Stochastic mean-field approach to fission observables

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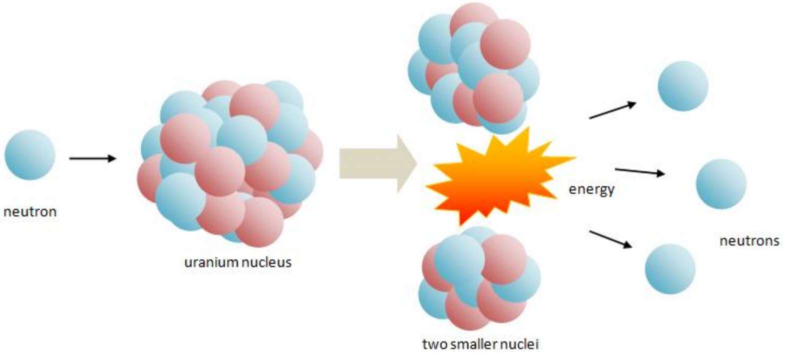
IPN Orsay

"Fission at FUSTIPEN II: recent observables and their modeling" at GANIL, May 3, 2016

Nuclear fission

- **Importance**
  - Energy production
  - Synthesis of super heavy elements
  - Astrophysical process
  - Production of radioactive isotopes



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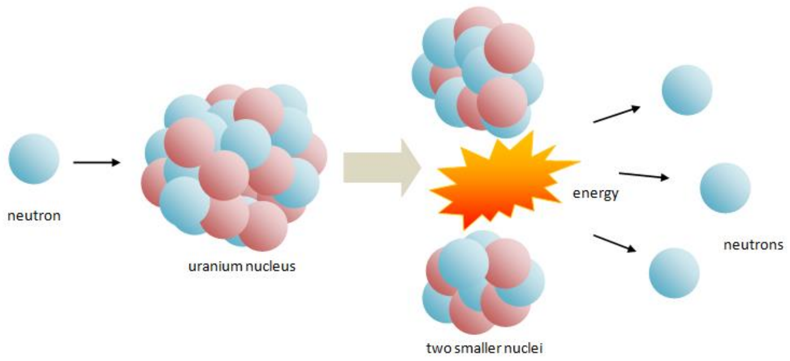
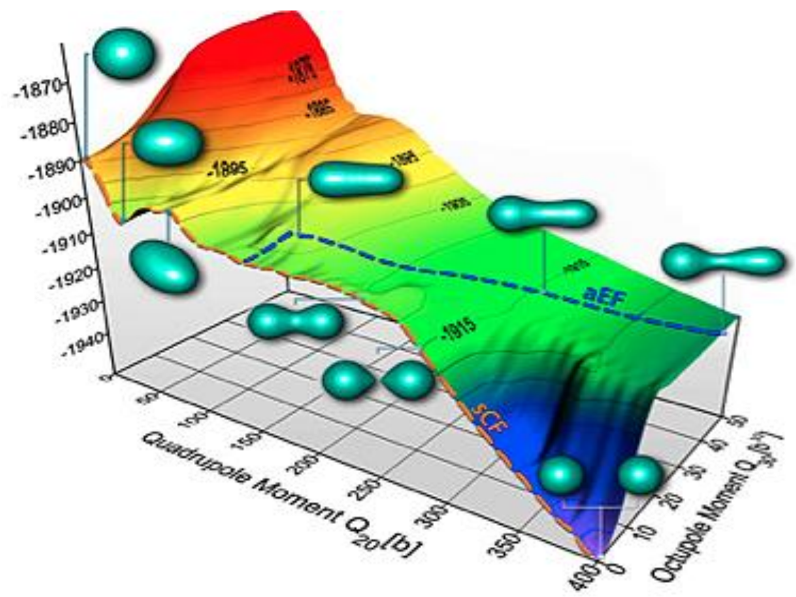


- **Theoretical challenges**
  - Phenomenological models in terms of a few macroscopic degrees of freedom (elongation, mass asymmetry,...) have been developed
  - Successful fully microscopic models are still under development
  - Complicated dynamical process of quantum many-body system
    - Quantal treatments for both single-particle and collective DOFs
    - Dynamical and non-adiabatic effects
    - Different time scales

Microscopic models for fission

1. Static approach

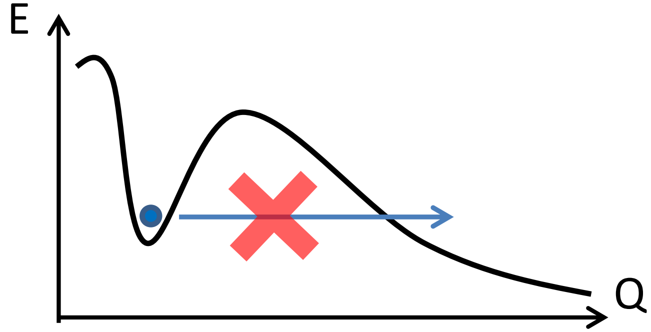


- With energy density functional (EDF) theory (Skyrme, Gogny, RMF)
- Fission paths on the **potential energy surface**
- **Adiabatic**
- **Dynamics is not fully treated**

2. Dynamical approach

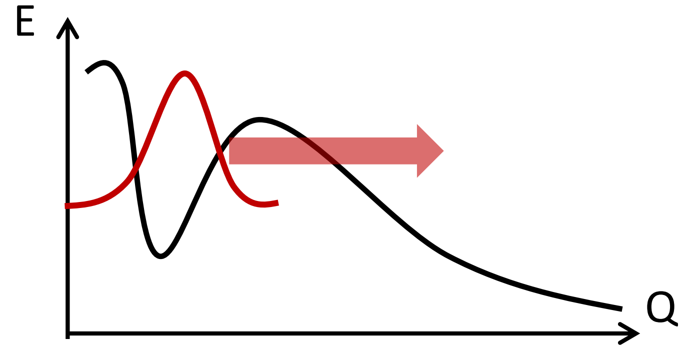
TDHF

- No need to select collective coordinates (3D)
- Fully non-adiabatic
- Collective d.o.f. are nearly classical
- No spontaneous symmetry breaking



TDGCM

- Quantum treatment of collective degrees of freedom
- Numerical cost rises rapidly with number of coordinates



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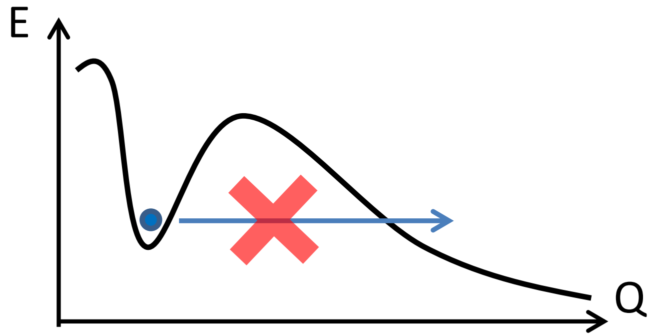
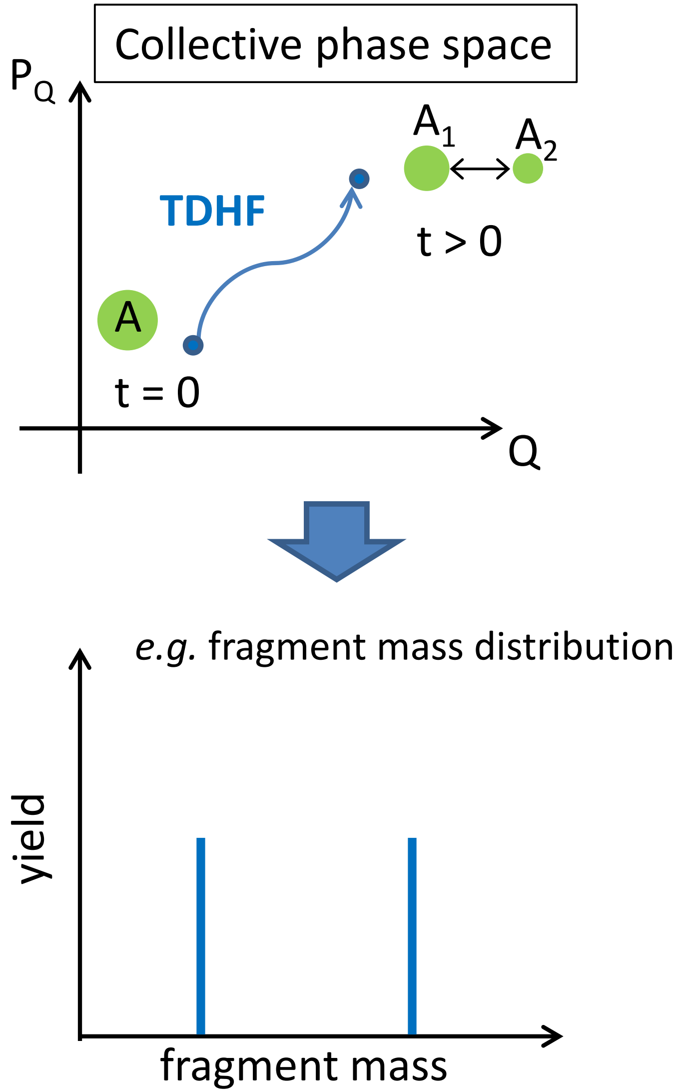


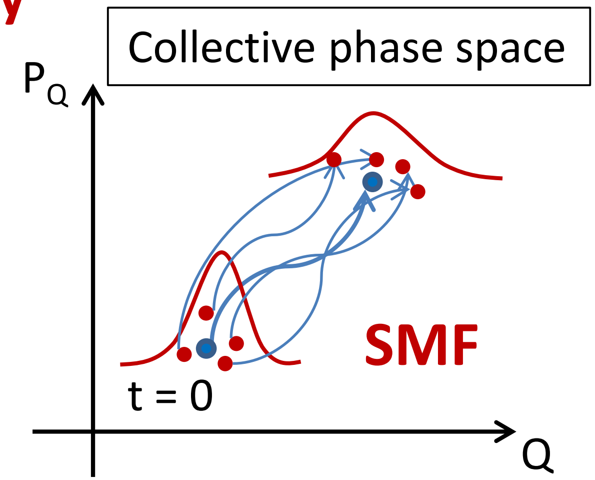


Our method:

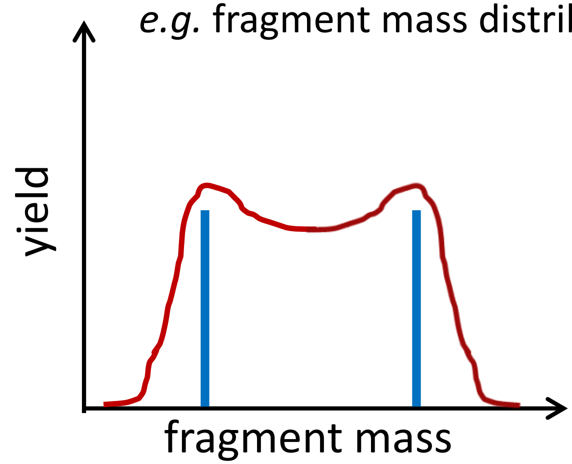
S. Ayik, PLB**658**, 174 (2008)

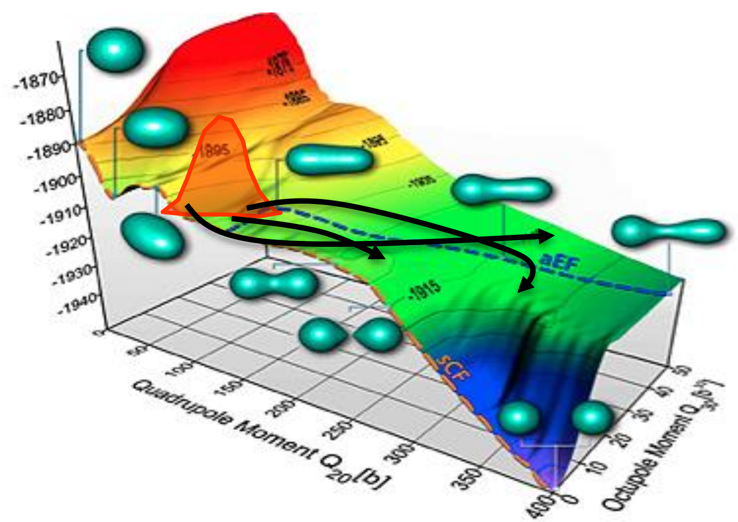
TDHF → Stochastic mean field (SMF) theory

- No need to select collective coordinates (3D)
- Fully non-adiabatic
- **Quantum fluctuations by initial-state sampling**



→ microscopic and dynamical description of fission





Stochastic mean-field theory

S. Ayik, PLB**658**, 174 (2008)

- Quantum fluctuation at $t = 0$ is taken into account by random sampling of one-body density matrix $\{\rho^{(n)}\}$

$$\rho^{(n)}(t=0) = \overline{\rho^{(n)}(t=0)} + \delta\rho^{(n)}$$

- Evolution of a quantum wave packet is simulated by an ensemble of classical (TDHF) trajectories

$$i\hbar\dot{\rho}^{(n)} = [h[\rho^{(n)}], \rho^{(n)}]$$

- Expectation values and dispersions of one-body observables

$$\langle Q \rangle \quad \rightarrow \quad \overline{Q^{(n)}} = \overline{\mathrm{Tr}[\rho^{(n)} Q]}$$

$$\langle Q^2 \rangle - \langle Q \rangle^2 \quad \rightarrow \quad \overline{Q^{(n)2}} - \overline{Q^{(n)}}^2$$

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$$\rho^{(n)}(t=0) = \overline{\rho^{(n)}(t=0)} + \delta\rho^{(n)}$$

If the initial many-body state is a Slater determinant:

$$\overline{\delta\rho_{ij}^{(n)}} = 0$$

$$\overline{\delta\rho_{ij}^{(n)}\delta\rho_{i'j'}^{(n)*}} = \frac{1}{2}\delta_{ii'}\delta_{jj'}[n_i(1-n_j)+n_j(1-n_i)]$$

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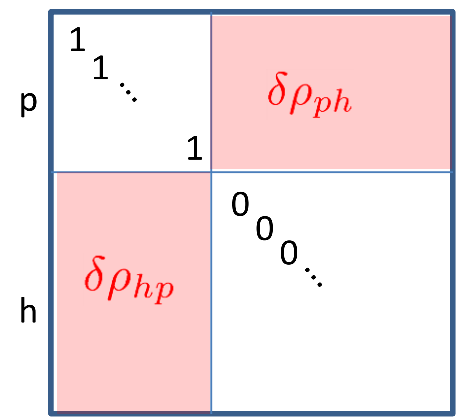

Configuration-mixing effect

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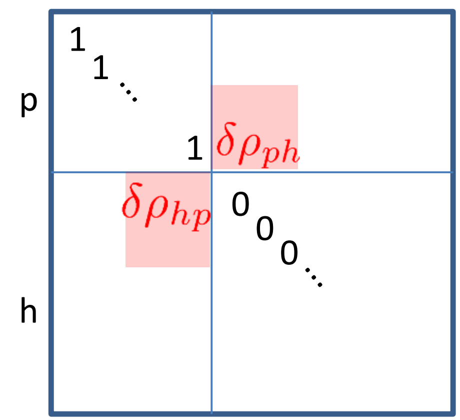
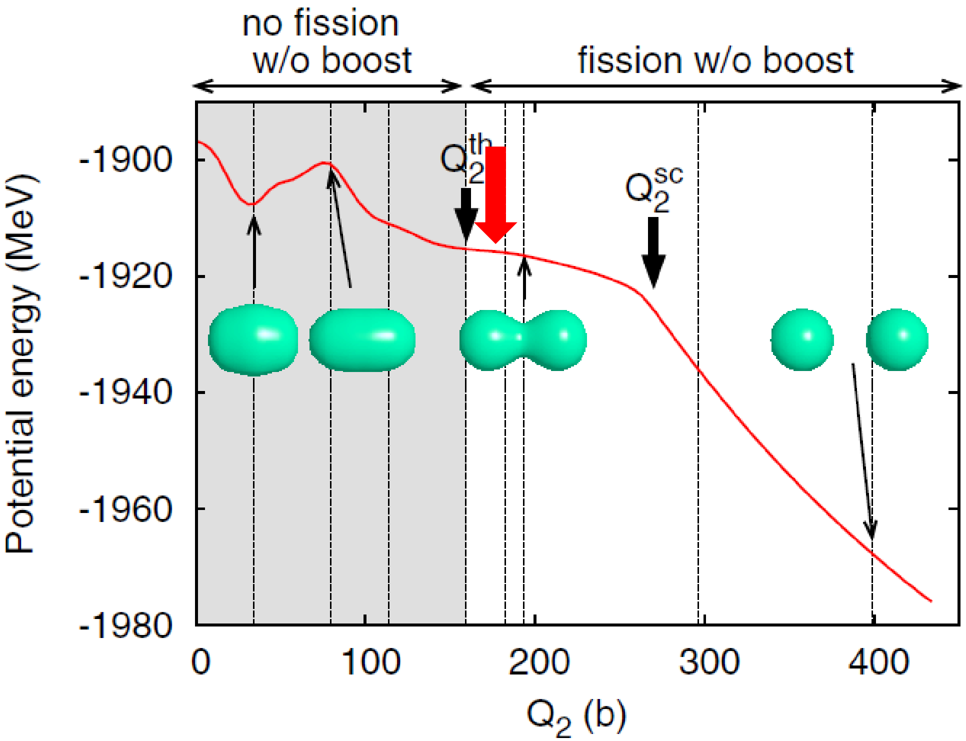
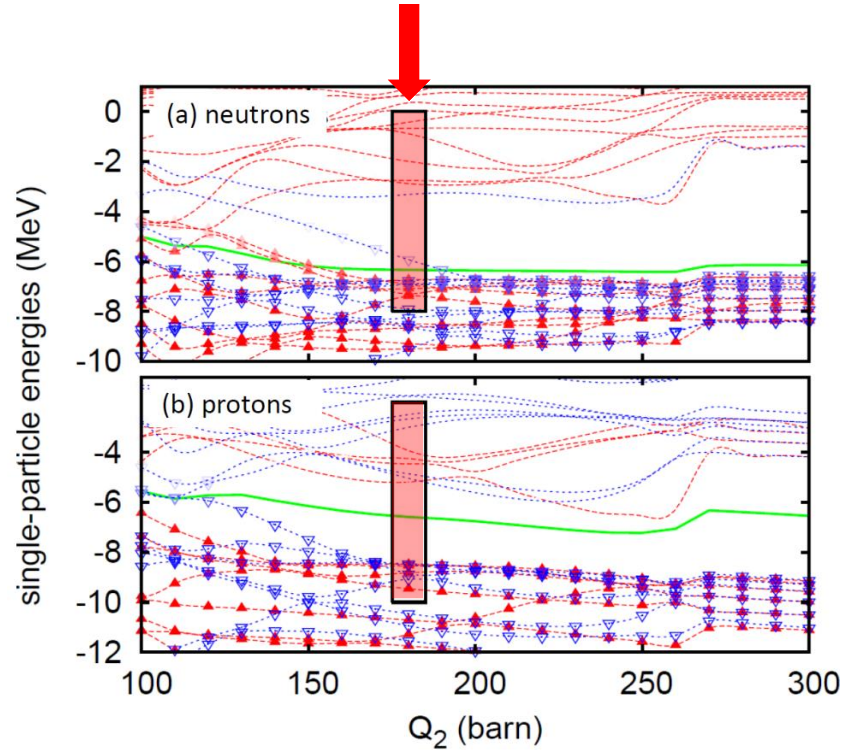


Configuration-mixing effect

Application to ^{258}Fm





- SLy4d (+ pure pairing force) with frozen-occupation-number approx. (FOA)
- Starting from Q_2 = 180 barn
- Fluctuation in ρ_{ij} within a limited window
- 200 events (11 of which did not fissioned)

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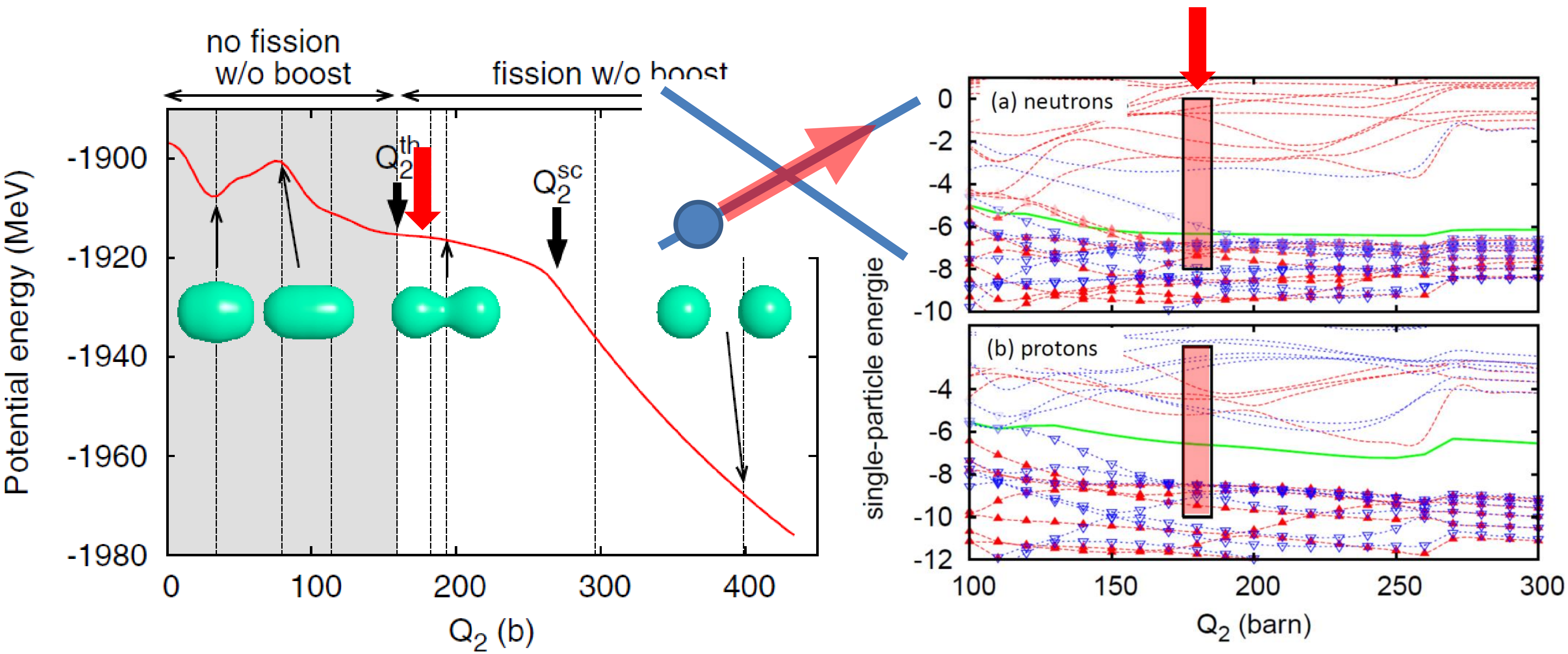

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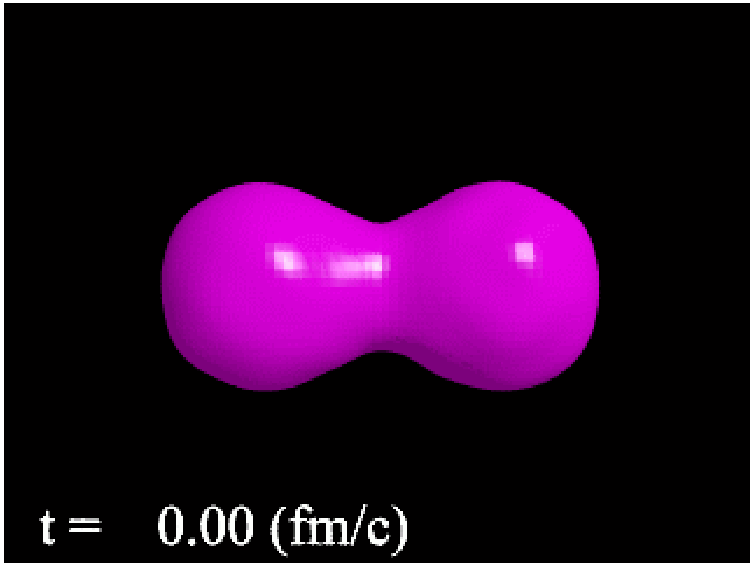
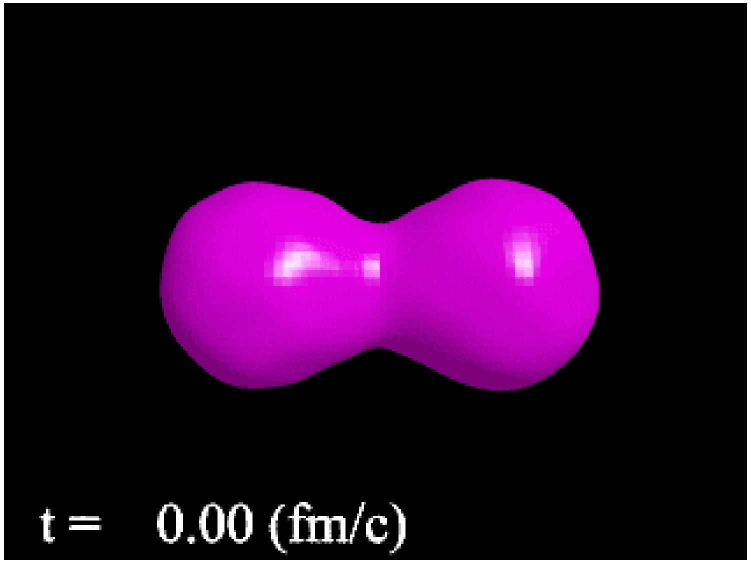
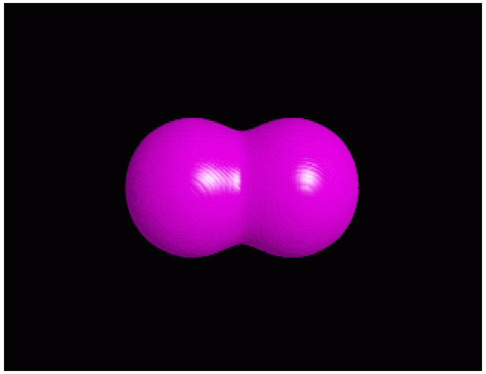
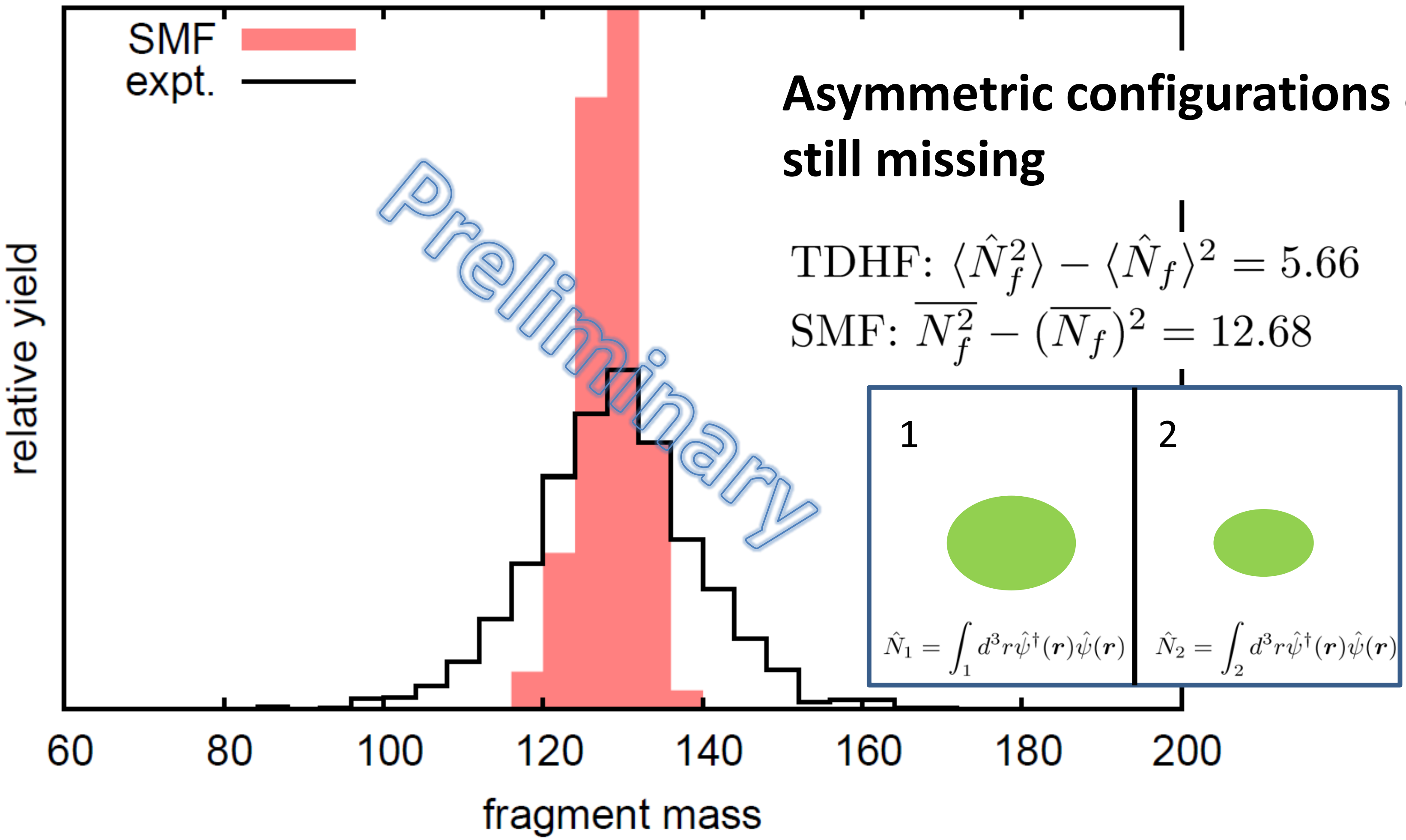






← TDHF starting from Q = 160 b

Fragment-mass distribution

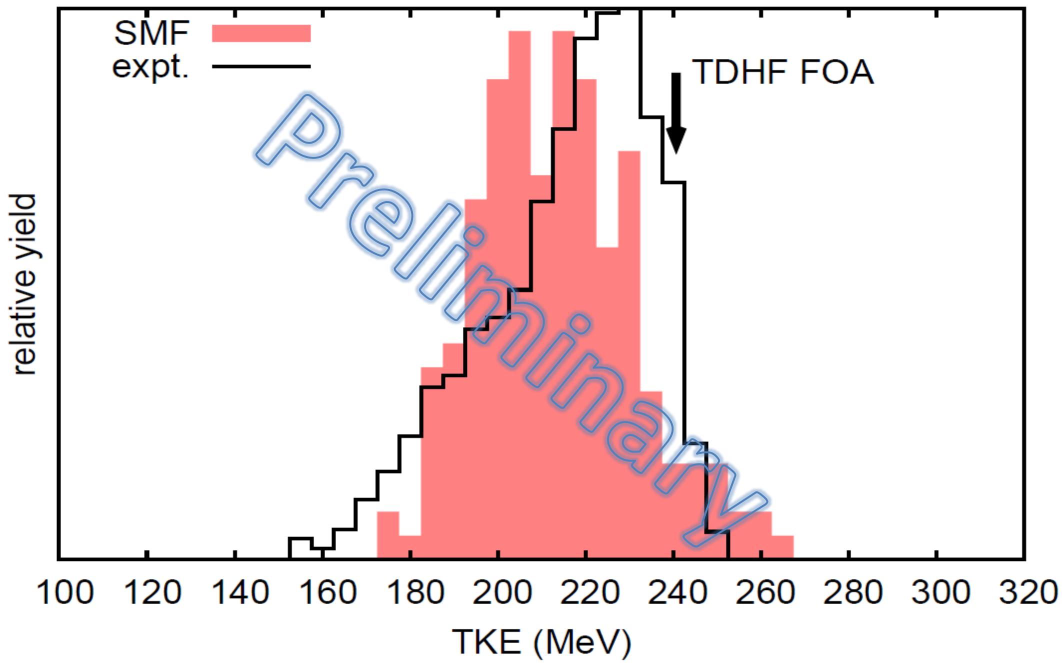


Asymmetric configurations are still missing

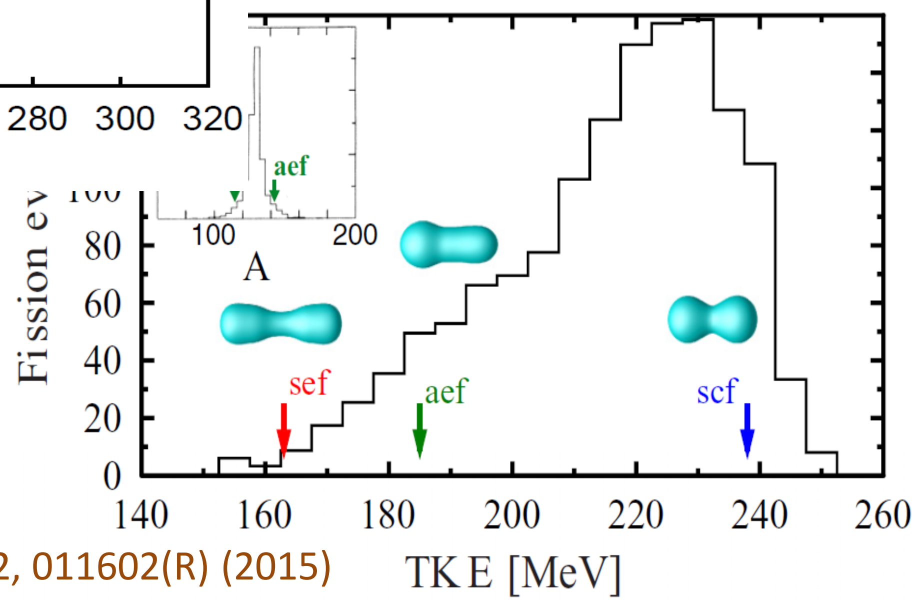
$$\text{TDHF: } \langle \hat{N}_f^2 \rangle - \langle \hat{N}_f \rangle^2 = 5.66$$

$$\text{SMF: } \overline{N_f^2} - (\overline{N_f})^2 = 12.68$$

Total kinetic energy of fragments

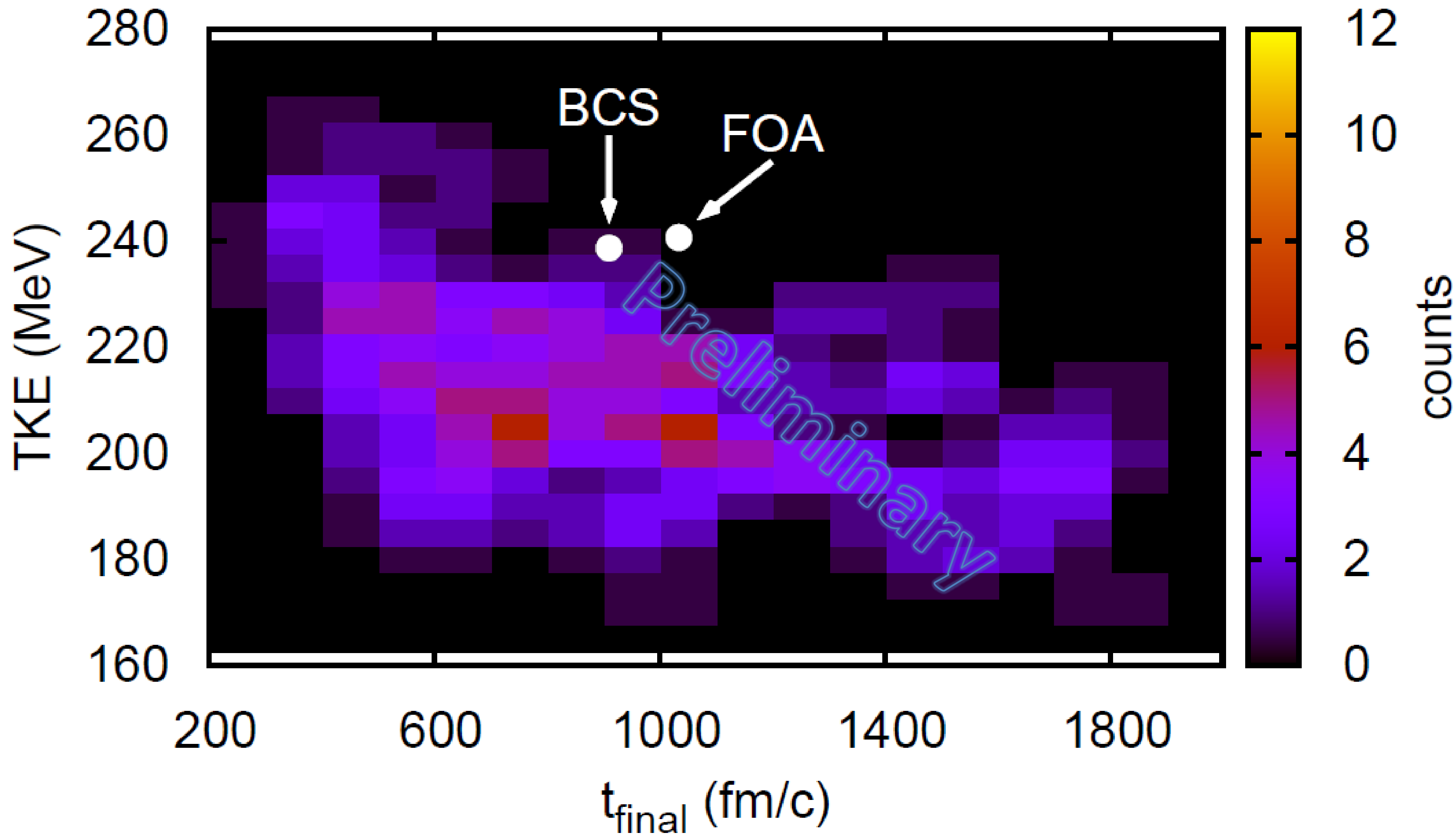


- **Width of distribution is reasonably reproduced**
- **Peak position is shifted from TDHF value**
- **Does not reproduce the asymmetric TKE distribution**
- **Asymmetric and elongated configurations are missing?**



G. Scamps, C. Simenel, and D. Lacroix, PRC92, 011602(R) (2015)

TKE and final time



Summary

- **Aim: Fully microscopic and dynamical description for fission**
- **We tested the SMF theory to take into account the fluctuations missing in TDHF**
  - fluctuation of ρ_{ij} is introduced at t = 0 by random sampling
  - **possible to obtain TKE and fragment-mass distributions**
- Fission of ^{258}Fm → asymmetric and elongated fission modes are still missing
  - we should start from more compact shape
  - more fluctuation needed in ρ_{ij}?

If we start from Q = 100 barn...