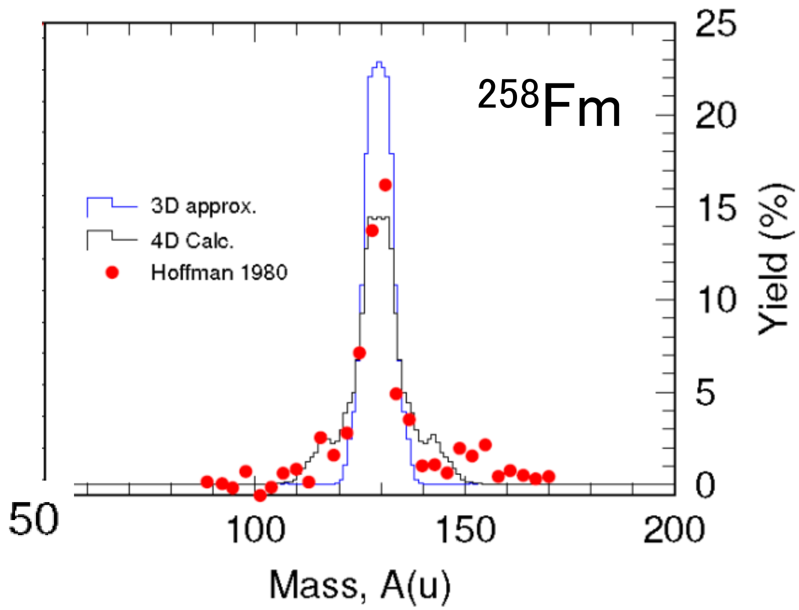
Systematic measurement of such mass-TKE correlation will be very important to understand fission mechanisms, especially in the transition region

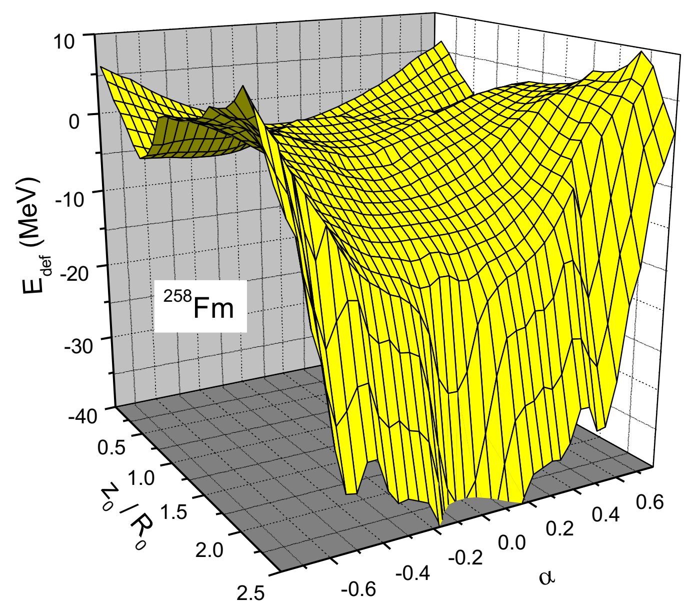


Importance of dynamical treatment

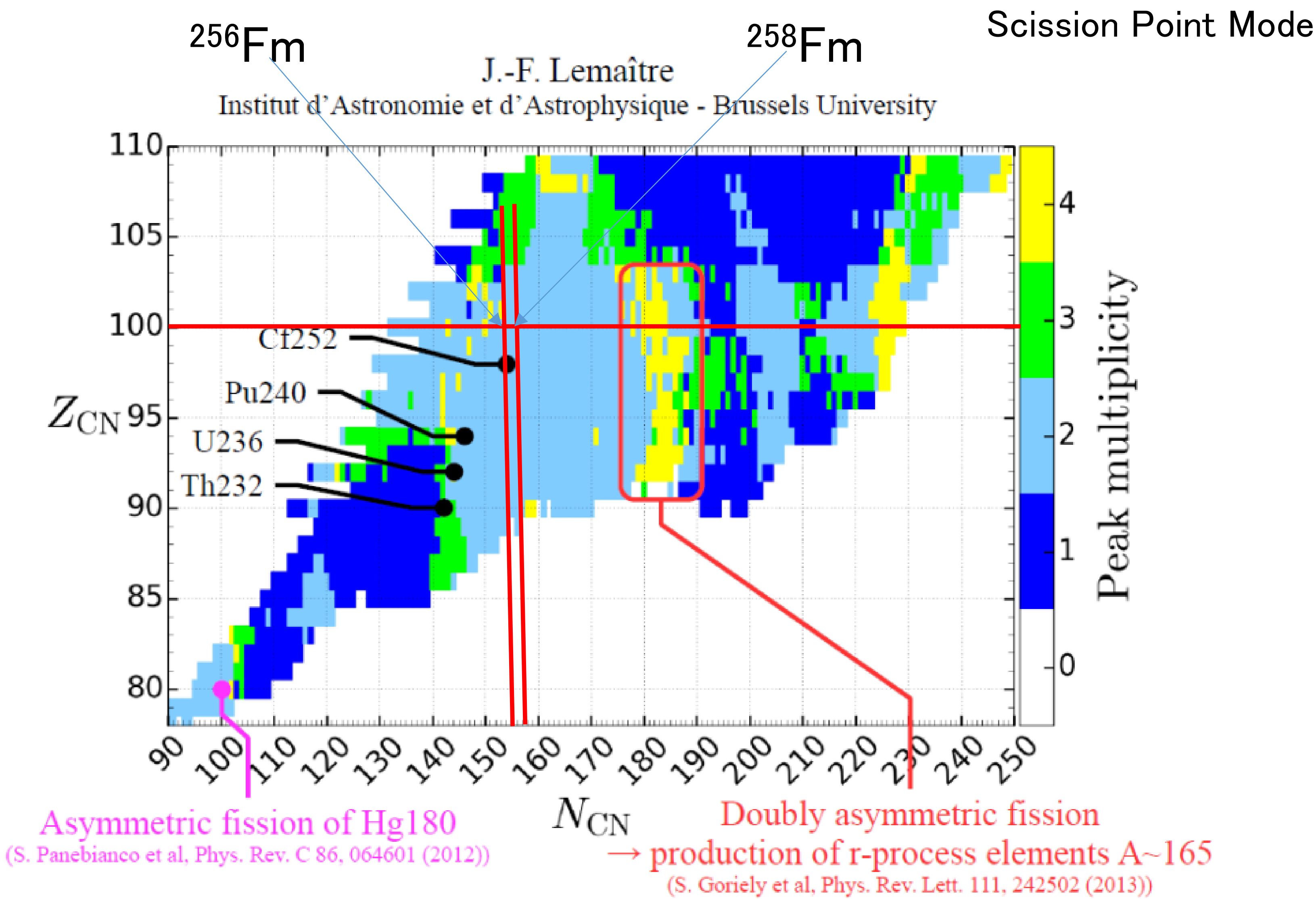




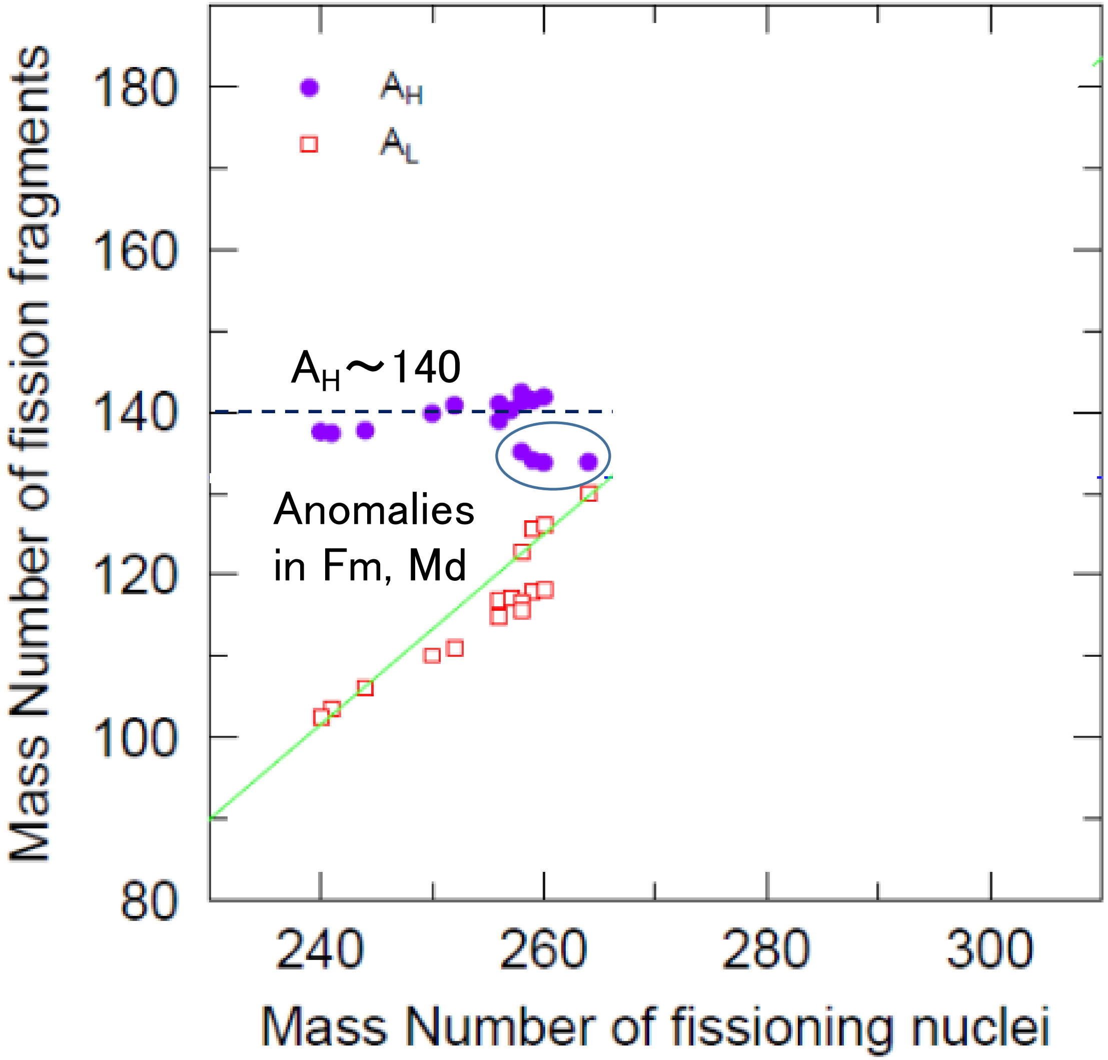




Microscopic description of fission for the r-process in neutron-star mergers ejecta



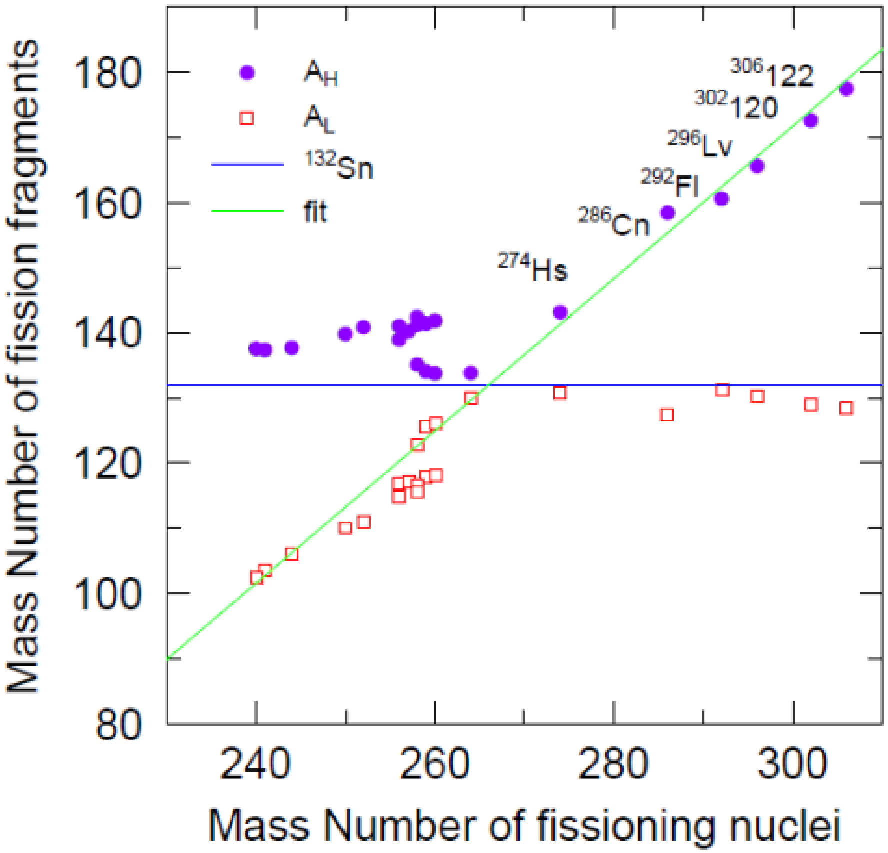
Peak positions of FF in broader region of compound mass number



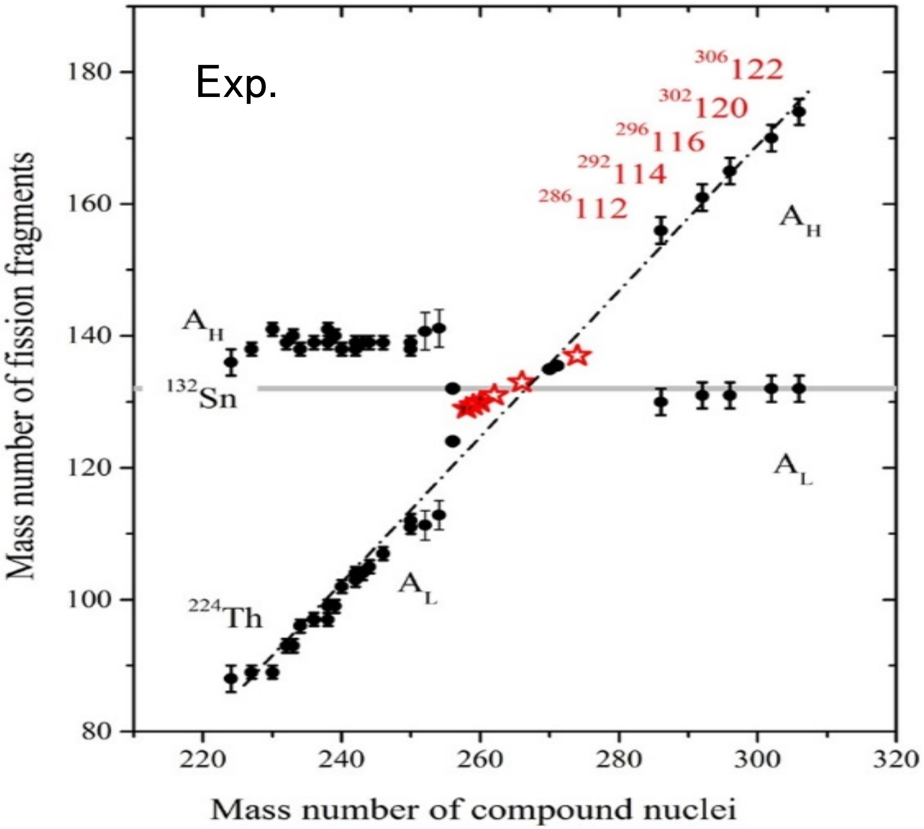
Comparison with experimental data (right)

No parameter is adjusted

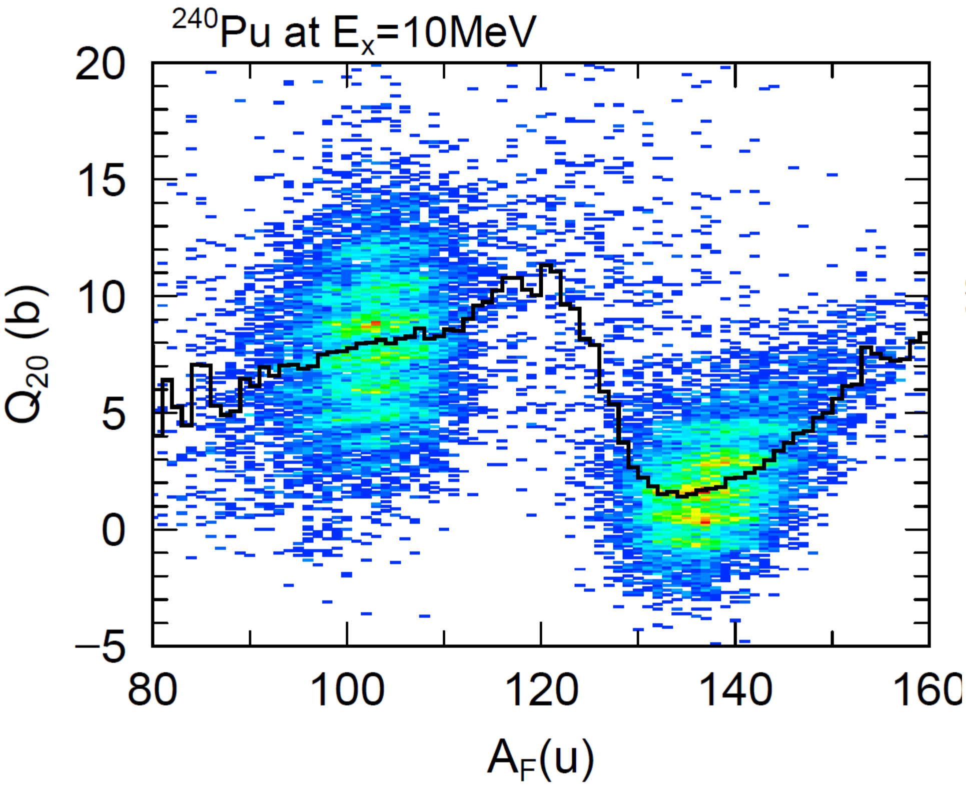
Our calculation (4D Langevin)

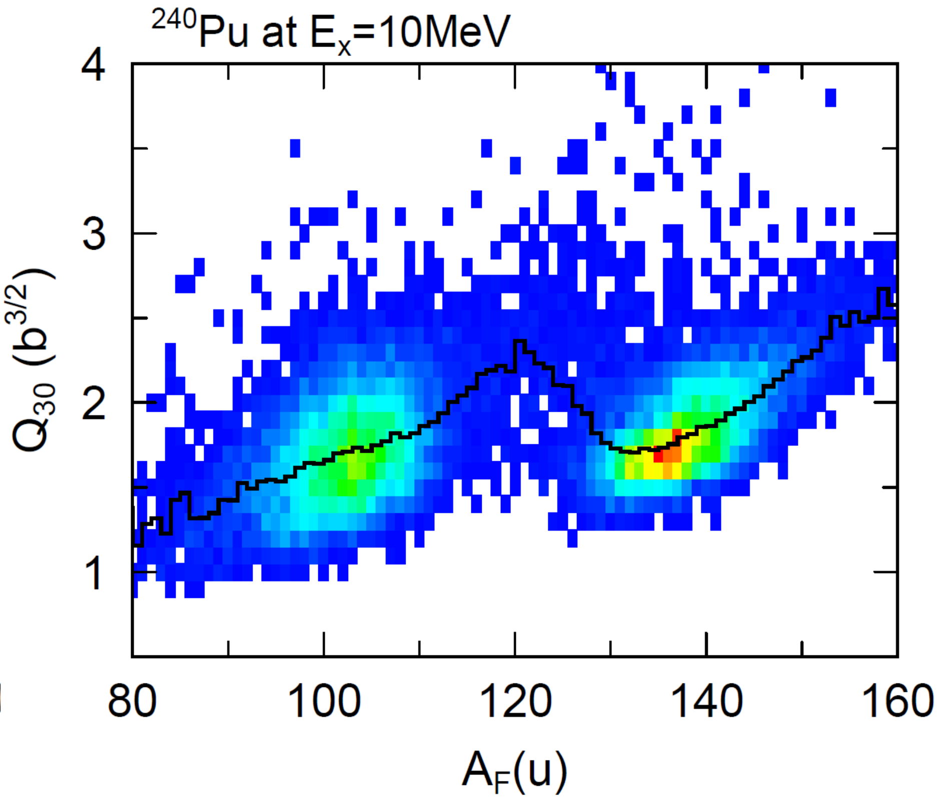


Itkis et al., Nucl. Phys. A944(2015)204–237



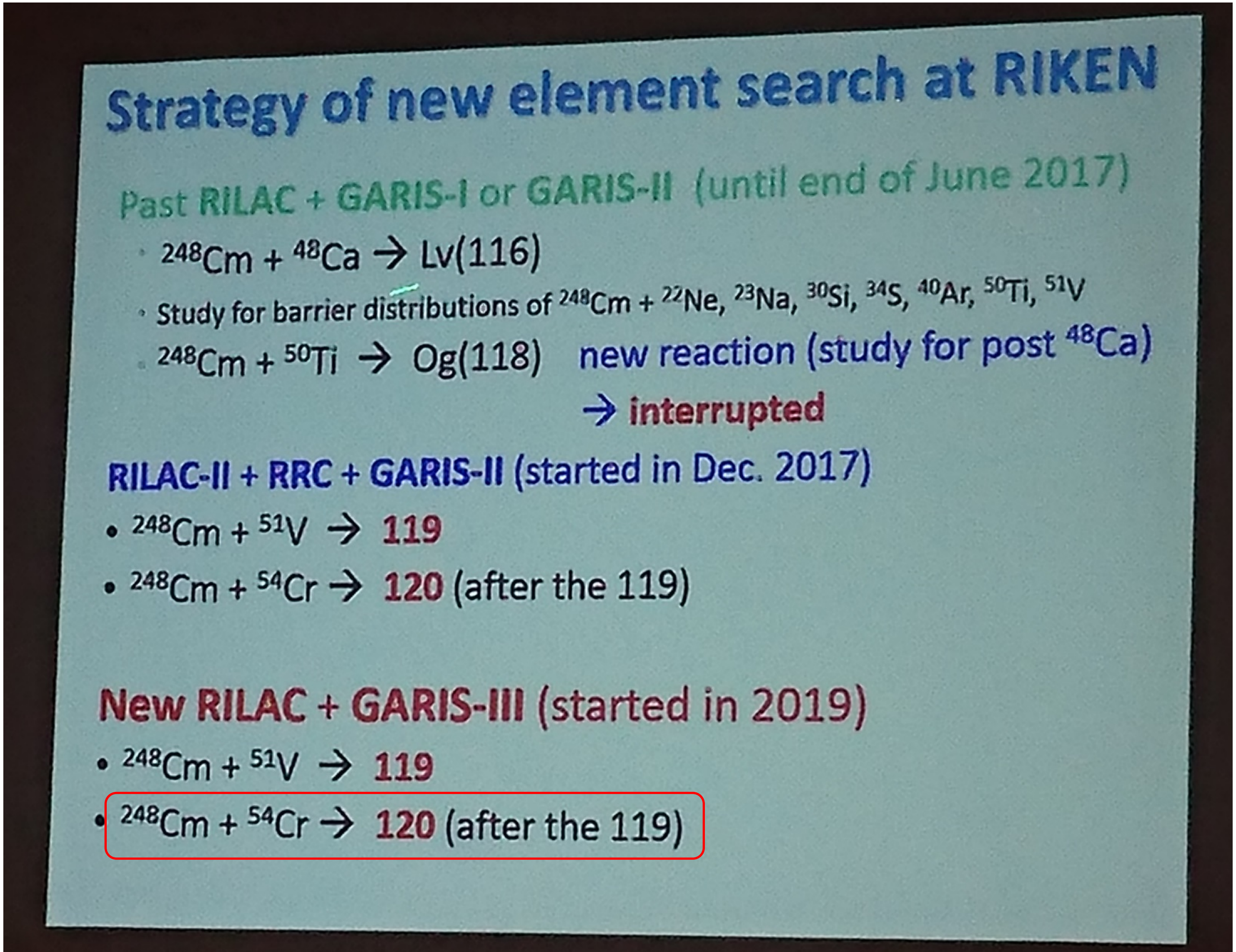
Fragment shape at scission



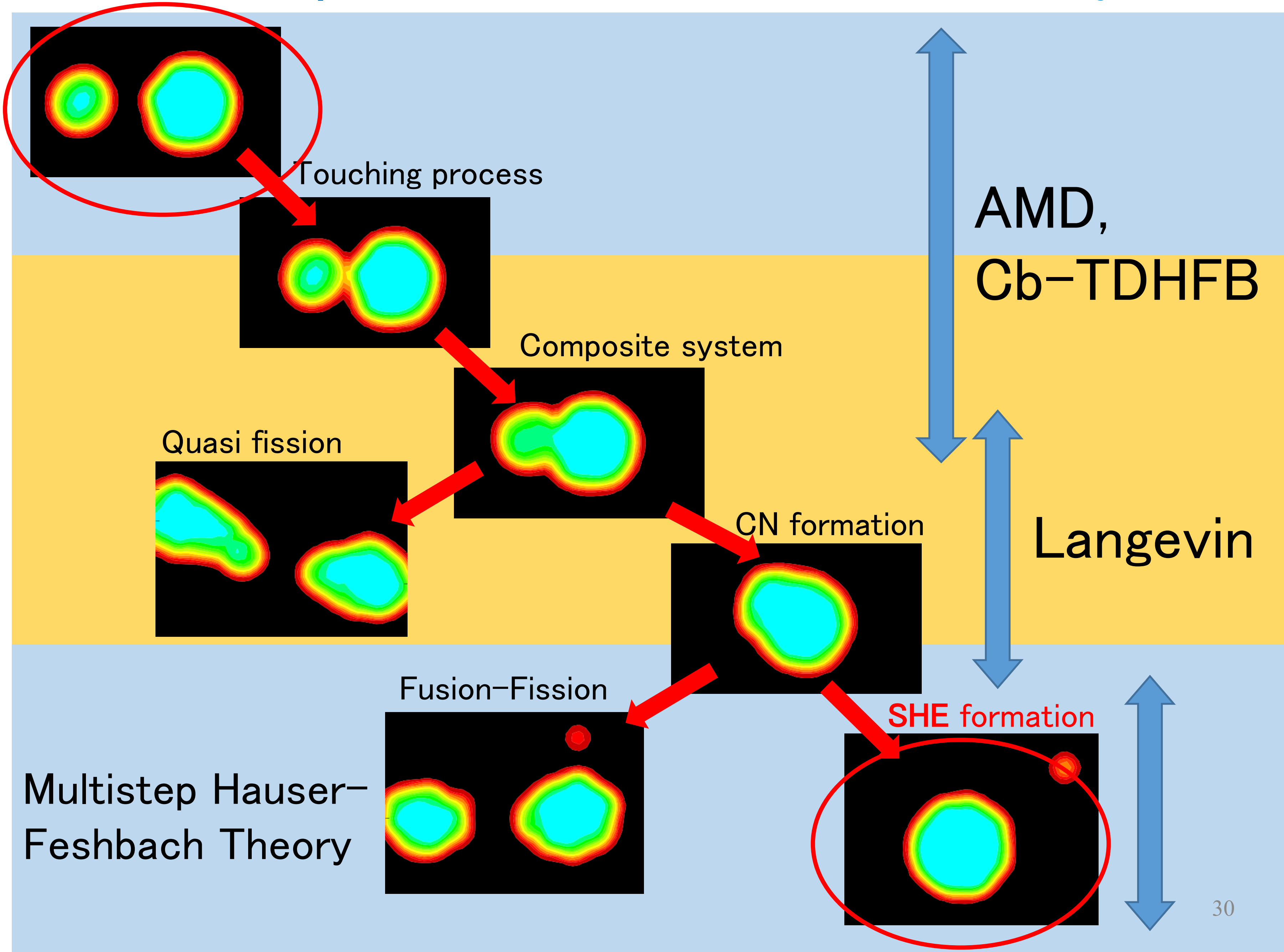


- Estimation of deformation energy is now possible
- Spin and parity distribution?

Z=120 SHE formation: Morimoto-san’s talk in Hawaii 2018



SHE formation process and theories available at Tokyo Tech.



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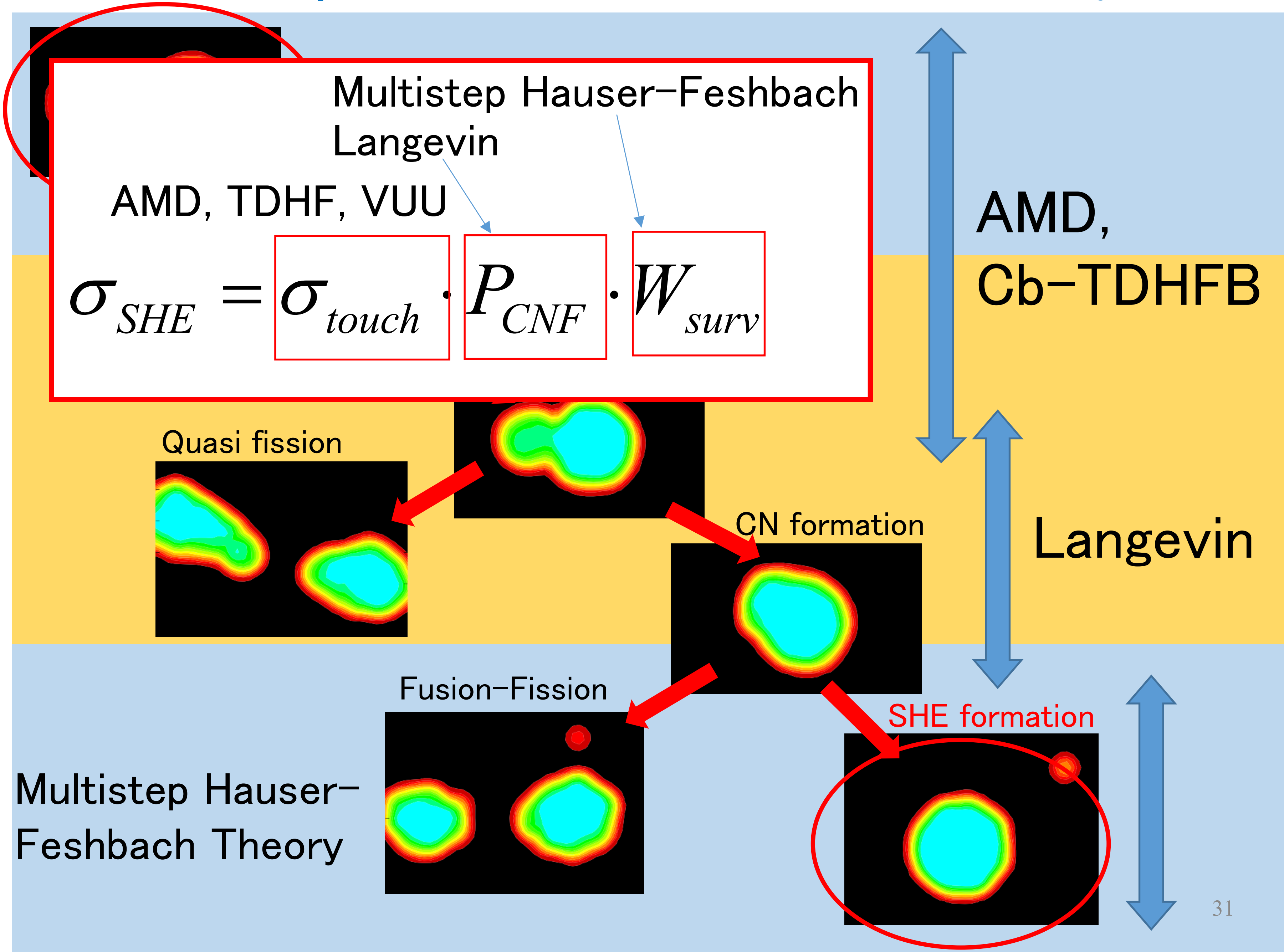


$$\sigma_{SHE} = \sigma_{touch} \cdot P_{CNF} \cdot W_{surv}$$

Antisymmetrized Molecular Dynamics : AMD

Mean Field + Stochastic NN collision

Total wave function：Single Slater det. $|\Phi(r_1, r_2, \dots, r_A)\rangle = \frac{1}{\sqrt{A!}} \det[\phi_i(r_j)]$

Single particle w.f.：Gaussian coherent state: $\langle \vec{r} | \phi_{\vec{Z}_i} \rangle = \left(\frac{2\nu}{\pi}\right)^{\frac{3}{4}} \exp\left[-\nu\left(\vec{r} - \frac{\vec{Z}_i}{\sqrt{\nu}}\right)^2\right]\chi_i$

$$\vec{Z} = \sqrt{\nu}\vec{D} + \frac{i}{2\hbar\sqrt{\nu}}\vec{K},\ \ \chi_i = p\uparrow, p\downarrow, n\uparrow, n\downarrow$$

time−dependent variational principle

→ Equation of motion:

evolution of mean field

Effective interaction：SLy4

$$i\hbar \sum_{j\tau} C_{i\sigma,j\tau} \dot{Z}_{j\tau} = \frac{\partial \mathcal{H}}{\partial Z^*_{i\sigma}}$$

$$\mathcal{H} = \frac{\langle \Phi | \hat{H} | \Phi \rangle}{\langle \Phi | \Phi \rangle},\ C_{i\sigma,j\tau} = \frac{\partial^2}{\partial Z^*_{i\sigma} \partial Z_{j\tau}} log\langle \phi_i | \phi_j \rangle$$

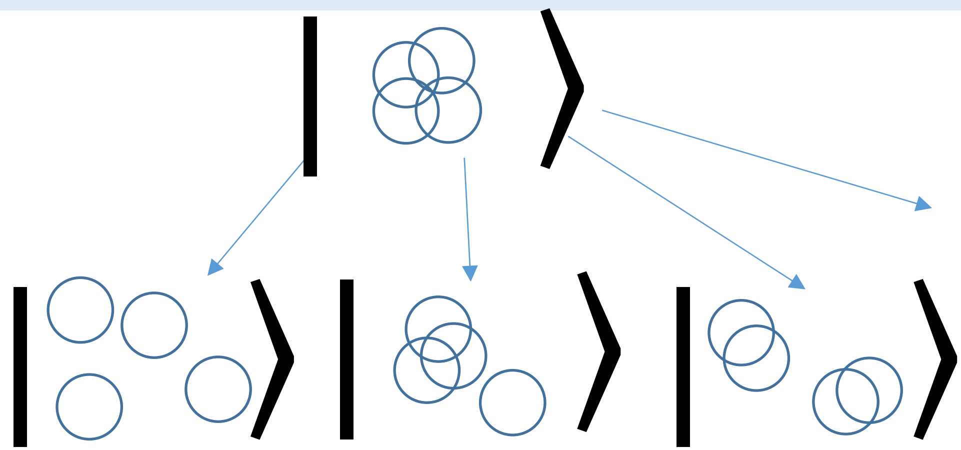
$$\sigma, \tau = \{x, y, z\}$$

Stochastic NN collision

like in cascade model

(nearest Distant model)

gives rise to branching of wave function→distribution

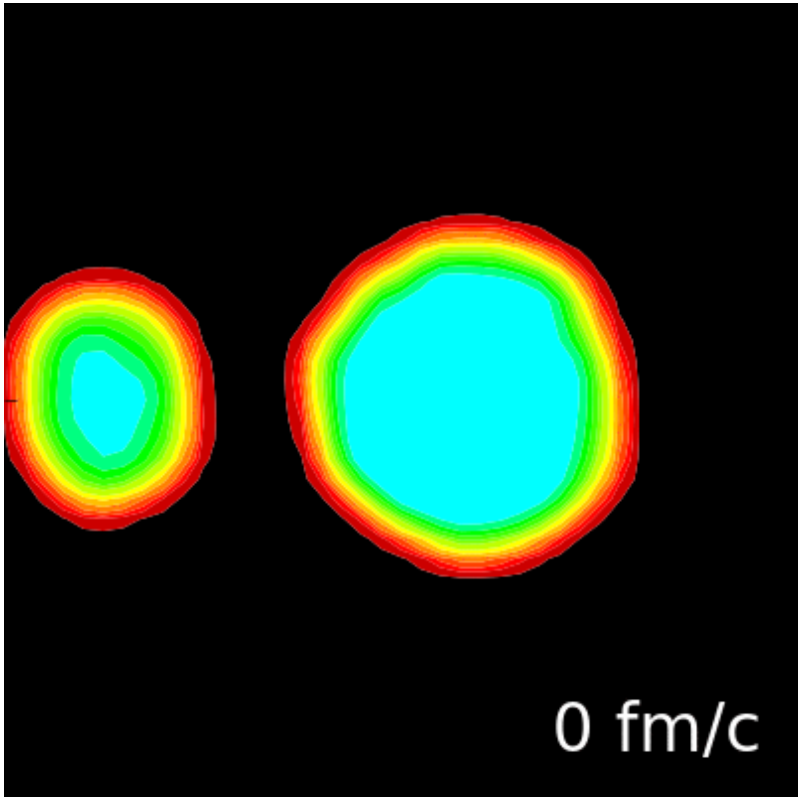


Akira ONO et al, Progress of Theoretical Physics, Vol. 87, No. 5 (1992)

Trial calculation: ^{54}Cr (310MeV) + ^{248}Cm

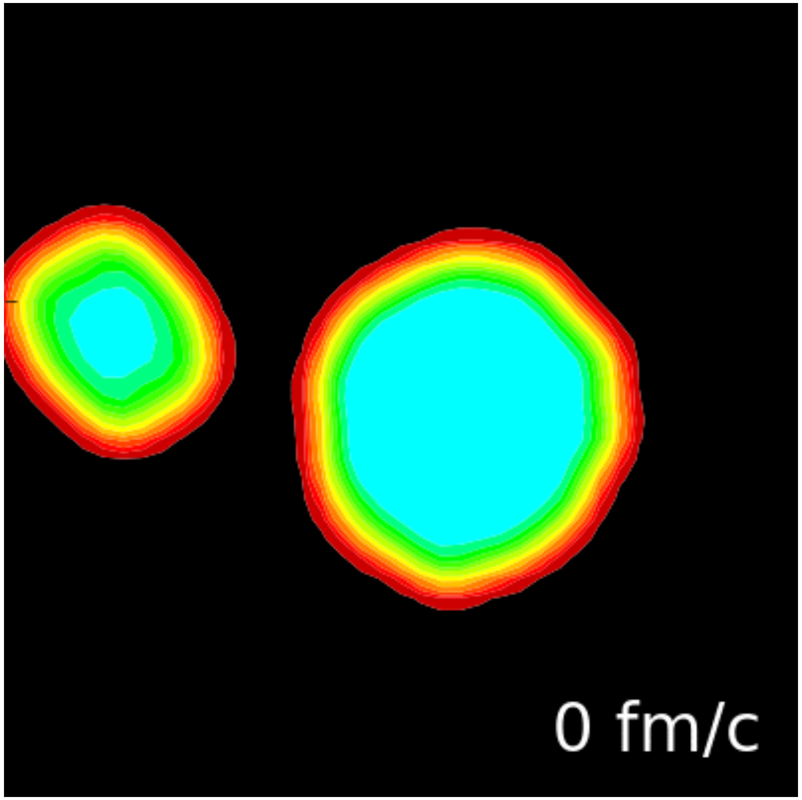
by AMD

b = 0.03 fm



$^{60}Mn+^{242}Am$

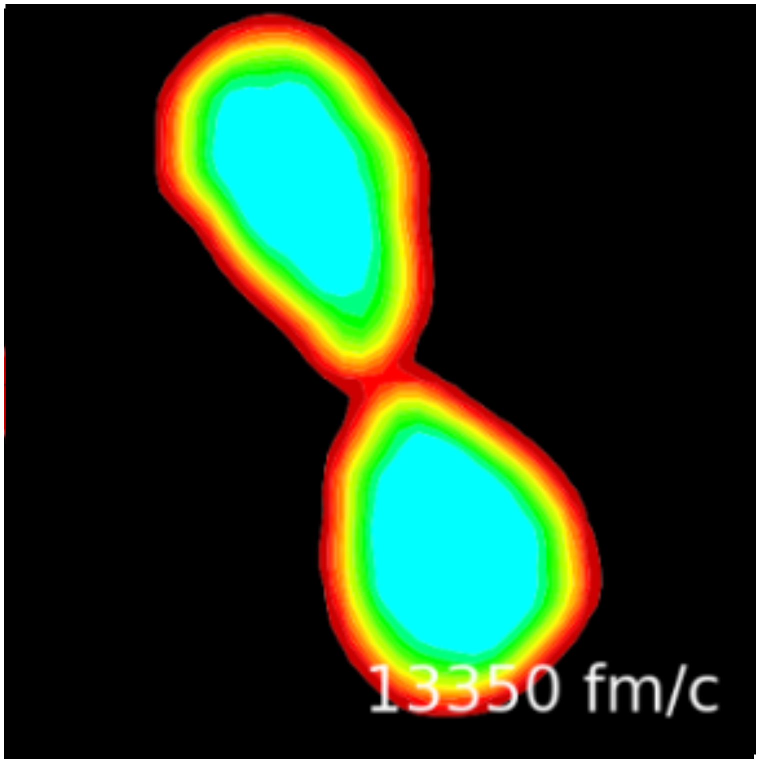
b = 3.12 fm

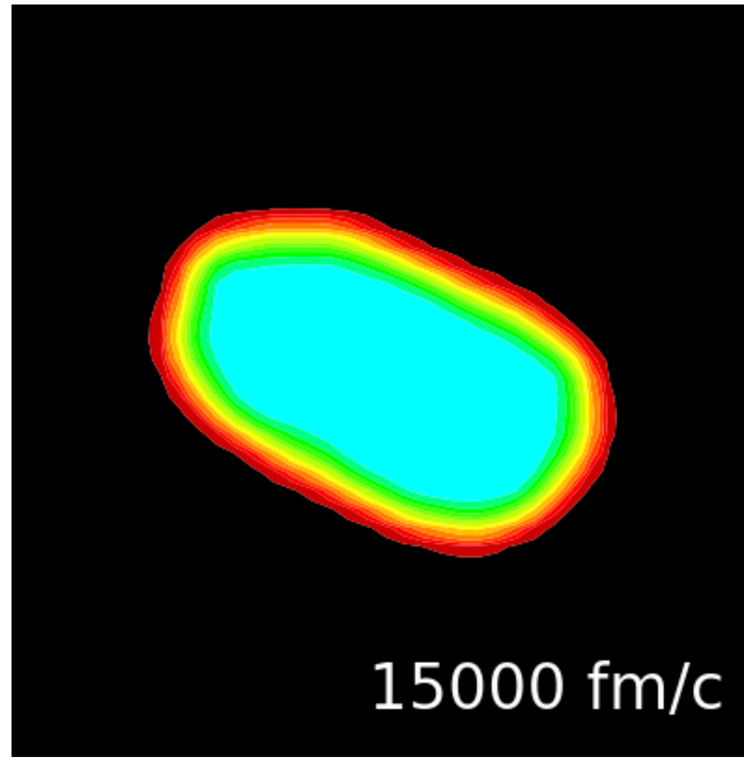


$^{53}V+^{249}Bk$

Touching process (b=0) by AMD

^{54}Cr (324MeV)+$^{248}Cm \rightarrow {}^{302}120$

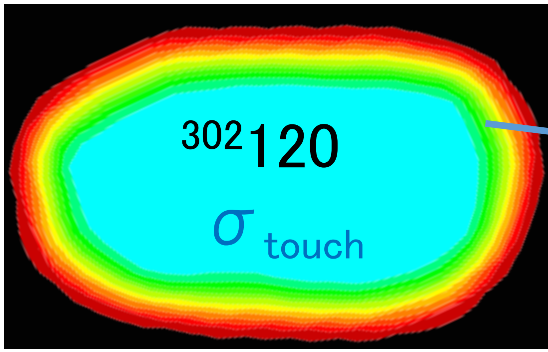




Dynamical large-scale reconfiguration of single-particle orbits is taking place. The fates of these 2 events are different due to stochasticity brought by the NN collision : TDHF is a deterministic theory

Hybrid model of SHE formation of Tokyo Tech.

Touching process



Shape profile
U*, L

AMD, Cb-TDHFB, VUU

Microscopic theories

Multistep Hauser-Feshbach calculation for W_{surv} :

N, Z, U*,J

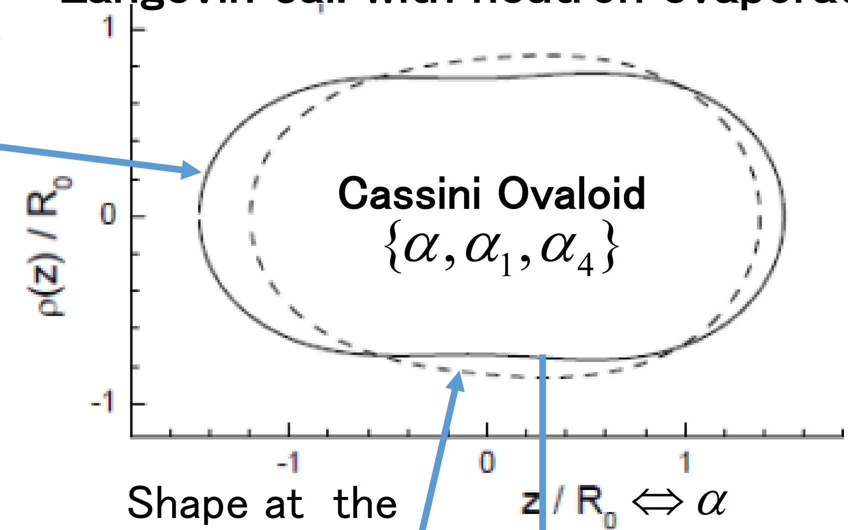
Survival probability W_{surv}

$$= \left[\frac{\displaystyle\sum_{\alpha'=\{n,\gamma\}:l'j'} \int_0^{E_{x\max}} \rho(E_{x'},J^{\pi})\, T^{J}_{\alpha'l'j'}(E_{\alpha'})\, dE_{x'}}{\displaystyle\sum_{\alpha''=\{n,p,d,t,h,\alpha,\gamma,F\}:l''j''} \int_0^{E_{x\max}} \rho(E_{x''},J^{\pi})\, T^{J}_{\alpha''l''j''}(E_{\alpha''})\, dE_{x''}} \right]^n$$

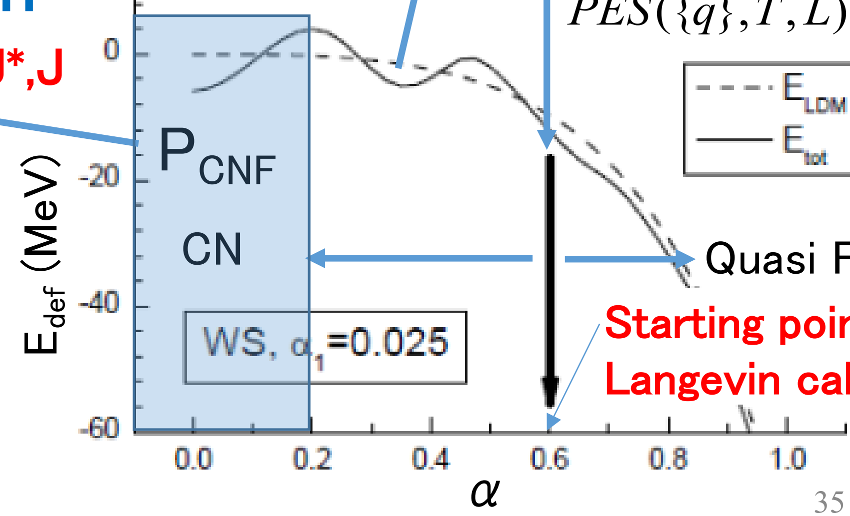
BeOH+HFBTHO

CNF or Quasi Fission

Langevin cal. with neutron evaporation



Shape at the 2nd minimum



Quasi Fission

Starting point of Langevin cal.

Langevin calculation : E*=50MeV for ^{302}120

P_{CNF}

- Shape parametrization : Cassini ovaloid
- Dynamical variables : 3 (α , α_1, α_4)
- Transport coefficients : Linear Response Theory
- Free energy surface : Woods–Saxon model (Pashkevich)
- Washing out of shell effects : taken into account
- Neutron emission : Iljinov *et al.*, (Nucl. Phys. A **543**, 517 (1992))
- Rotational energy : taken into account
- Langevin equation:

$$\begin{cases} \dot{q}_\beta = \mu_{\beta\nu} p_\nu , \quad \mu \equiv M^{-1} \\ \dot{p}_\beta = -\dfrac{\partial F}{\partial q_\beta} - \dfrac{1}{2} p_\nu p_\eta \dfrac{\partial \mu_{\nu\eta}}{\partial q_\beta} - \gamma_{\beta\nu} \mu_{\nu\eta} p_\eta + \theta_{\beta\nu} \xi_\nu . \end{cases}$$

Neutron emission Width:

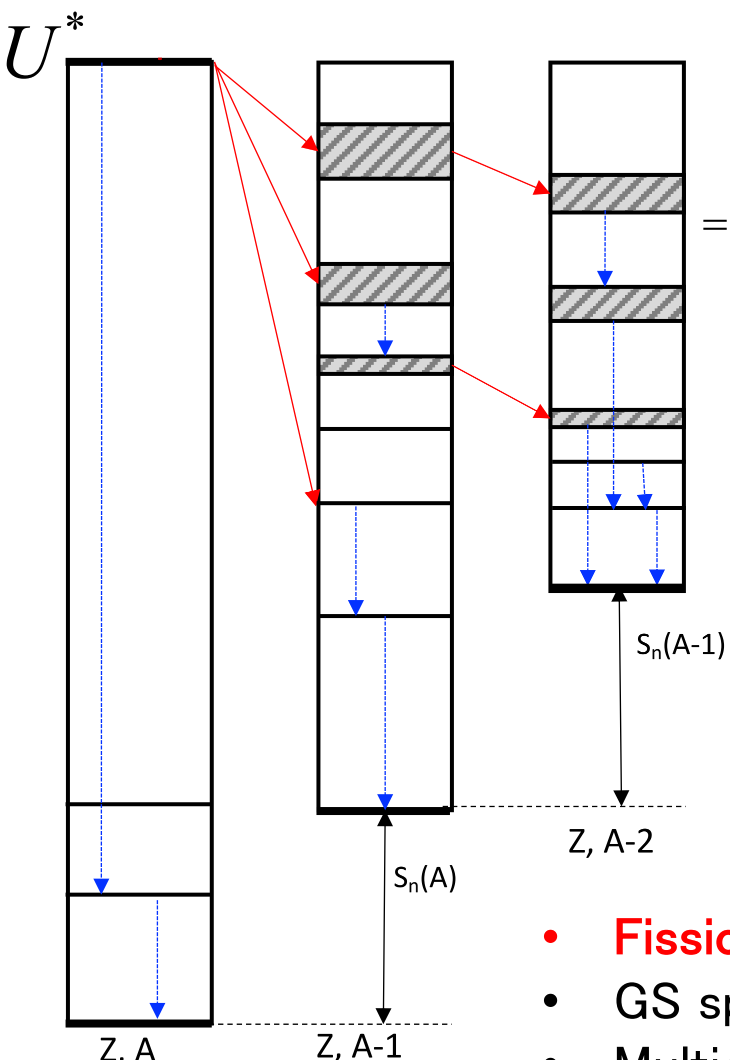
$$\Gamma_n = \frac{(2s_n + 1) m_n}{(\pi\hbar)^2 \rho_0(U_0)} \int_0^{U_n - B_n} \sigma_{inv}(E) \rho_n (U_n - B_n - E) E dE$$

Neutron emission probability at each time step:

$$P_n(\Delta\tau) = \frac{\Delta\tau}{\tau} = 2 \frac{\Delta\tau}{\hbar} \Gamma_n$$

Multistep Hauser-Feshbach decay calculation

BeoH : Okumura, Kawano, SC. *J. Nucl. Sci. Technol.*, 55,1009–1023(2018).



$$W_{surv} = \left[\frac{\sum_{\beta'=\{n,\gamma\}:l'j'} \int_0^{E_{\beta' \max}} \rho(U^* - S_{\beta'} - E_{\beta'}, J^\pi) T^J_{\beta' l' j'}(E_{\beta'}) dE_{\beta'}}{\sum_{\beta''=\{n,p,d,t,h,\alpha,\gamma,F\}:l''j''} \int_0^{E_{\beta'' \max}} \rho(U^* - S_{\beta''} - E_{\beta''}, J^\pi) T^J_{\beta'' l'' j''}(E_{\beta''}) dE_{\beta''}} \right]^n$$

ρ : Level density (Kawano-Koura-Chiba) JNST 43, 1-8(2006).

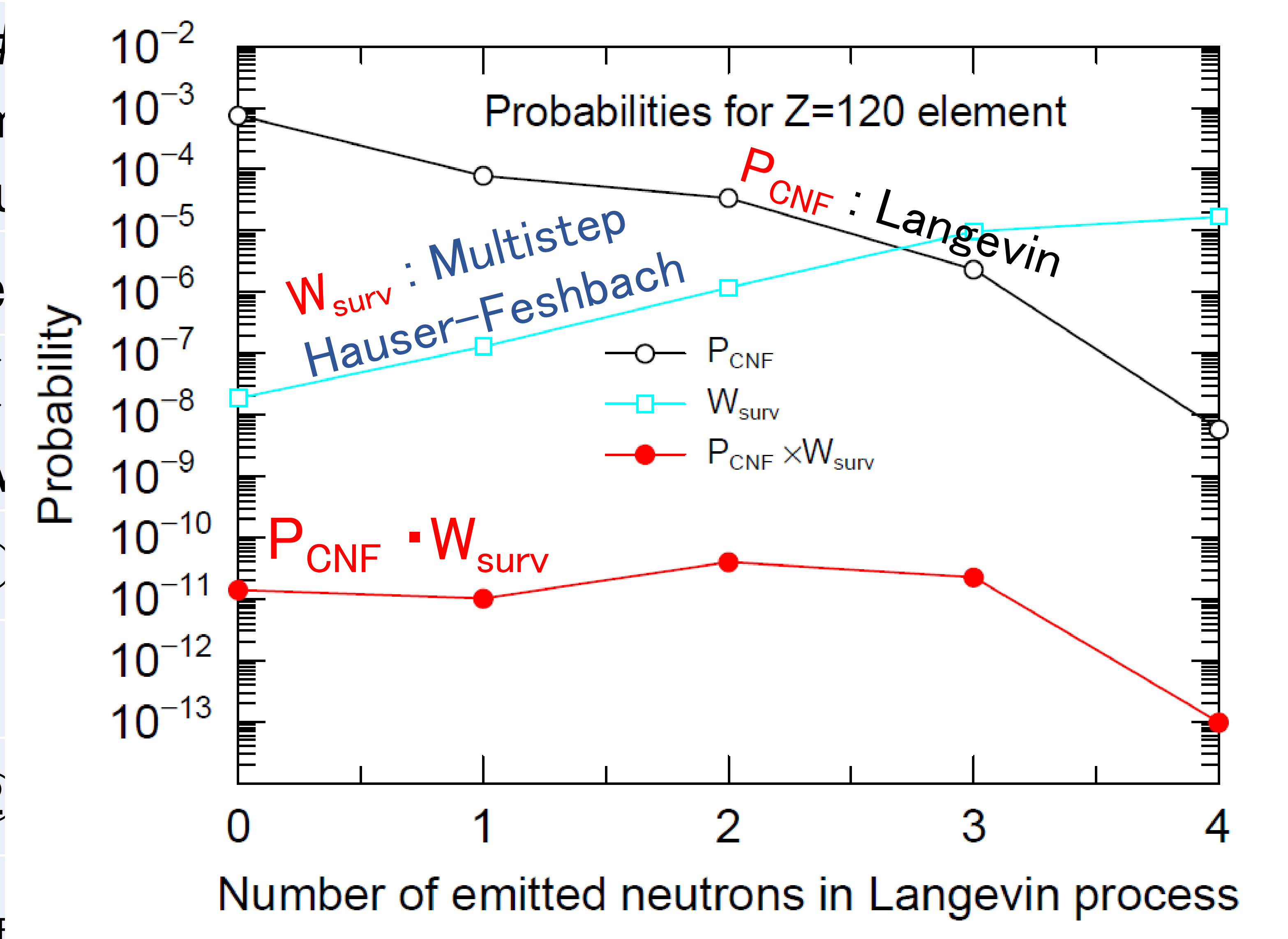
T : Transmission coefficients

- $n \sim \alpha$: optical model
- γ : Kopecki-Uhl EGLO(up to E3)
- Fission : Double-humped Hill-Wheeler

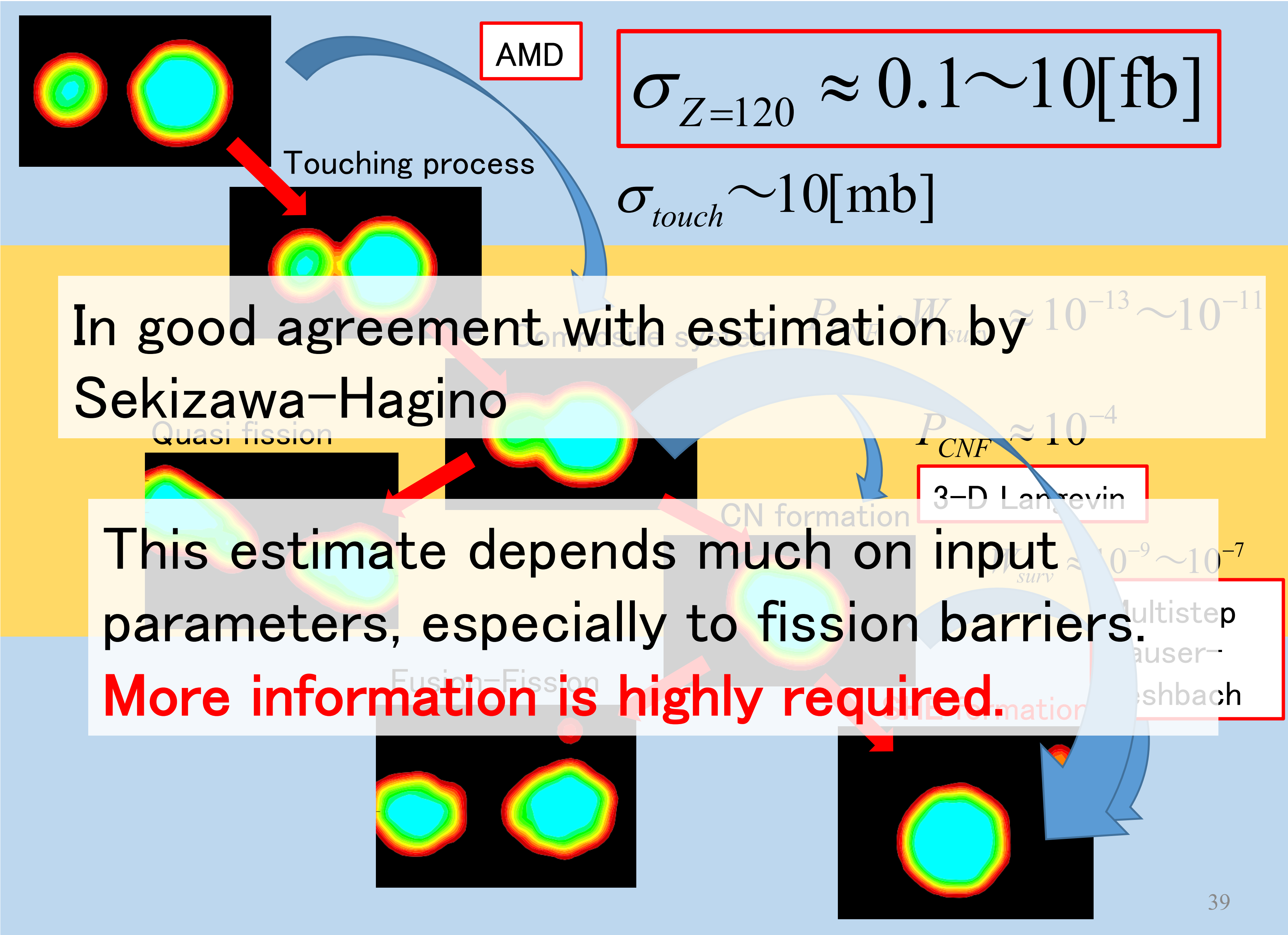
- **Fission barrier : Litnevsky et al., PRC 89, 034626(2014)**
- GS spin and parity : HFBTHO code (blocking method)
- Multichance fission automatically included

Results from AMD+Langevin＋HF

# em neu	4n
Re	120
＜ (M	7.1
①	$\times 10^{-9}$
Bf	.92
②	$\times 10^{-5}$
P_{CNF}	$\times 10^{-14}$



SHE formation process and theories available at Tokyo Tech.



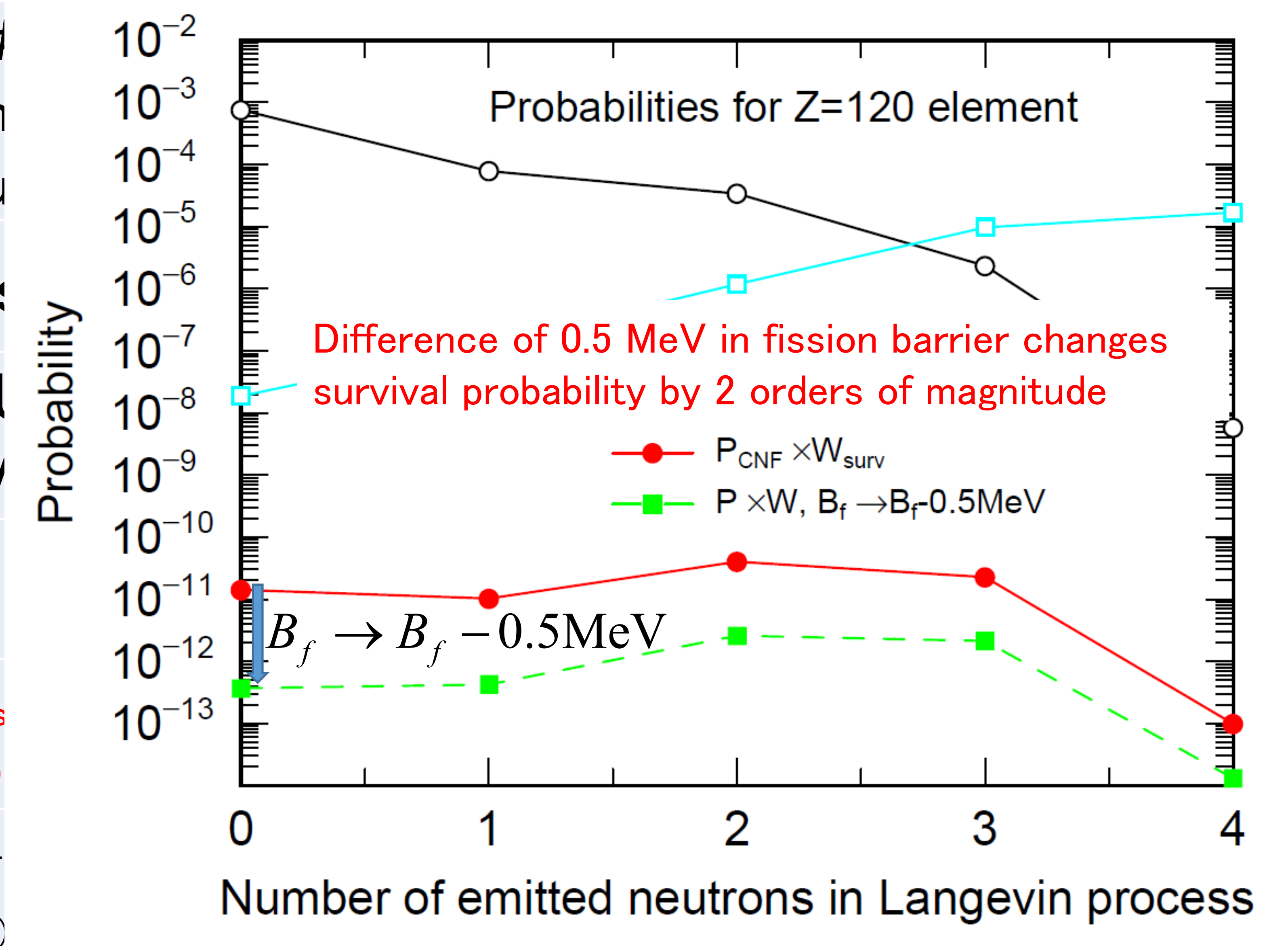
In good agreement with estimation by Sekizawa-Hagino

This estimate depends much on input parameters, especially to fission barriers.

More information is highly required.

Results from AMD+Langevin＋HF

# em neu	n
Res	20
<U (M	.1
①	$< 10^{-9}$
②Ws 0.5	$< 10^{-6}$
PCNF ①	10^{-14}



Concluding remarks

1. Tokyo-Tech. 4-D Langevin model for nuclear fission has been revealing origin of systematical and anomalous trends in mass and TKE distributions of fission fragments in terms of the transition of symmetric components from super long to super short as well as transition of the dominant mode
2. We have applied the methodologies we have developed for fission study to formation of Z=120 super heavy elements. It will be an independent important alternative to the more orthodox (mainstream) methods
3. We have been providing nuclear data, including fission fragment yields, neutron cross sections and ranching ratios to r-process community (Kajino-san, Wanajo-san, Hayakawa-san, Suzuki-san ..) I hope such collaboration would yield excellent new outcomes

Collaborators

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Thank you very much!!