Cluster formation and emission in ^{294}Og

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FRIB

Overarching questions

- How can we model fission yields?
- What is the mechanism responsible for the formation of fission fragments?
- Can we exploit our knowledge of the mechanism of fragment formation to compute fission yields in a fast, efficient way?

^{294}Og

Produced at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia by a collaboration of scientists from Dubna and LLNL using the reaction:

$^{249}Cf + ^{48}Ca \rightarrow ^{294}Og + 3n$

Its discovery was officially recognized in 2015.

With Z=118, it is currently the heaviest element to have been produced in a laboratory setting.

It decays primarily via alpha decay with a half-life around a millisecond. However...

Cluster emission in ^{294}Og?

- Cluster emission is a decay channel in which a heavy actinide nucleus decays to ^{208}Pb (or something nearby) and a small nuclear cluster.
- Poenaru et al [PRC 85, 034615 (2012)] predicted using a phenomenological model that cluster emission may be the dominant fission channel in superheavy nuclei.
- Around the same time, Warda et al [PRC 84, 044608 (2011)] showed using a microscopic model that cluster emission can be thought of as highly-asymmetric fission.
- Using our microscopic fission model, we investigate the possibility of cluster emission in ^{294}Og.

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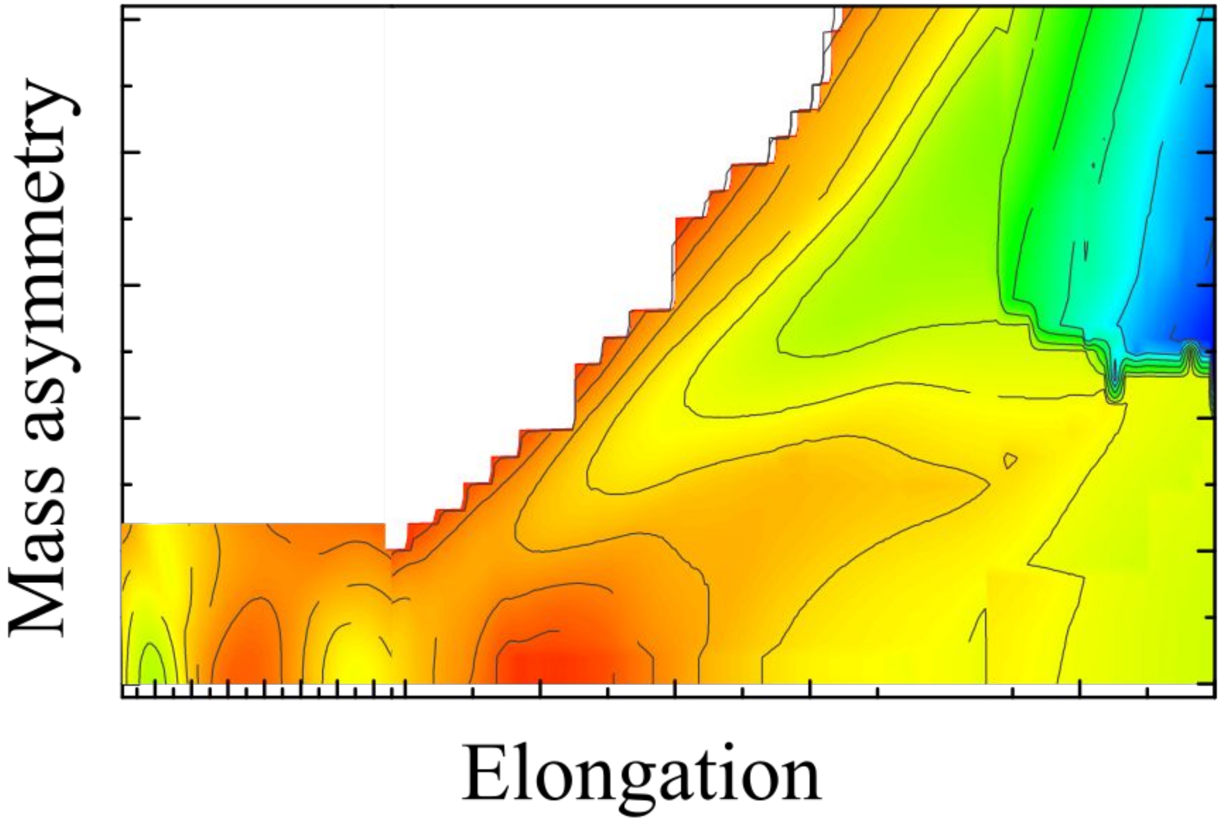
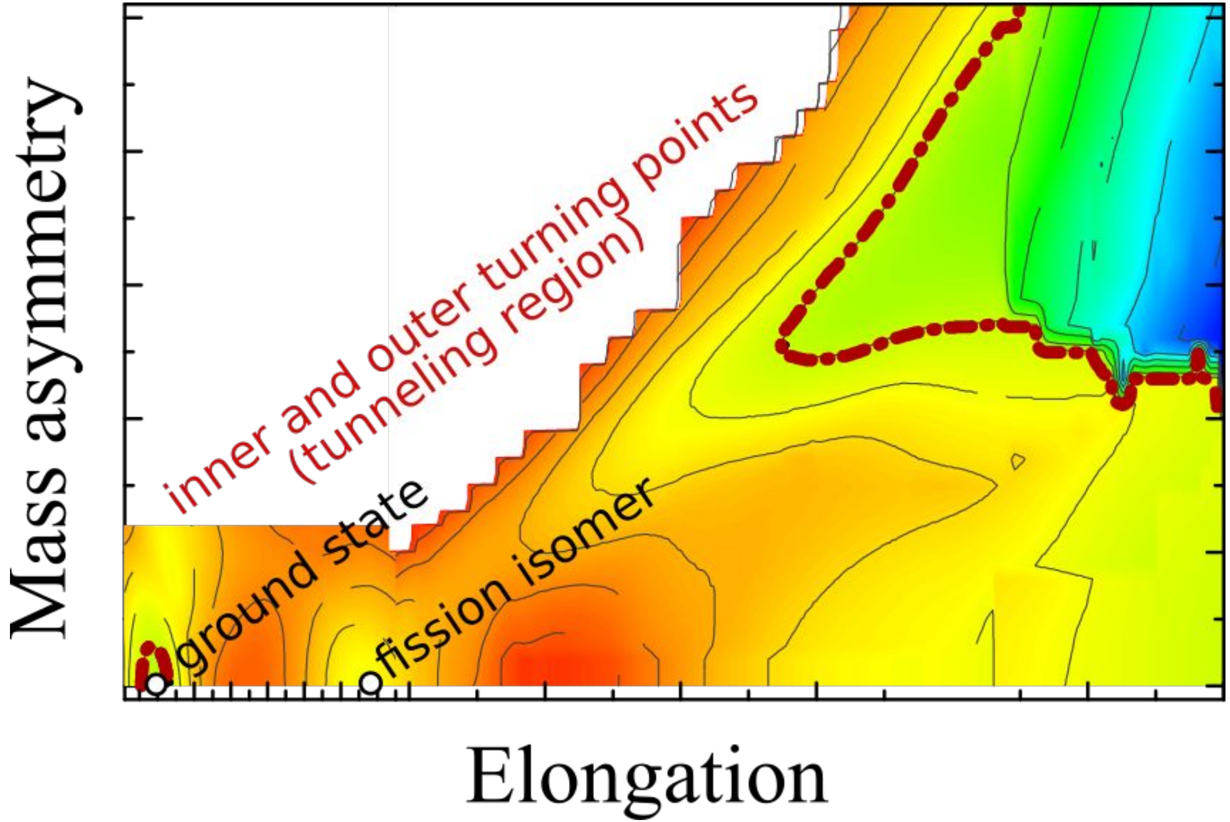
The model

- PES constructed using nuclear DFT
- Tunneling via WKB approximation
- Langevin dynamics between saddle and scission
- See J. Sadhukhan et al, Phys. Rev. C 93, 011304(R) (2016)



1. Use DFT to generate a potential energy surface and calculate the collective inertia.

PES and Inertia | Tunneling | Dissipation | Fragments!



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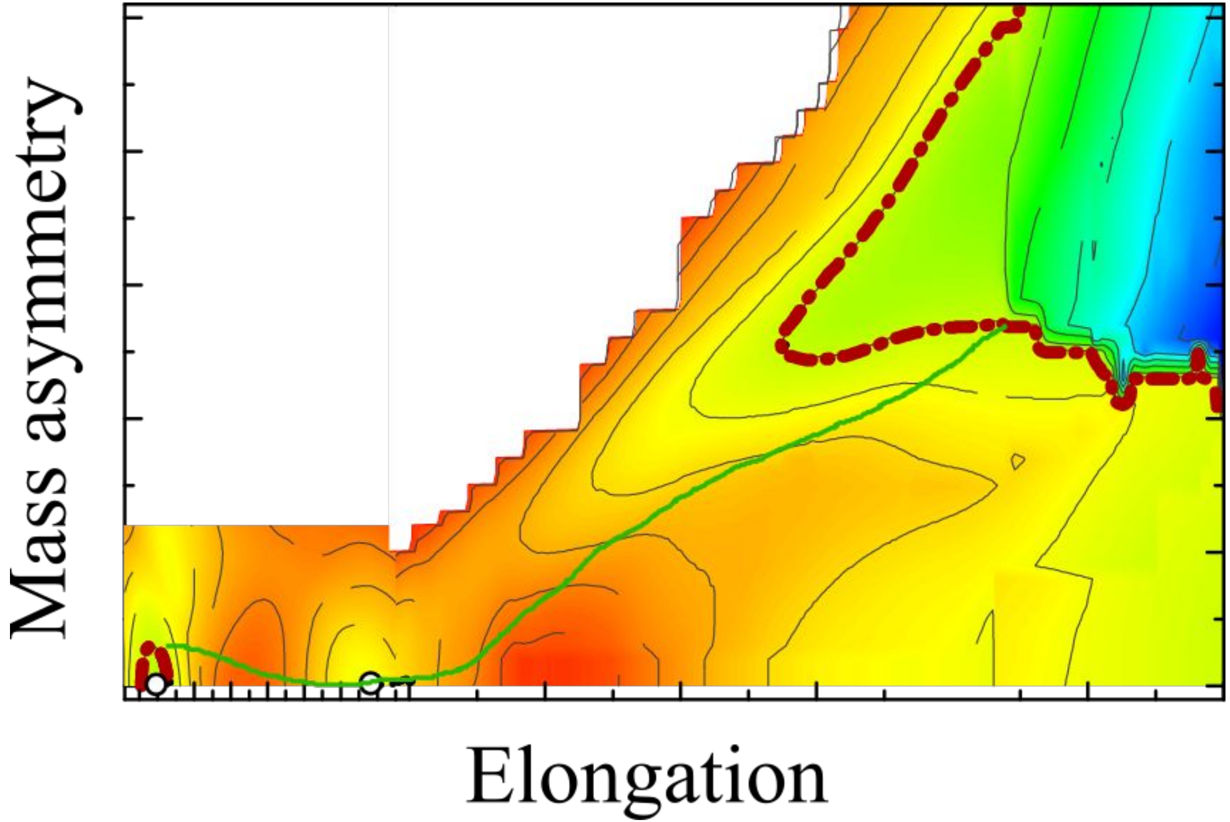

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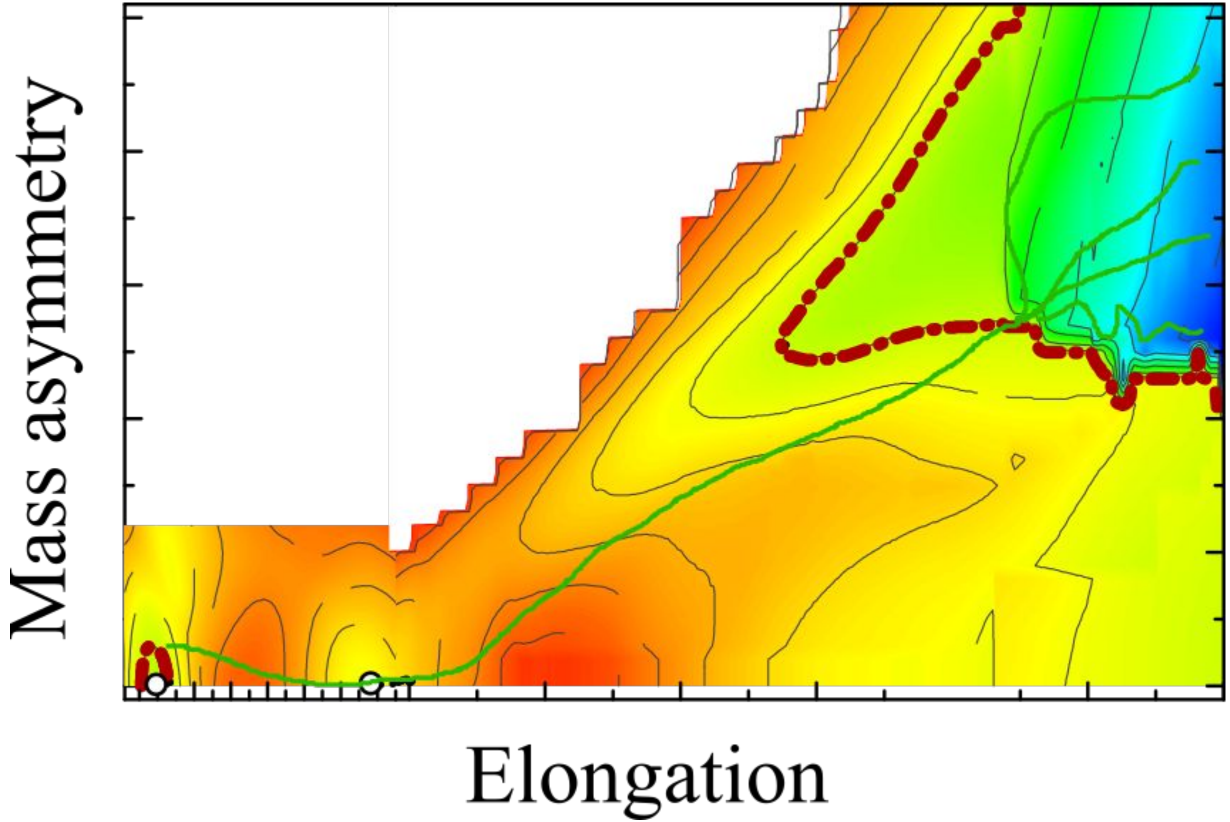
2. Use WKB to compute tunneling probability by minimizing collective action.



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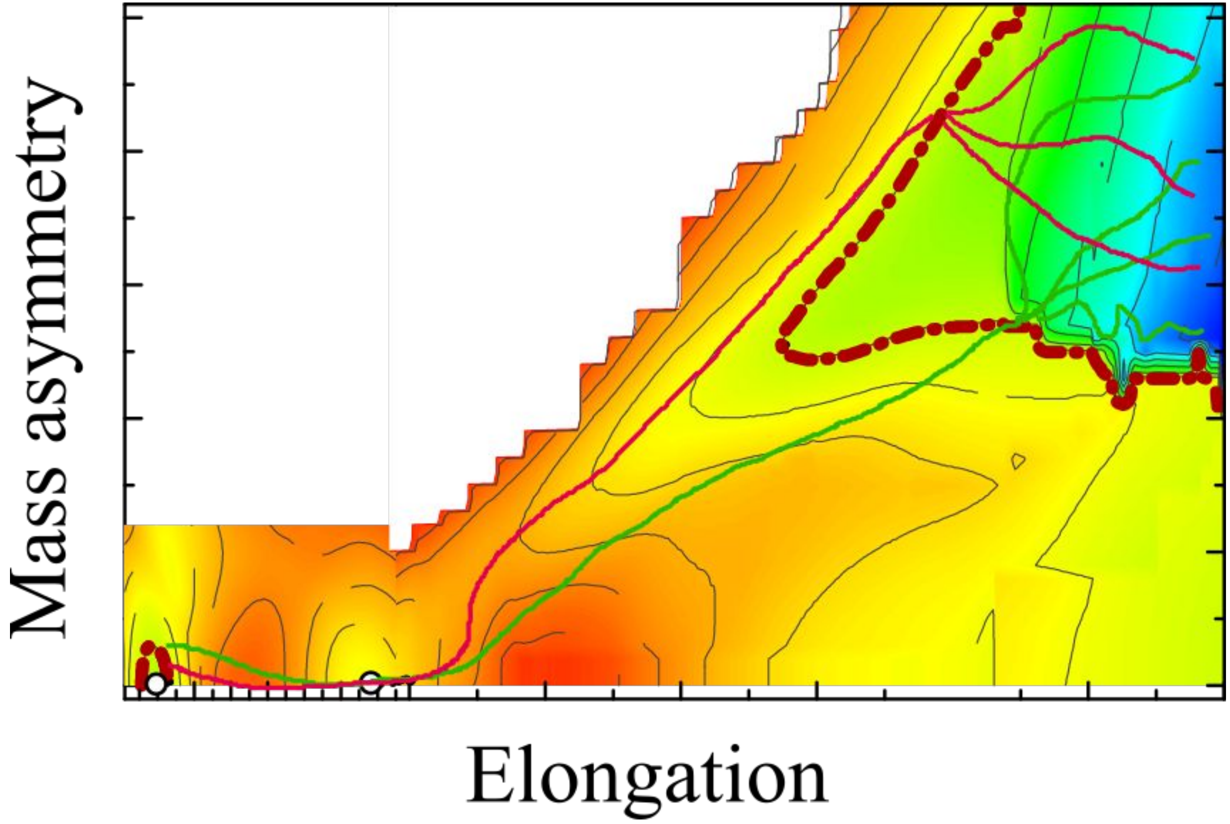
PES and Inertia | Tunneling | Dissipation | Fragments!



1. Use DFT to generate a potential energy surface and calculate the collective inertia.
2. Use WKB to compute tunneling probability by minimizing collective action.
3. Use Langevin dynamics to predict semiclassical motion outside of tunneling region.
4. Repeat over many trajectories to compute yields.

PES and Inertia | Tunneling | Dissipation | Fragments!

Using ^{294}Og to assess model errors

- Energy density functional
  - $UNEDF1_{HFB}$ vs SkM* vs Gogny D1S
- Size of collective space
  - 2D (Q_{20},Q_{30}) vs 3D (Q_{20},Q_{22},λ_2)+(Q_{20},Q_{30},λ_2) vs 4D (Q_{20},Q_{30},Q_{22},λ_2)
- Collective inertia
  - Perturbative vs non-perturbative
  - GCM vs ATDHFB
- Langevin dissipation tensor strength

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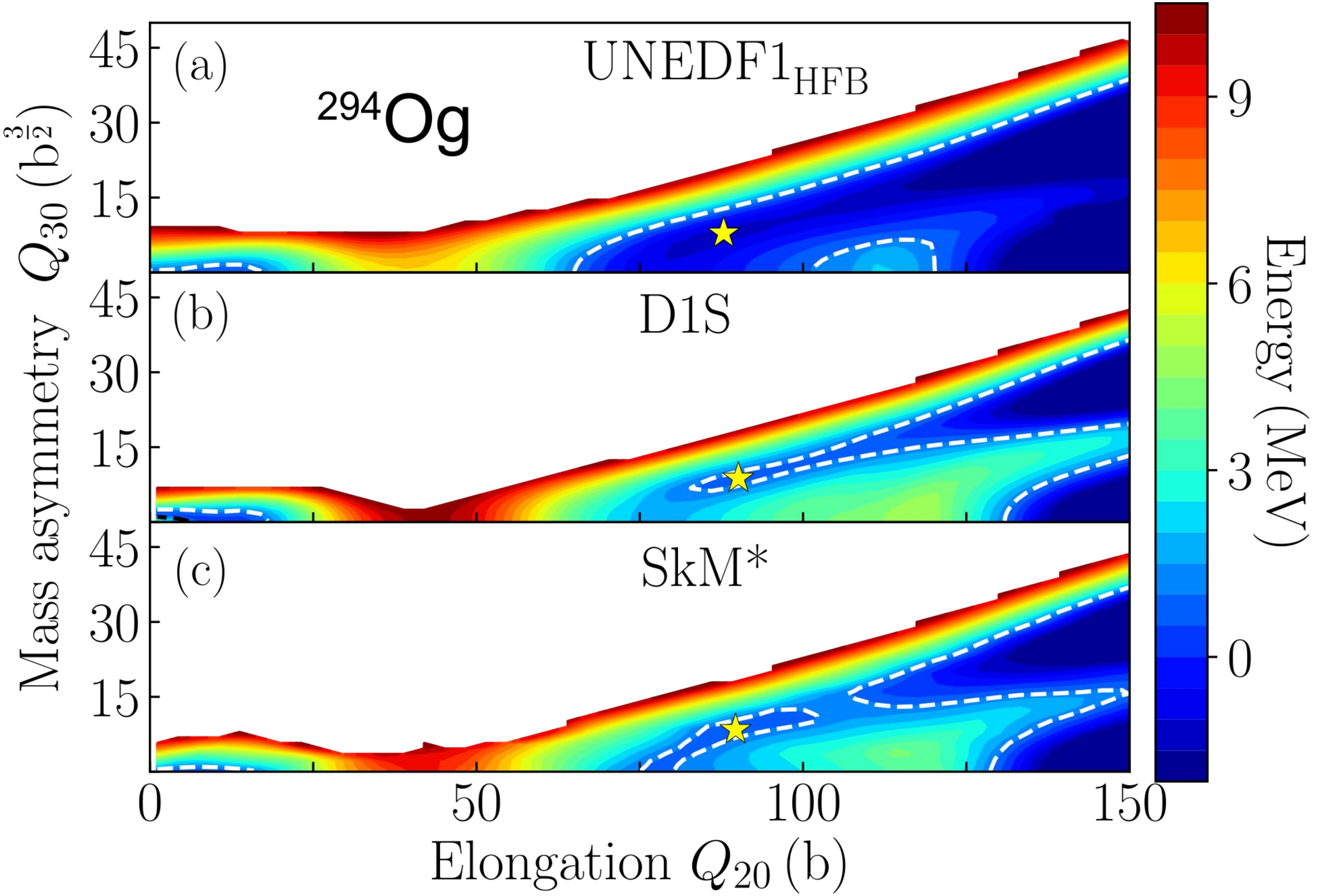
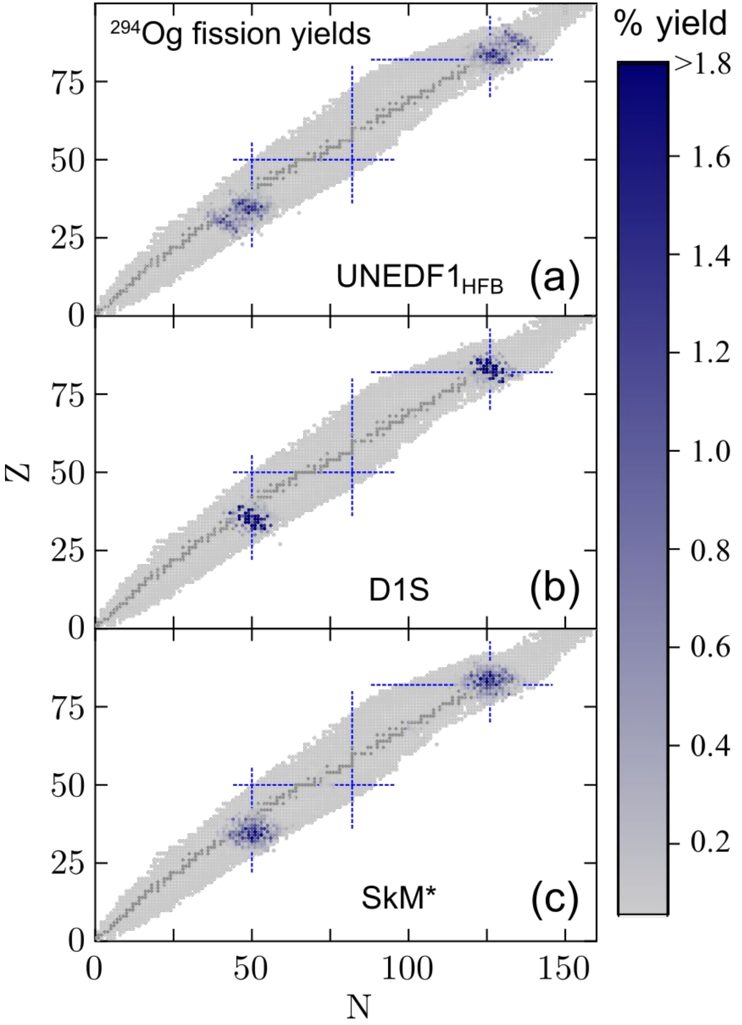
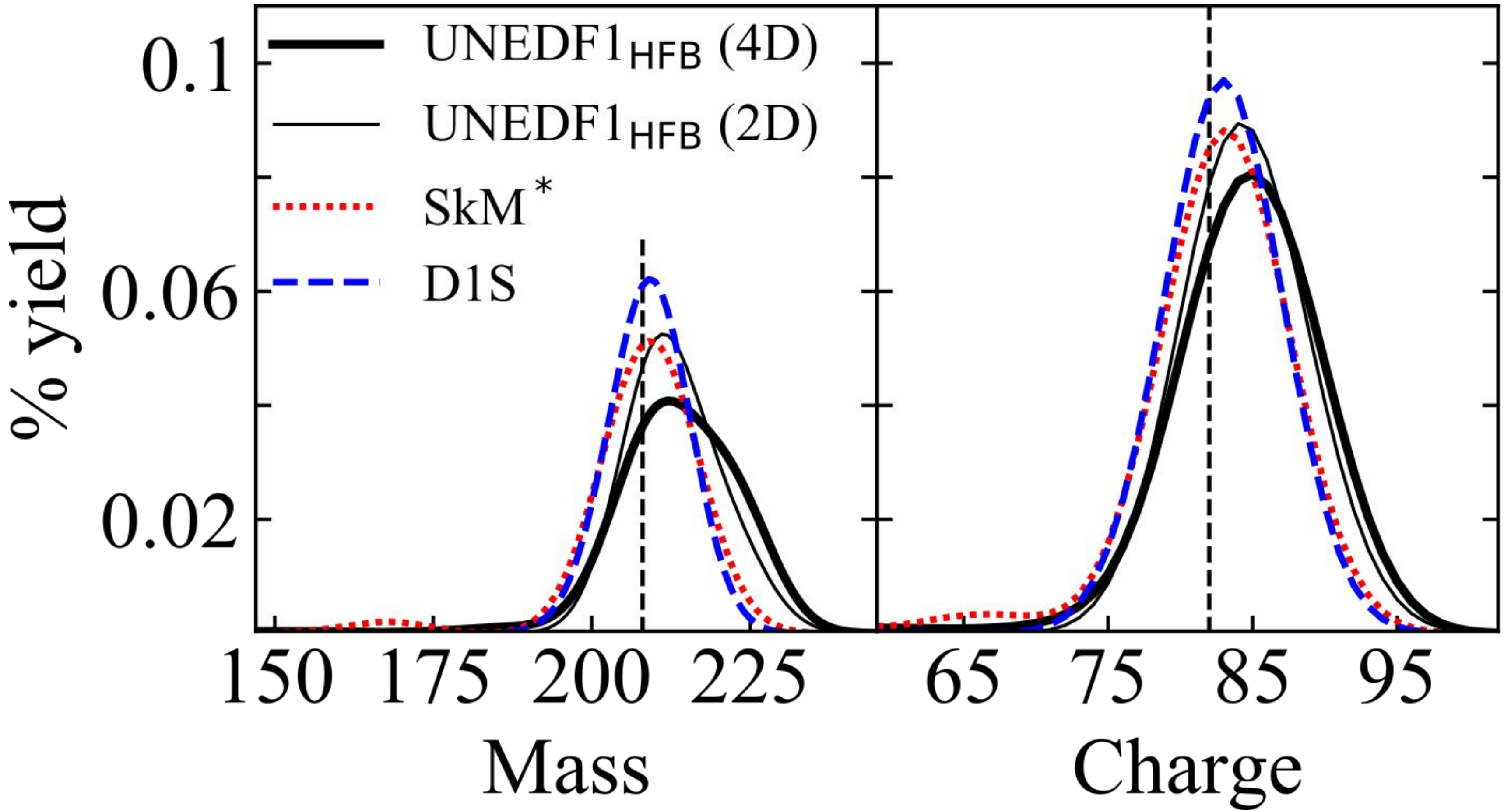


(a)
UNEDF1$_{HFB}$
^{294}Og
(b)
D1S
(c)
SkM*
Mass asymmetry Q_{30} (b$^{\frac{3}{2}}$)
Elongation Q_{20} (b)
Energy (MeV)



294Og fission yields
% yield
>1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
UNEDF1HFB (a)
D1S (b)
SkM* (c)
Z
N
0
25
50
75
100
150



% yield
0.1
0.06
0.02
UNEDF1$_{HFB}$ (4D)
UNEDF1$_{HFB}$ (2D)
SkM*
D1S
150
175
200
225
Mass
65
75
85
95
Charge

Using ^{294}Og to assess model errors

- Energy density functional
    - UNEDF1$_{HFB}$ vs SkM* vs Gogny D1S
- Size of collective space
    - 2D (Q_{20},Q_{30}) vs 3D (Q_{20},Q_{22},λ_2)+(Q_{20},Q_{30},λ_2) vs 4D (Q_{20},Q_{30},Q_{22},λ_2)
- Collective inertia
    - Perturbative vs non-perturbative
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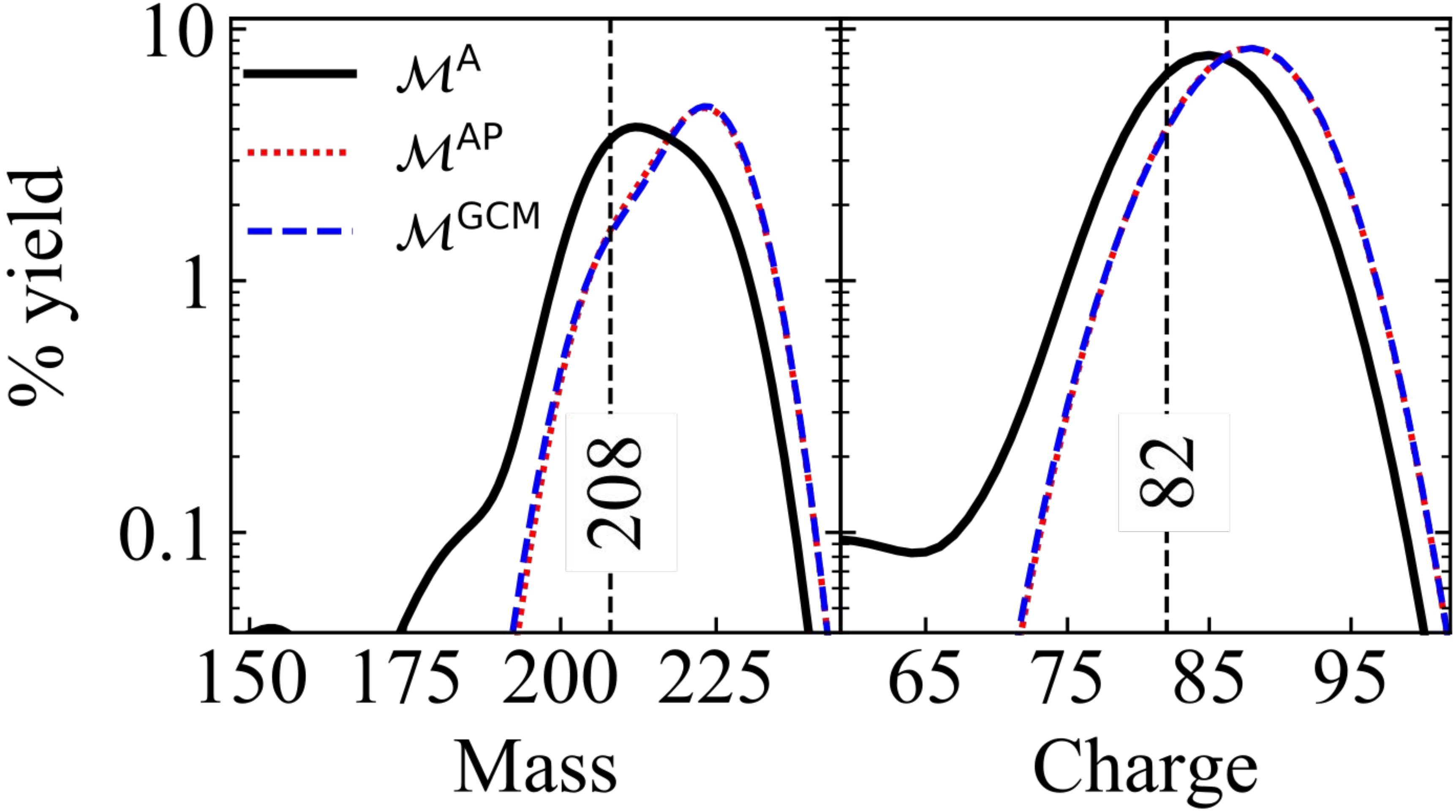

% yield
10
1
0.1
$\mathcal{M}^{\mathrm{A}}$
$\mathcal{M}^{\mathrm{AP}}$
$\mathcal{M}^{\mathrm{GCM}}$
208
82
150
175
200
225
65
75
85
95
Mass
Charge

Using ^{294}Og to assess model errors

- Energy density functional
  - UNEDF1$_{HFB}$ vs SkM* vs Gogny D1S
- Size of collective space
  - 2D (Q_{20},Q_{30}) vs 3D (Q_{20},Q_{22},λ_2)+(Q_{20},Q_{30},λ_2) vs 4D (Q_{20},Q_{30},Q_{22},λ_2)
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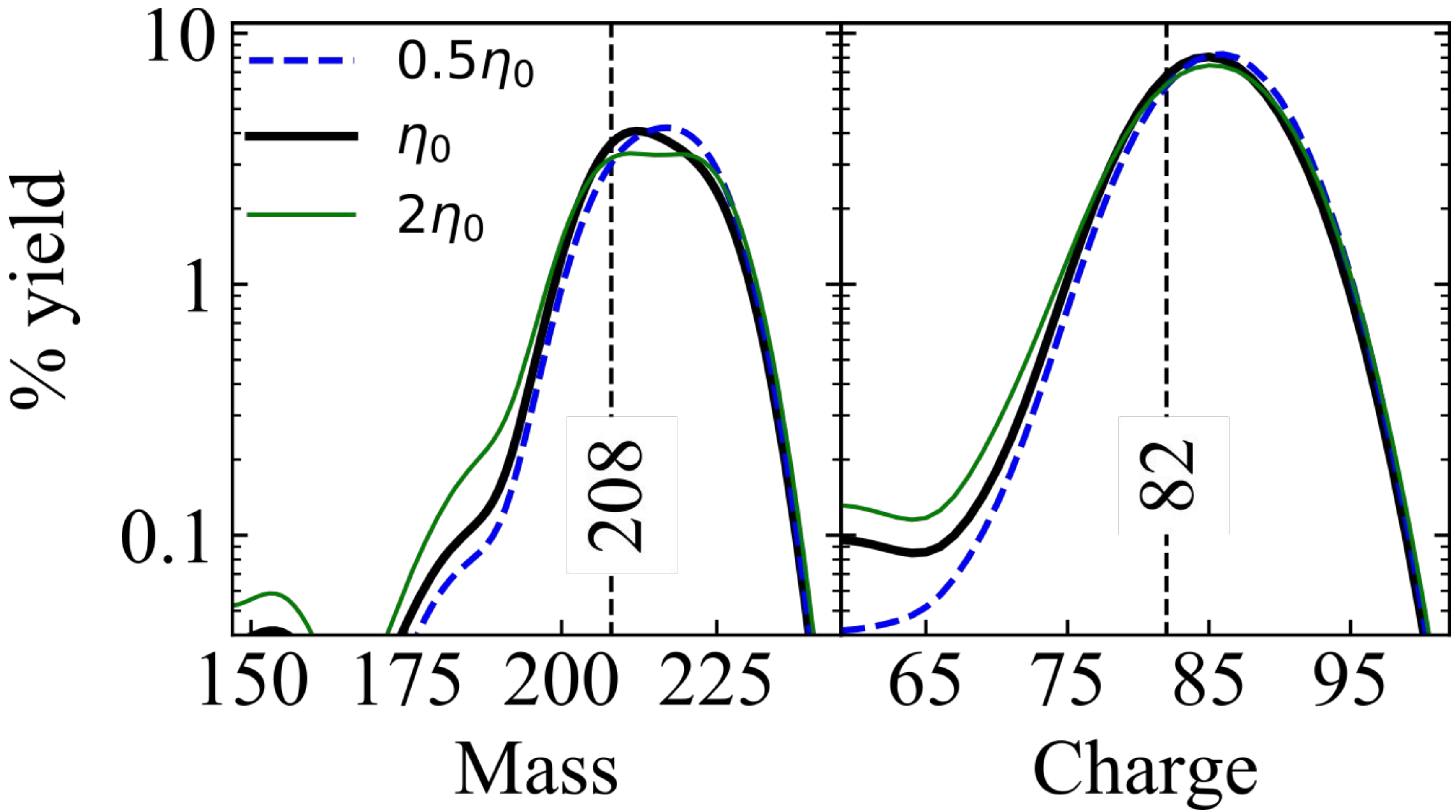

% yield
10
1
0.1
$0.5\eta_0$
η_0
$2\eta_0$
208
82
150
175
200
225
65
75
85
95
Mass
Charge

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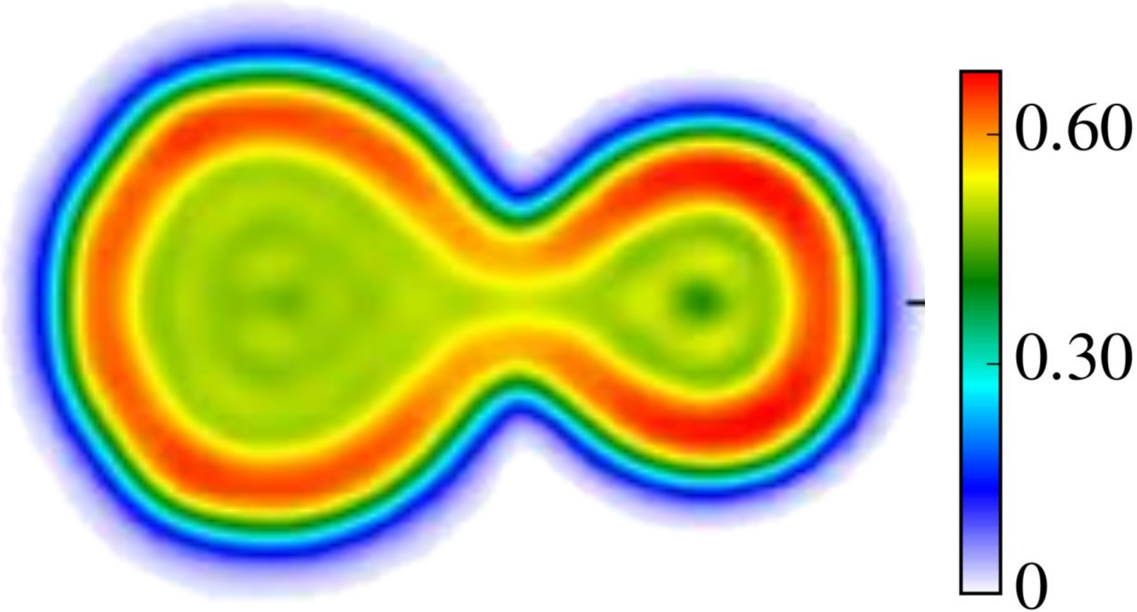
Nucleon localization function

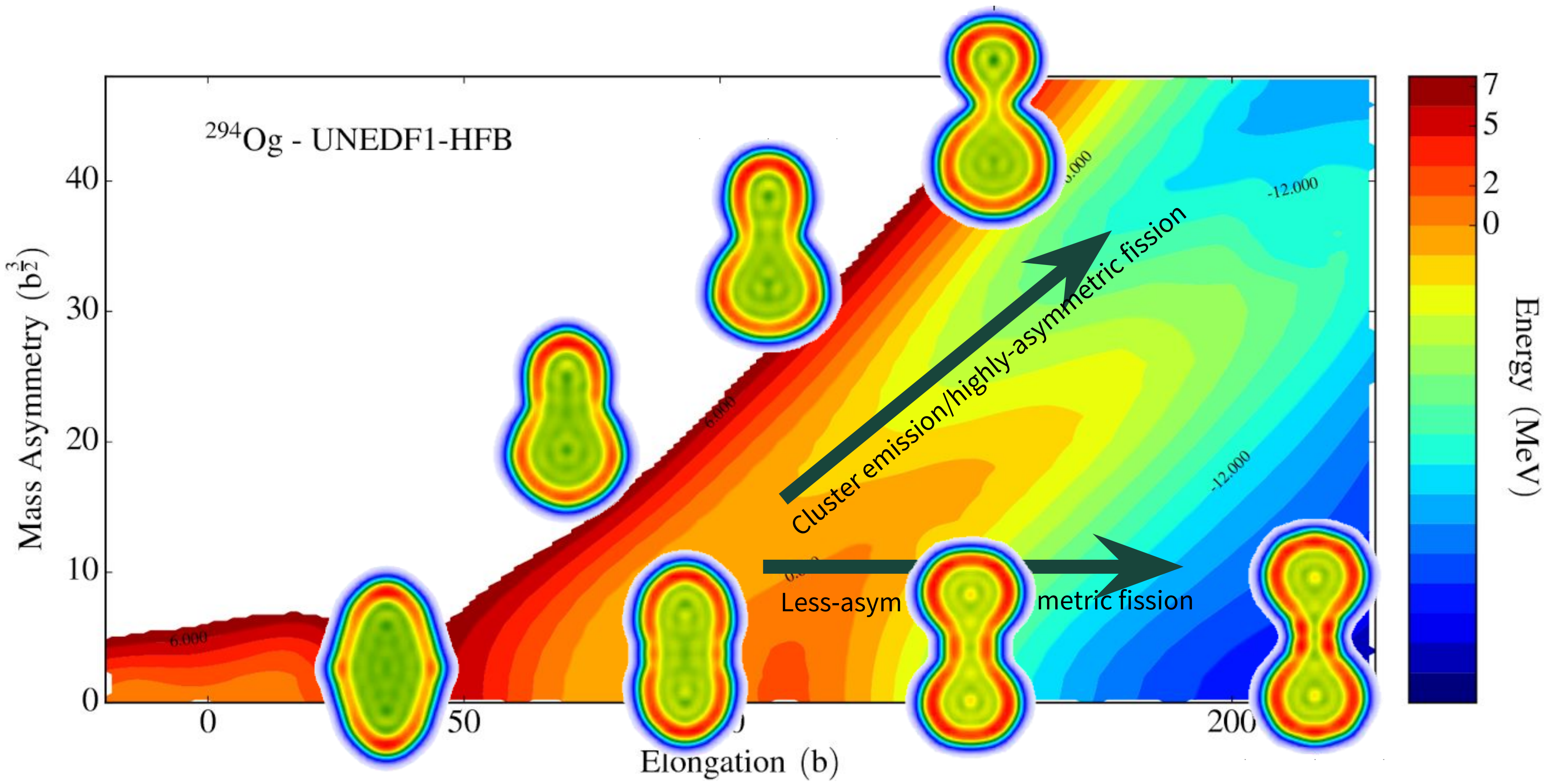
Comes from the probability of finding a well-localized nucleon (distinct spin, isospin, and spatial region)

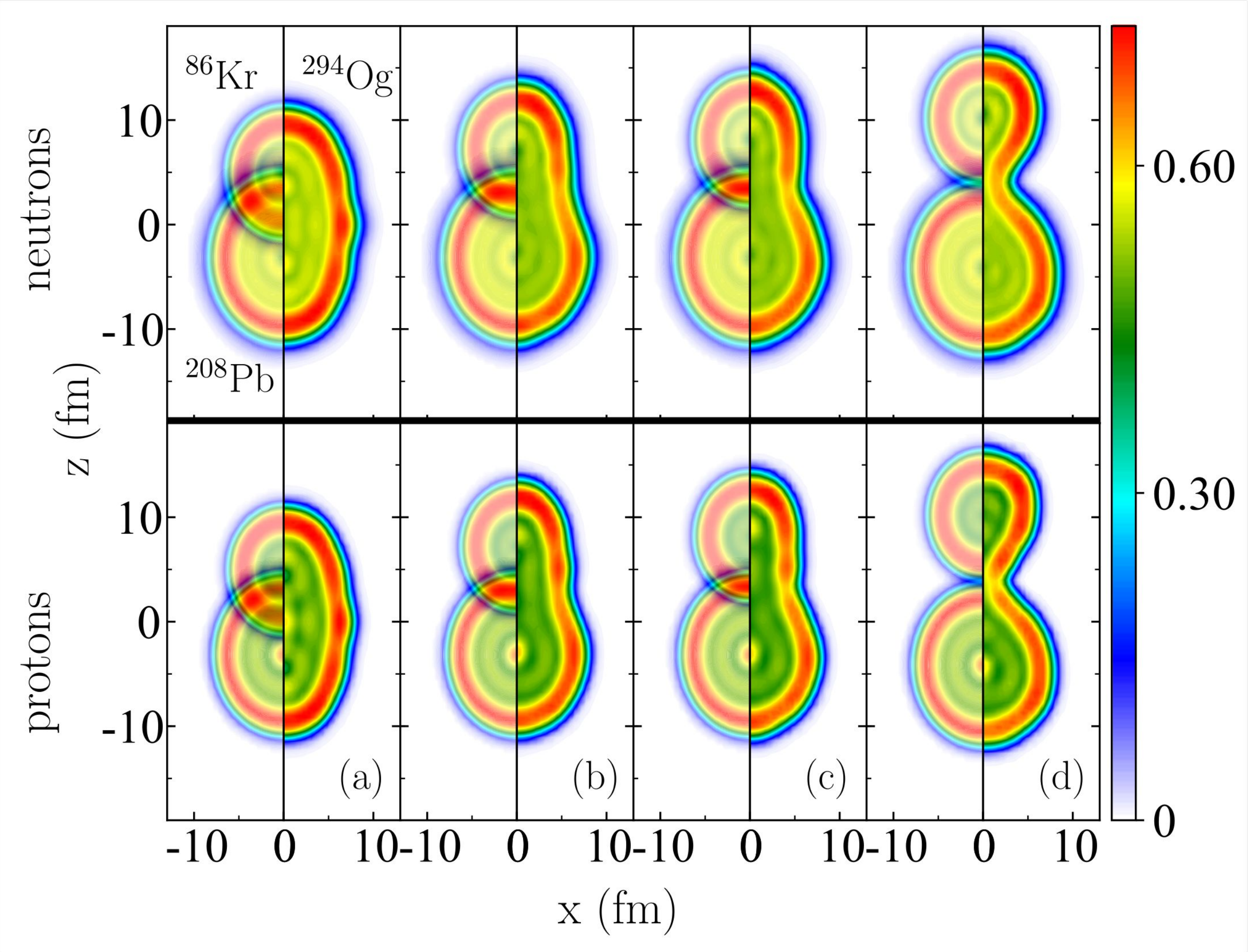
C=1: Well-localized nucleons

C=½: Fermi gas (nuclear matter)



P. G. Reinhard et al, Phys Rev C 83, 034312 (2011)


^{294}Og - UNEDF1-HFB
Mass Asymmetry ($b^{\frac{3}{2}}$)
Elongation (b)
Energy (MeV)
Cluster emission/highly-asymmetric fission
Less-asymmetric fission
-12.000
-12.000
6.000
-6.000



^{86}Kr
^{294}Og
^{208}Pb
neutrons
protons
z (fm)
x (fm)
10
0
-10
(a)
(b)
(c)
(d)
0.60
0.30
0

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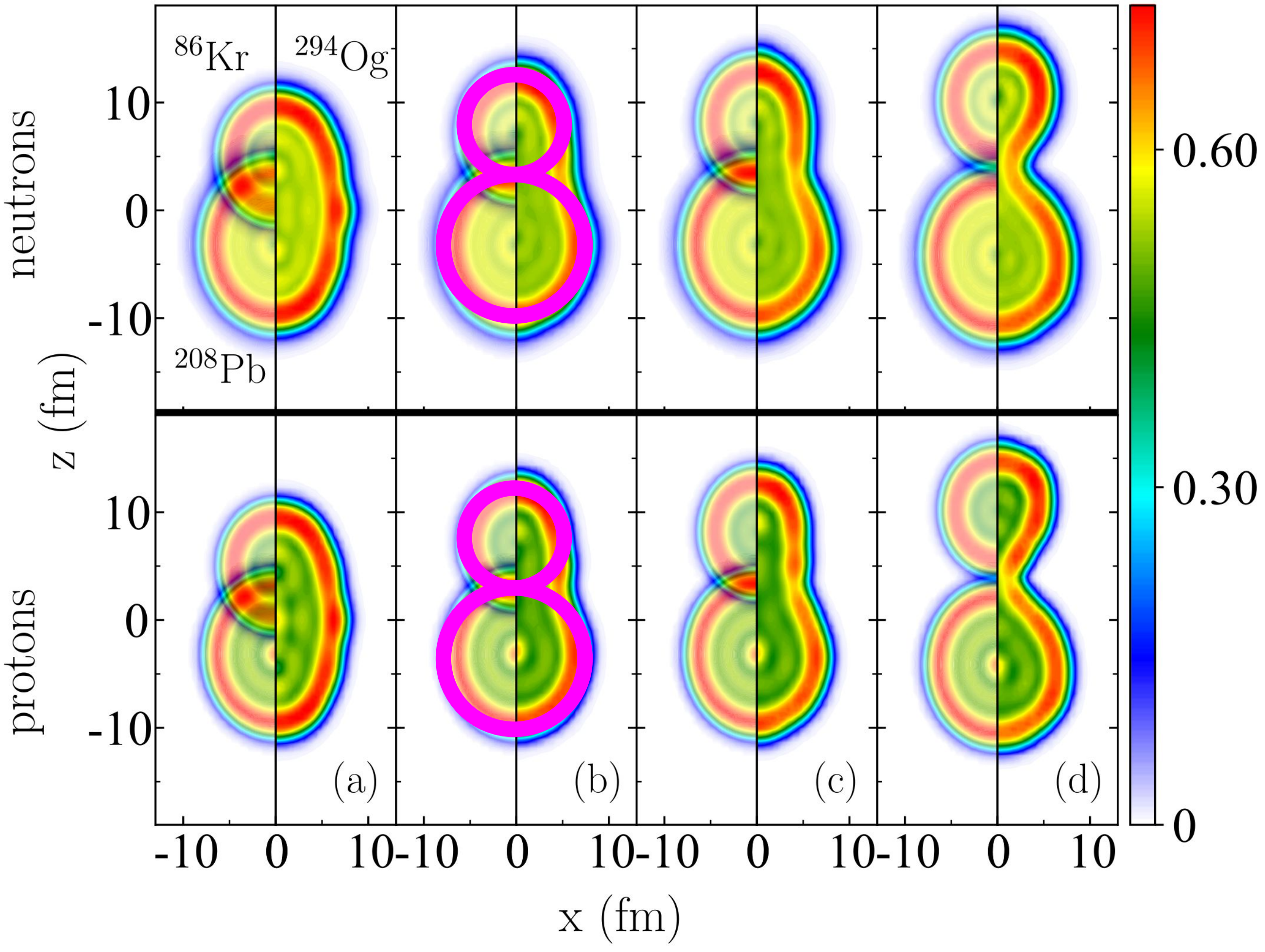
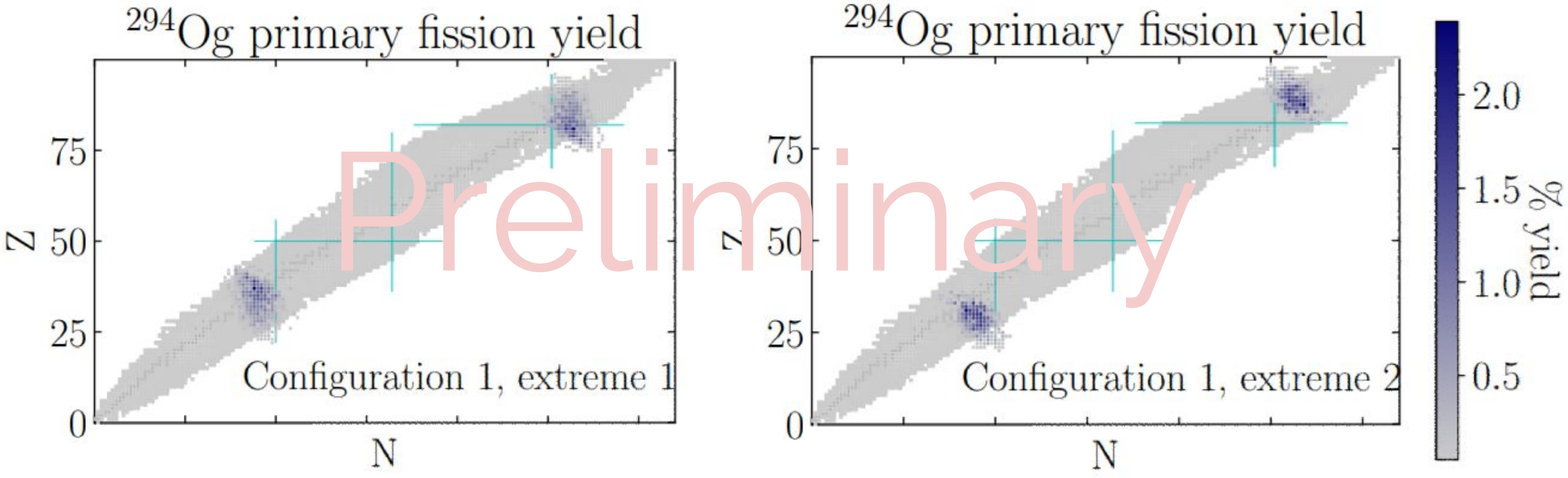


^{86}Kr
^{294}Og
^{208}Pb
neutrons
protons
z (fm)
x (fm)
10
0
-10
(a)
(b)
(c)
(d)
0.60
0.30
0

Identify “pre-fragments” + statistical redistribution of neck particles =



Conclusions

1. Cluster emission in ^{294}Og
   a. Very asymmetric channel appears to be highly-favored
   b. Despite differences in PES, the prediction is quite robust
   c. Lead prefragment seems to be driving the process
   d. arXiv: 1812.06490
2. Using Nucleon Localization Function to ID fission fragments

Thank you!

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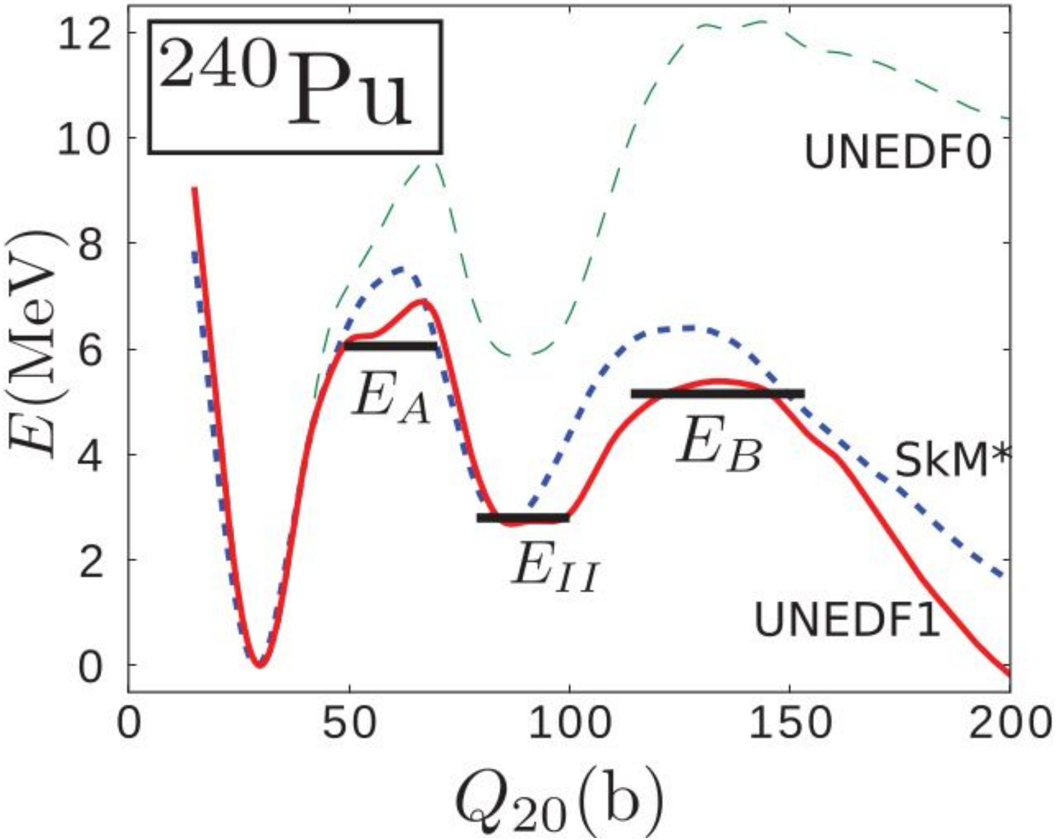
The parameter set UNEDF1-HFB

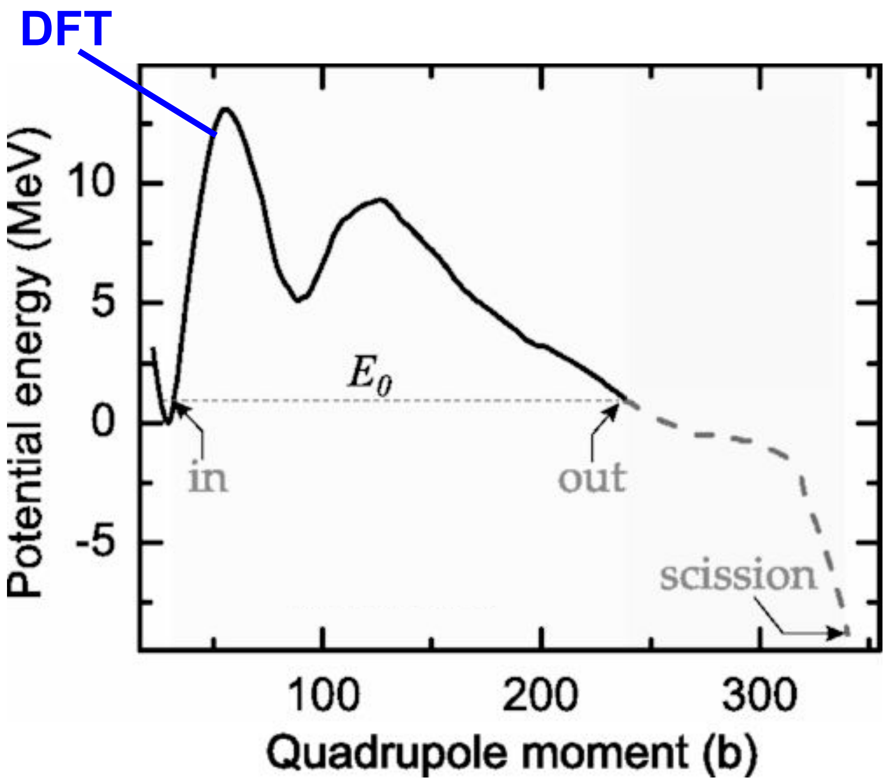
DFT as a many-body method is an exact formulation of quantum mechanics, but in reality it is only as good as the energy density functional (EDF) you use.

The goal of the UNEDF1 parameterization was to create a functional that worked well for highly-deformed nuclei, such as those which occur during fission.

UNEDF1-HFB is a functional based on the UNEDF1 functional, except without the Lipkin-Nogami procedure for particle number restoration [N. Schunck, et al, J. Phys. G 42, 034024 (2015)].

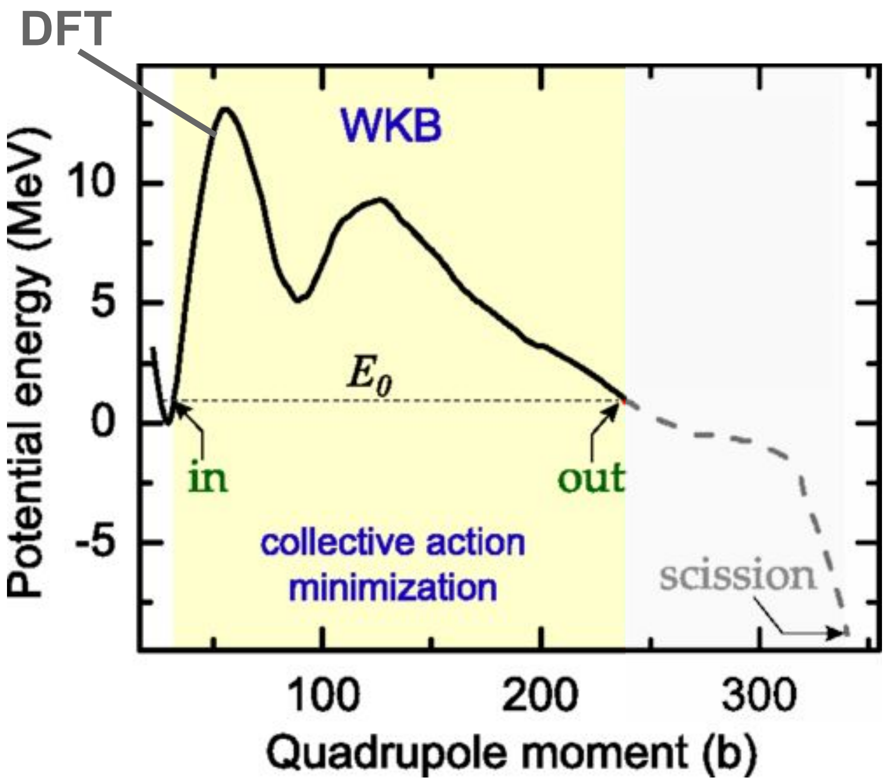


M. KORTELAINEN et al., PHYSICAL REVIEW C 85, 024304 (2012)



J. Sadhukhan et al, Phys. Rev. C 93, 011304(R) (Jan 2016)

- DFT formalism, based on HFB variational principle
  - DFT Solver: HFODD, which breaks all symmetries
  - UNEDF1-HFB energy density functional
- Collective Inertia
  - Non-perturbative cranked ATDHFB, calculated via finite differences

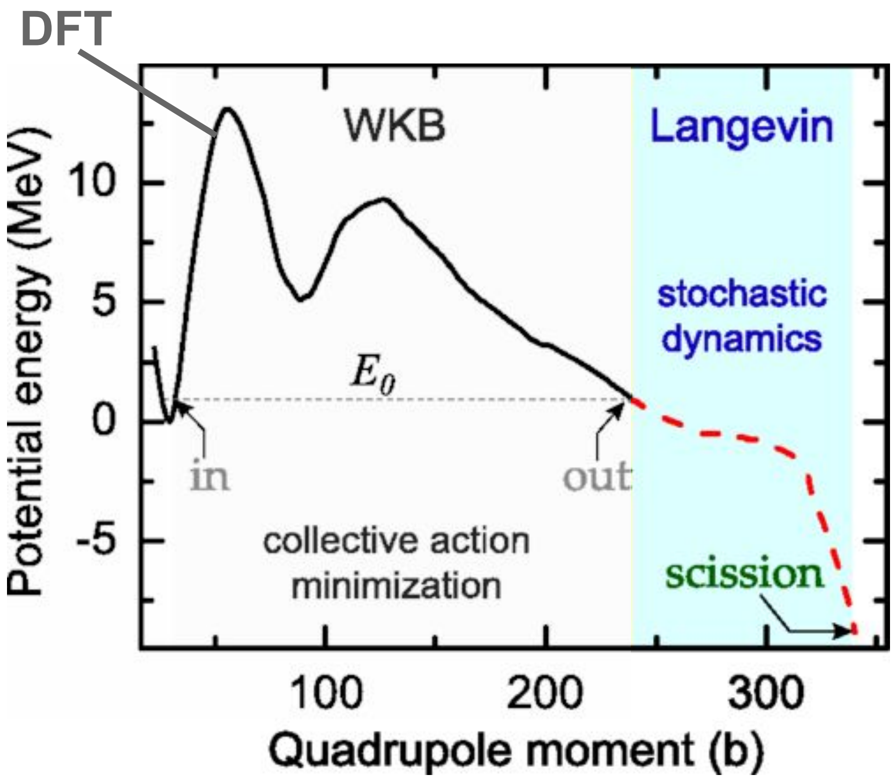


Find the trajectory L(s) which minimizes the collective action in the space defined by collective variables $q_i(s)$:

$$S(L) = \int_{s_{in}}^{s_{out}} \frac{2\pi}{h} \sqrt{2M_{eff}(s)(V_{eff}(s) - E_0)}ds$$

J. Sadhukhan et al, Phys. Rev. C 93, 011304(R) (Jan 2016)

PES and Inertia | Tunneling | Dissipation | Observables!



J. Sadhukhan et al, Phys. Rev. C 93, 011304(R) (Jan 2016)

Past the outer turning point, the dynamics is essentially classical random walk:

kinetic term

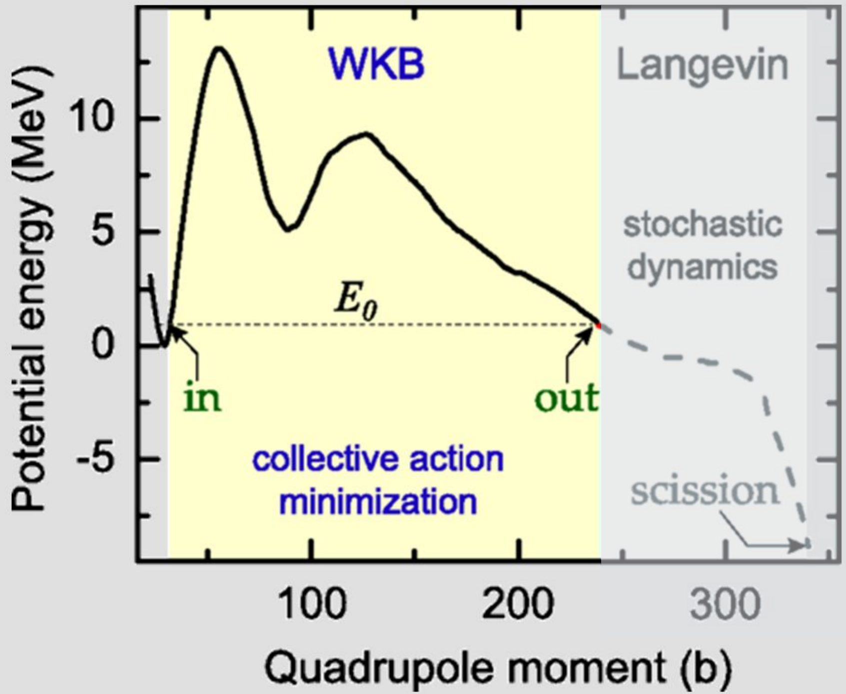
driving force

$$\frac{dp_i}{dt} = -\frac{p_j p_k}{2}\frac{\partial}{\partial q_i}(M^{-1})_{jk} - \frac{\partial V}{\partial q_i}$$
$$-\eta_{ij}(M^{-1})_{jk}p_k + g_{ij}\Gamma_j(t)$$

dissipation

random force

$$\frac{dq_i}{dt} = (M^{-1})_{ij}p_j$$



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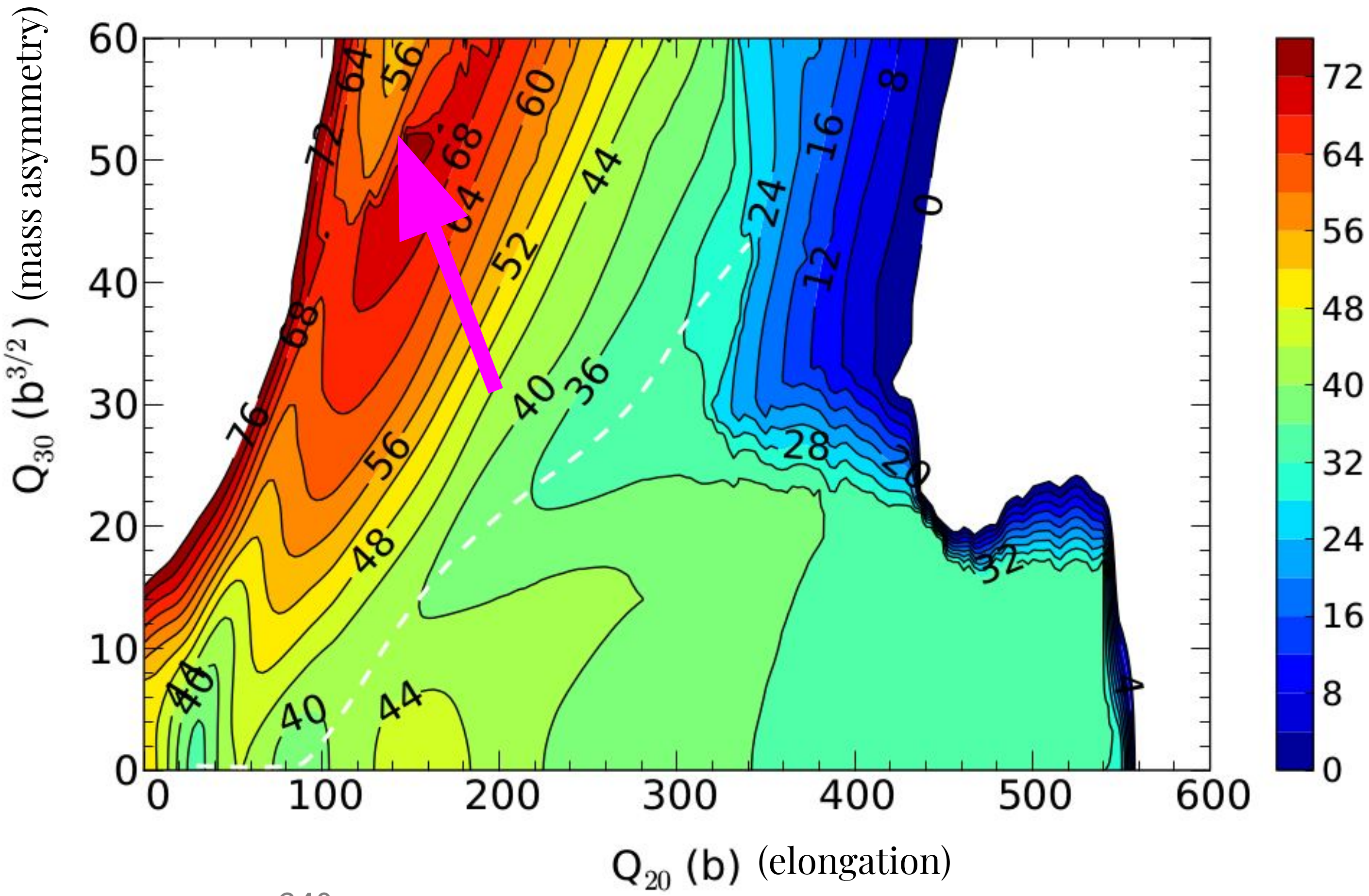
Compute the barrier penetration probability:

$$P = \left(1 + e^{2S(L)}\right)^{-1}$$

Estimate the fission half-life:

$$T_{1/2} = \frac{\ln 2}{nP}$$



Cluster formation in ^{240}Pu

Source: Schunck et al PRC 90, 054305 (2014)