Recent progress in the time-dependent description of Fission

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ENSAR2

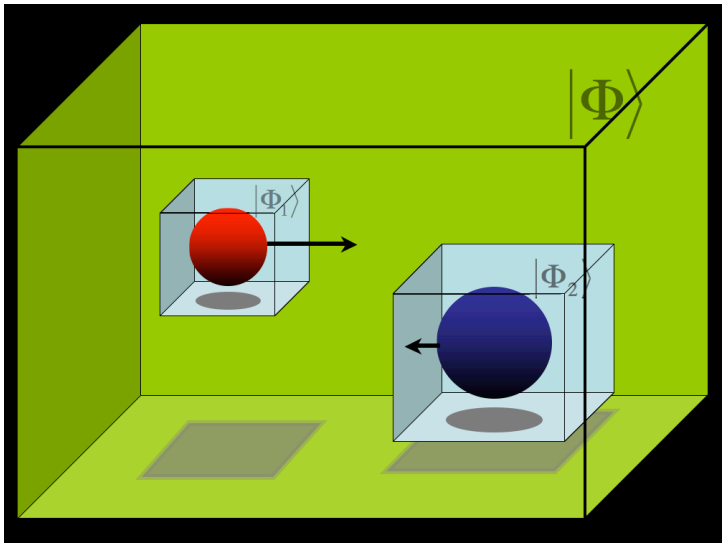
Outline:

- TDHF+BCS
- Application to fission
- Collective aspects of Large Amplitude Collective motion
- Stochastic Mean-Field Theories for Large Amplitude Motion
- Results on ^{258}Fm

Coll: S. Ayik, B. Yilmaz, C. Simenel,
G. Scamps, Y. Tanimura

Recent progress

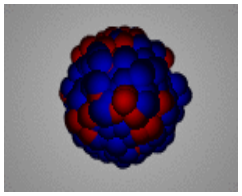
Nuclear motion of superfluid nuclei on a mesh (here within TDHF+BCS)



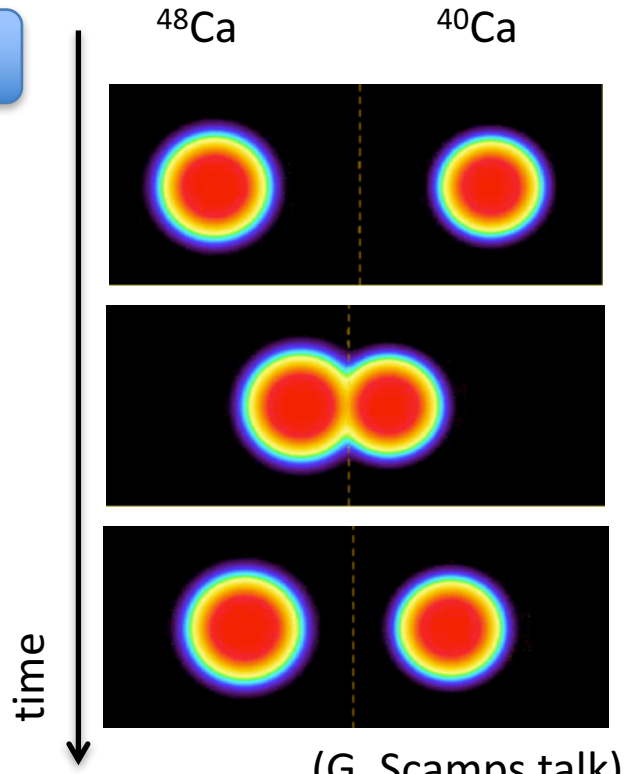
Scamps, Tanimura, Lacroix (2012-2016)

Applied to a number of physical process

Vibrations

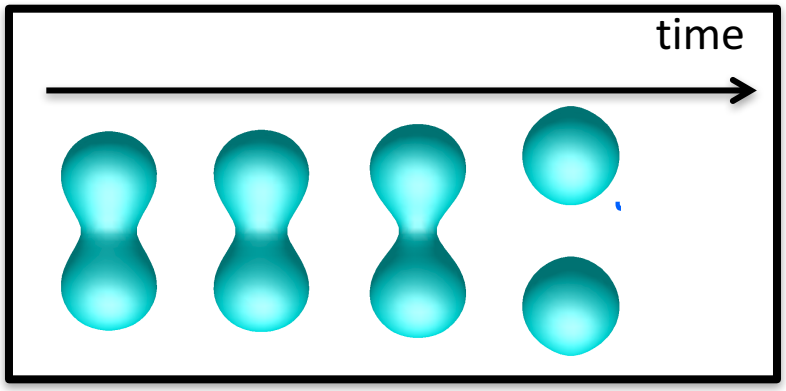


Fusion/Transfert



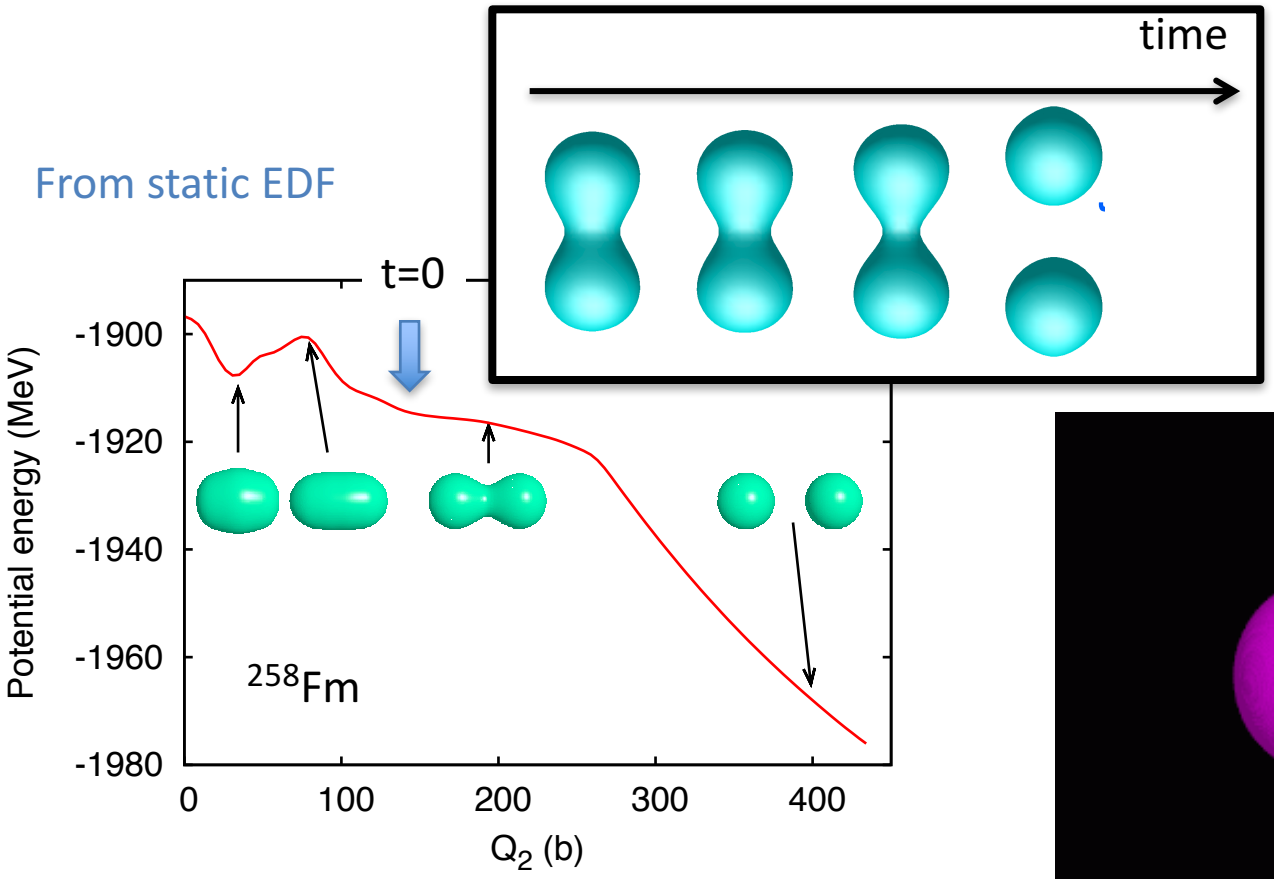
(G. Scamps talk)

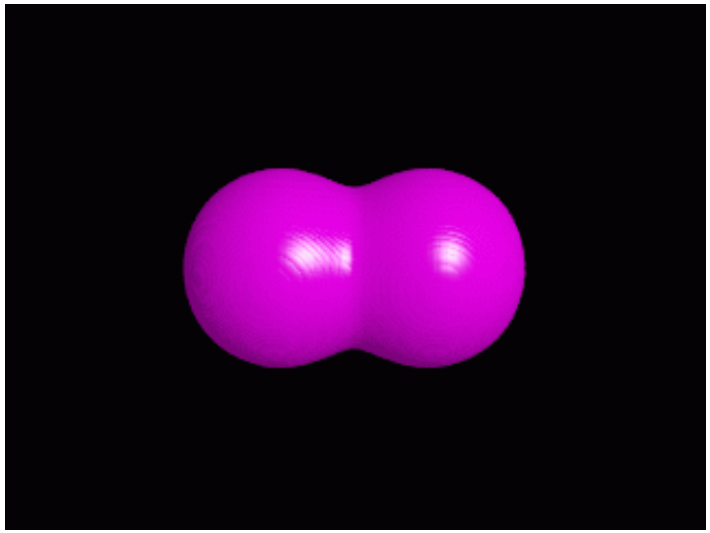
Fission



Fission with TD-EDF with pairing

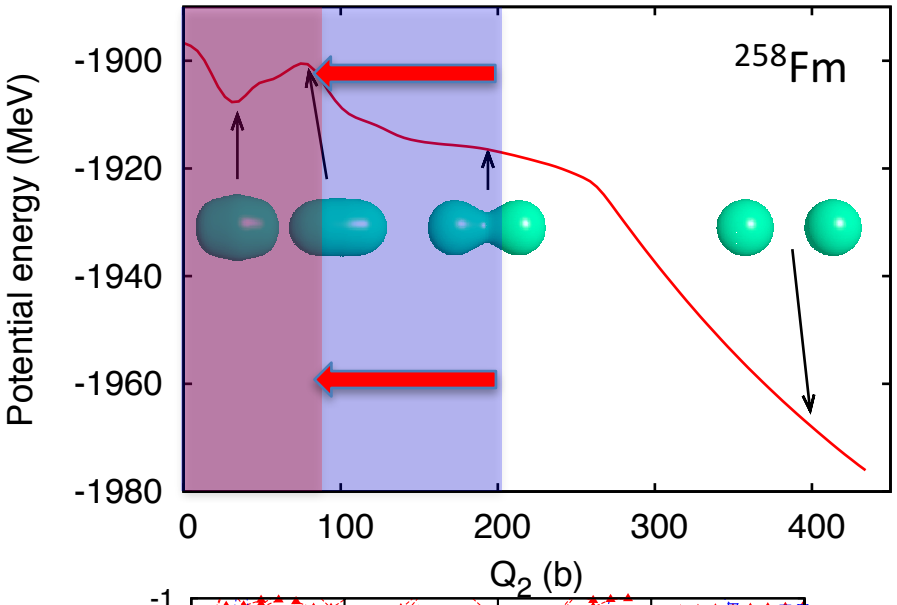
From static EDF





(courtesy Y. Tanimura)

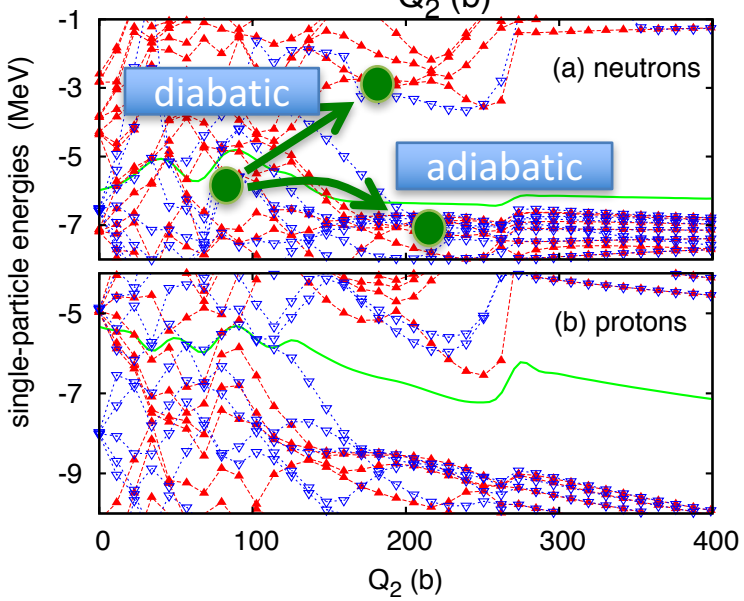
Is superfluidity important?



Fission with TD-EDF without pairing

➡ Threshold anomaly

Simenel, Umar, PRC C89 (2014).
Goddard, Stevenson, Rios, PRC 92 (2015), 93 (2016)



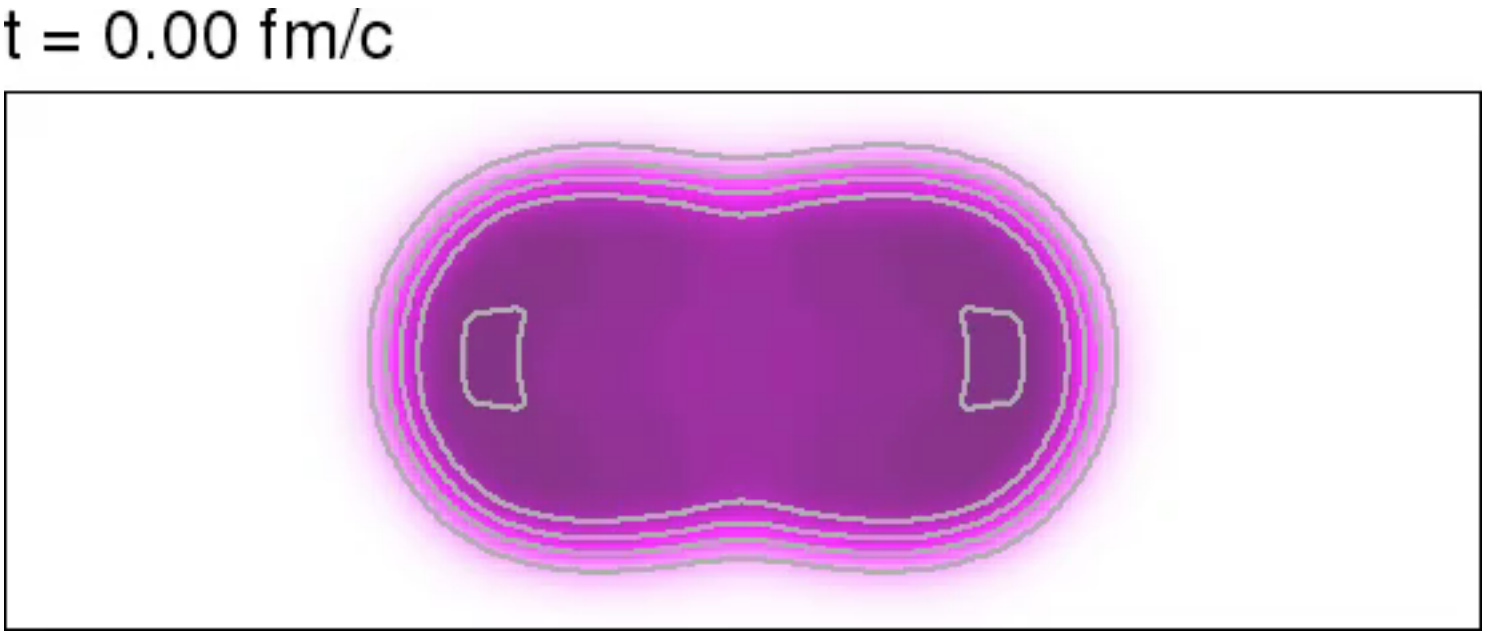
This problem is solved in TDHF+BCS (or TDHFB)

➡ Dynamical pairing is important

NB: quantum fluctuations also solve the problem (see later)

Scamps Simenel, Lacroix, PRC 92 (2015)
Tanimura, Lacroix, Scamps, PRC 92 (2015)

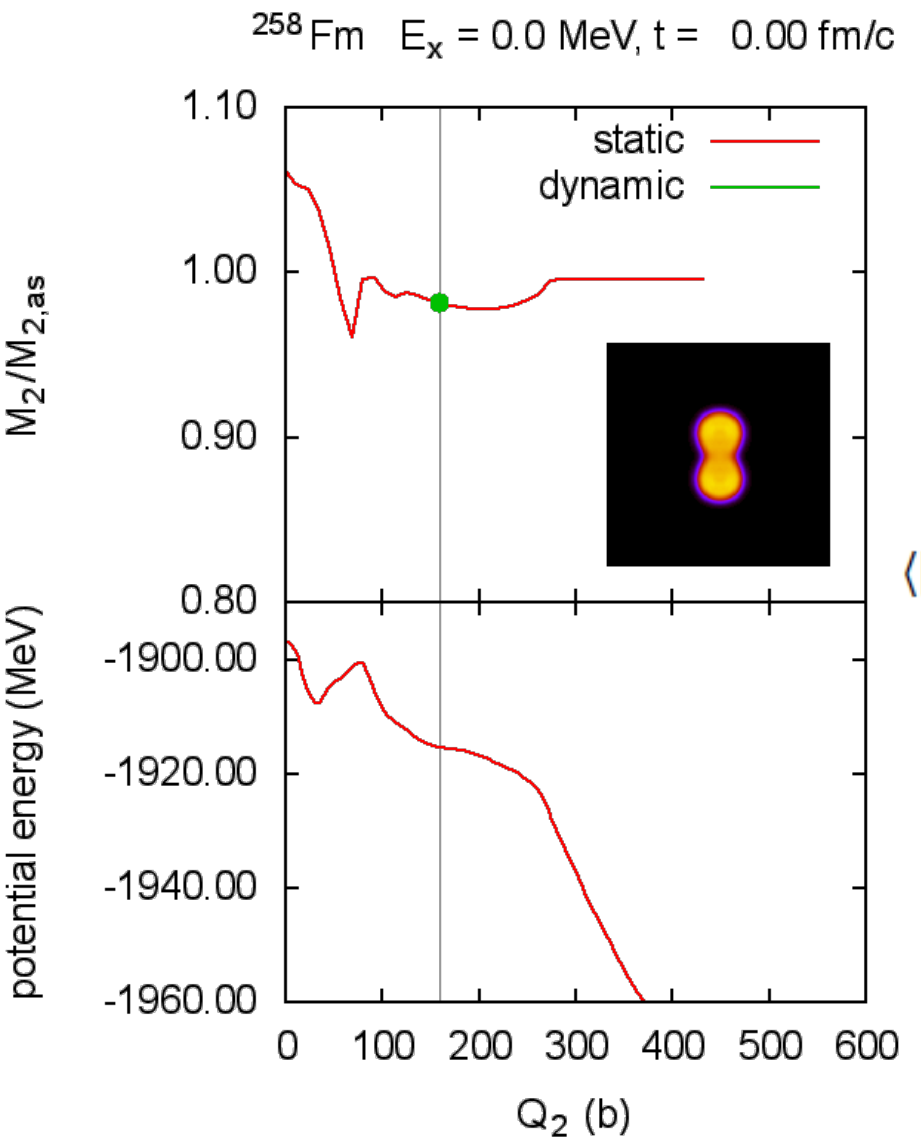
An additional remark on fission time scale:
Very sensitive to pairing type and much longer than anticipated



Confirms the finding of:

Bulgac, Magierski, Roche, and Stetcu
Phys. Rev. Lett. 116, 122504 (2016)

Tanimura, Lacroix, Scamps, PRC 92 (2015)



Microscopic dynamic

$$\frac{dq_\alpha}{dt} = -\frac{i}{2\hbar m}\mathrm{Tr}([Q_\alpha, p^2]\rho(t)) \equiv \frac{p_\alpha}{M_\alpha},$$

$$\hat{P}_\alpha \equiv -i\frac{M_\alpha}{2\hbar m}\sum_{ij}\langle i|[\hat{Q}_\alpha, \hat{p}^2]|j\rangle \hat{a}_i^\dagger \hat{a}_j.$$

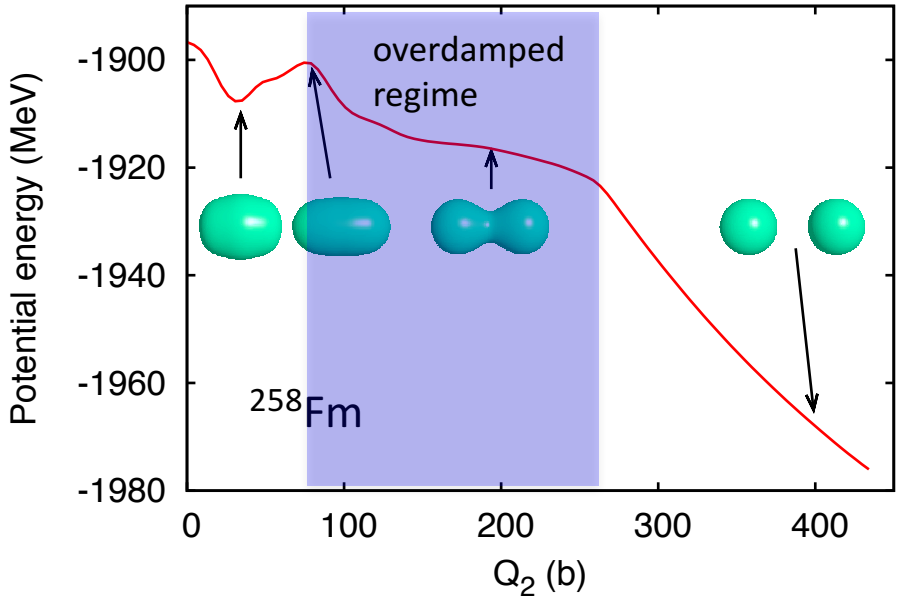
$$\langle[\hat{Q}_\alpha, \hat{P}_\alpha]\rangle = i\hbar, \Rightarrow \frac{1}{M_\alpha(t)} = \frac{1}{m}\mathrm{Tr}[\rho(t)\nabla Q_\alpha \cdot \nabla Q_\alpha],$$

Macroscopic evolution:
Dissipation, non-adiabatic effects…

- The system first follows the adiabatic limit
- Around scission, dynamic is faster and Becomes non-adiabatic

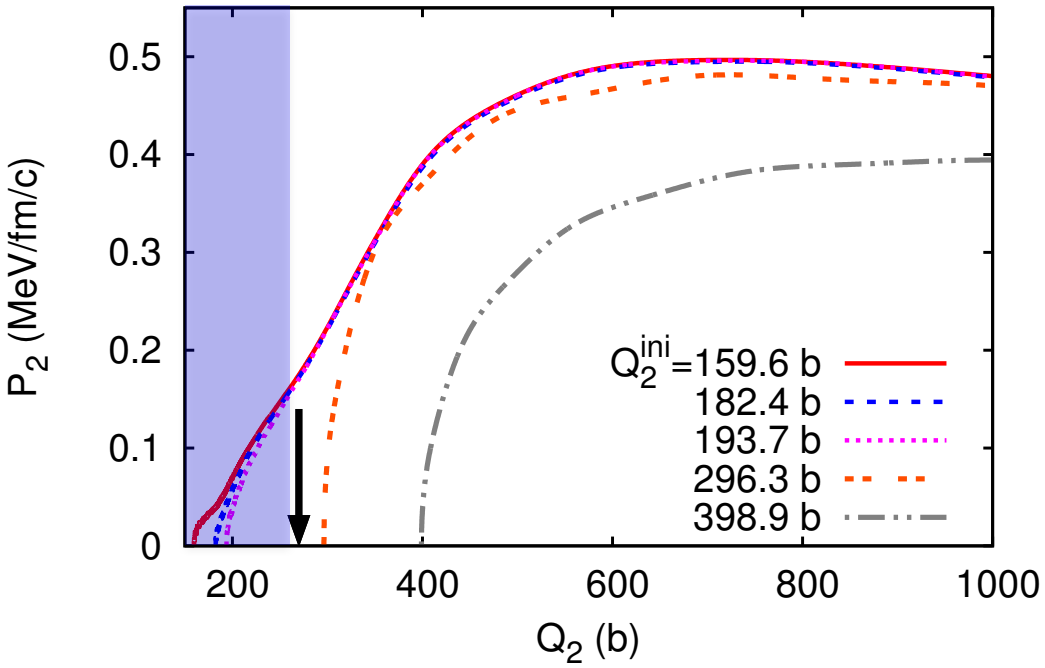
$E_{\mathrm{diss}} \simeq 20\mathrm{MeV}$ $\mathrm{TKE} \simeq 250\mathrm{MeV}$

Dissipative regime in TDDFT

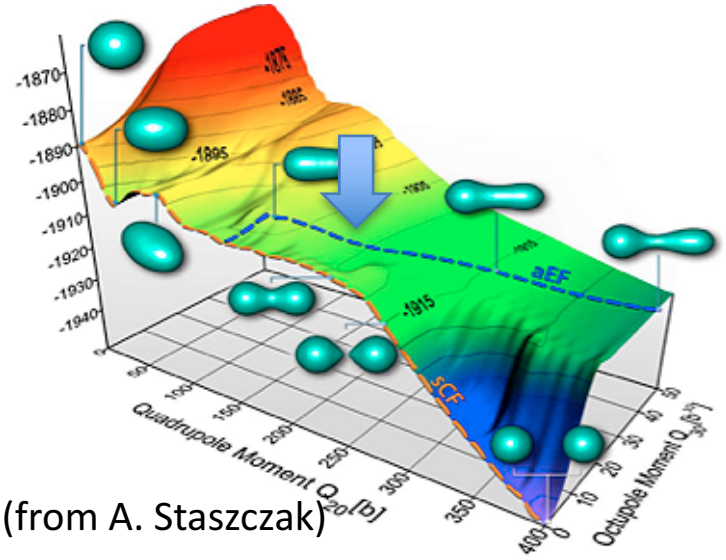


More or less
we confirm the overdamped regime before scission

Collective momentum evolution



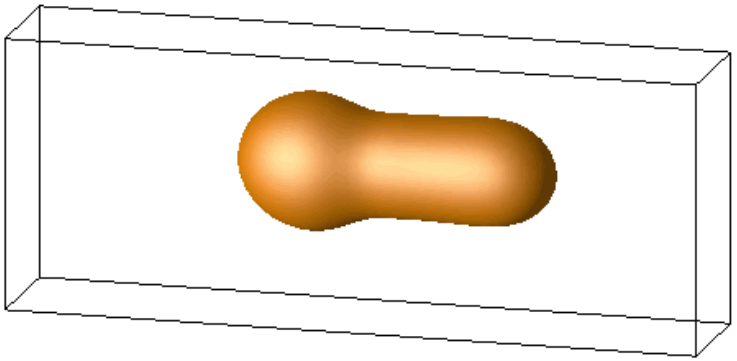
Still open :
Precise values of dissipative transport coefficients



(from A. Staszczak)

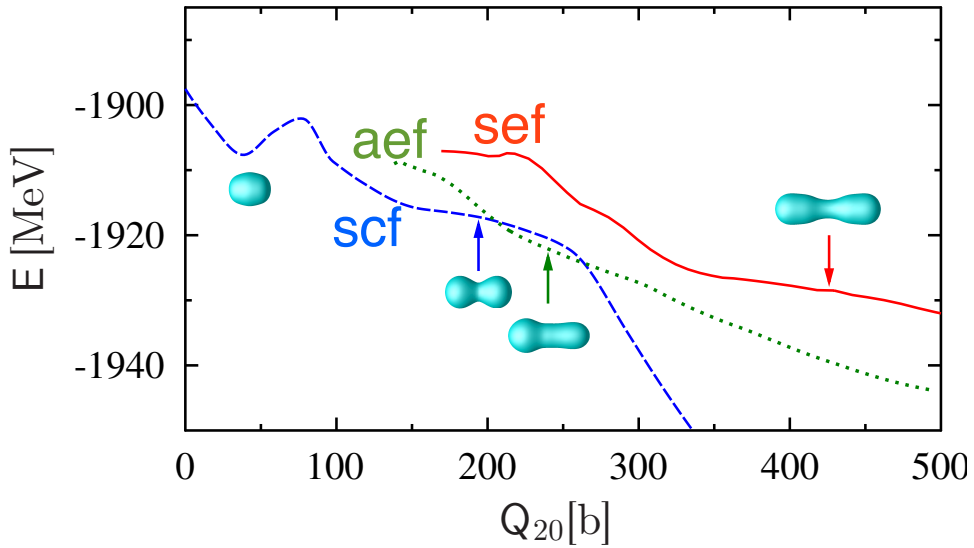
Time-dependent picture of fission

Scamps, Simenel, Lacroix, PRC92 (2015)



(courtesy G. Scamps/C. Simenel)

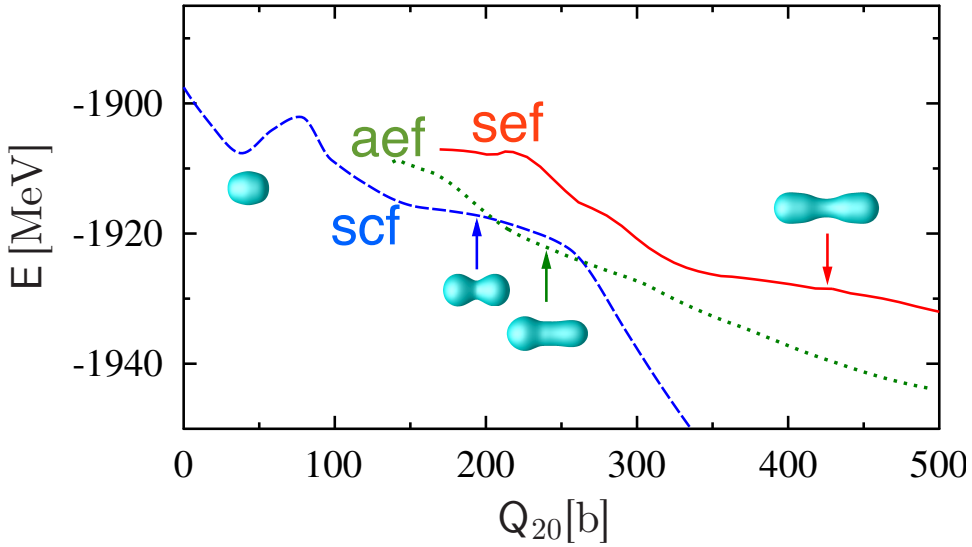
Fission along different paths



scf: symmetric compact fission

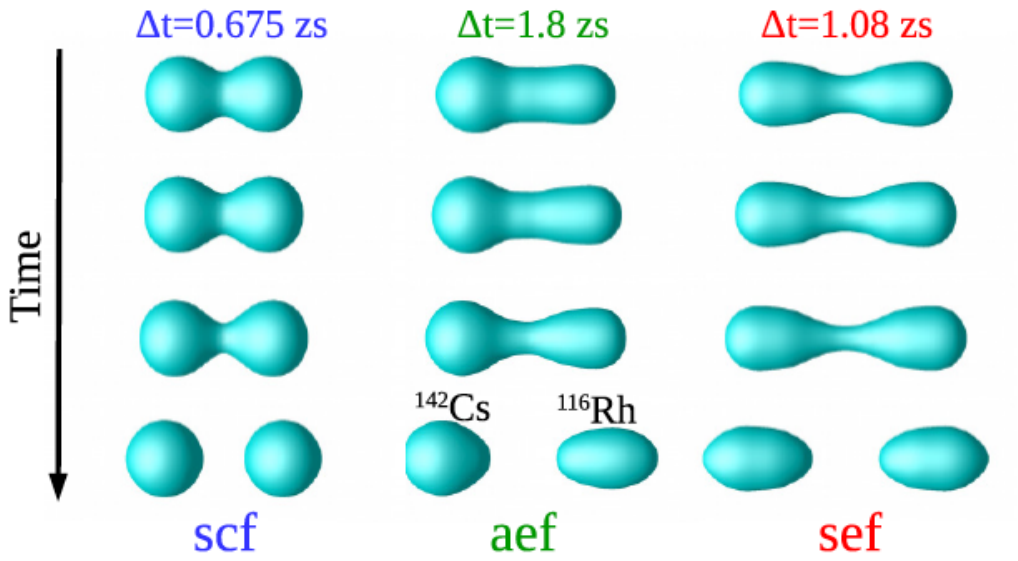
sef: symmetric elongated fission

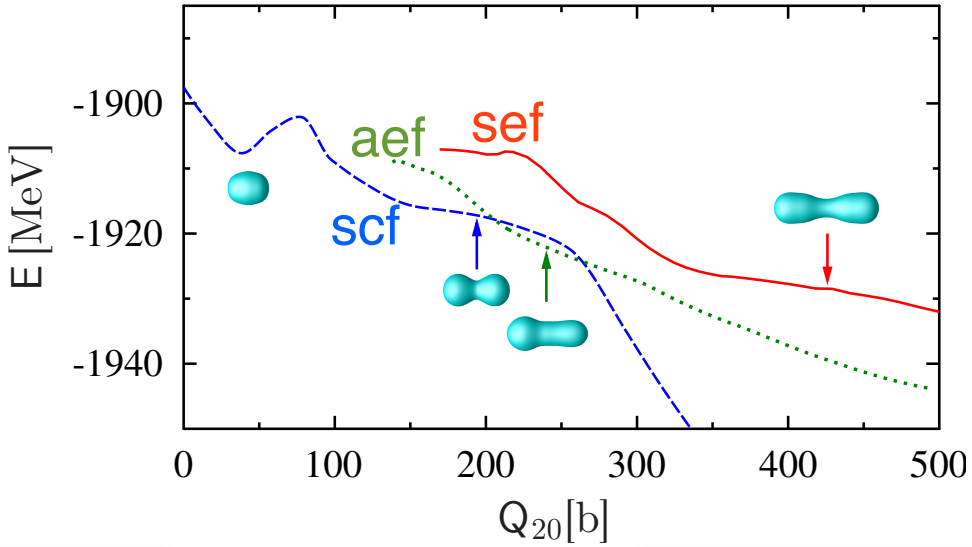
aef: asymmetric elongated fission



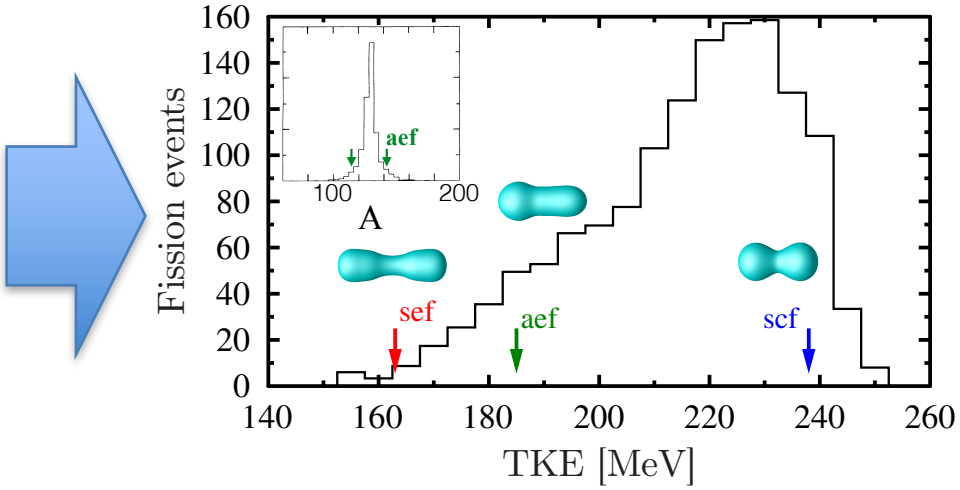
Time-scale

1 zs = 10^{-21} s





Total Kinetic Energy



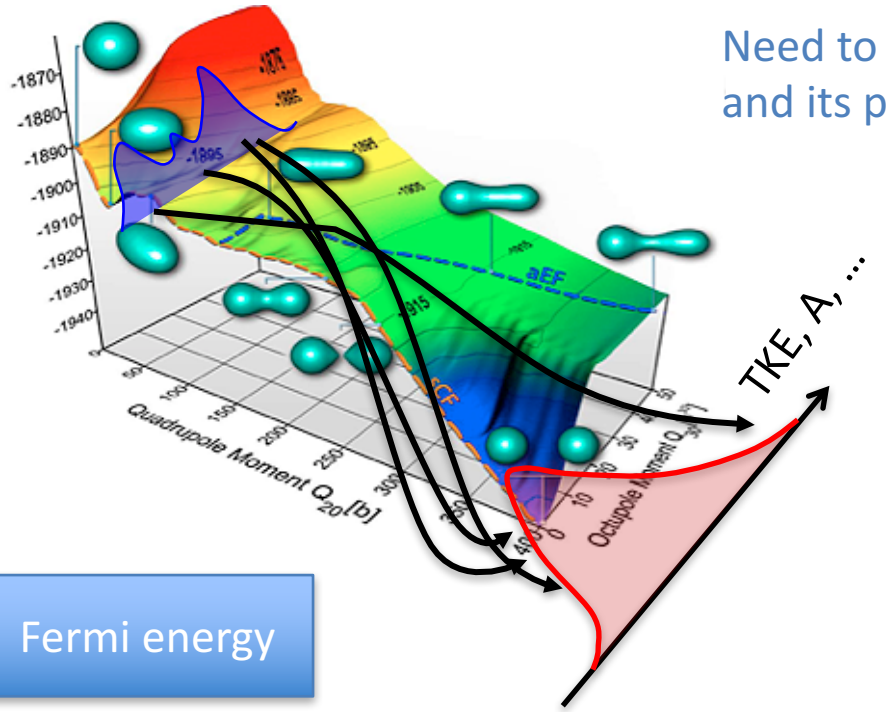
Scamps, Simenel, Lacroix, PRC 92 (2015)

Some conclusions

- TKE seems compatible with experiments
- Dynamic seems almost adiabatic up to scission point and then is Well describe by TD-BCS

Remaining problem

- Fluctuations are underestimated
- Weight of each paths?



Need to describe configuration mixing and its propagation

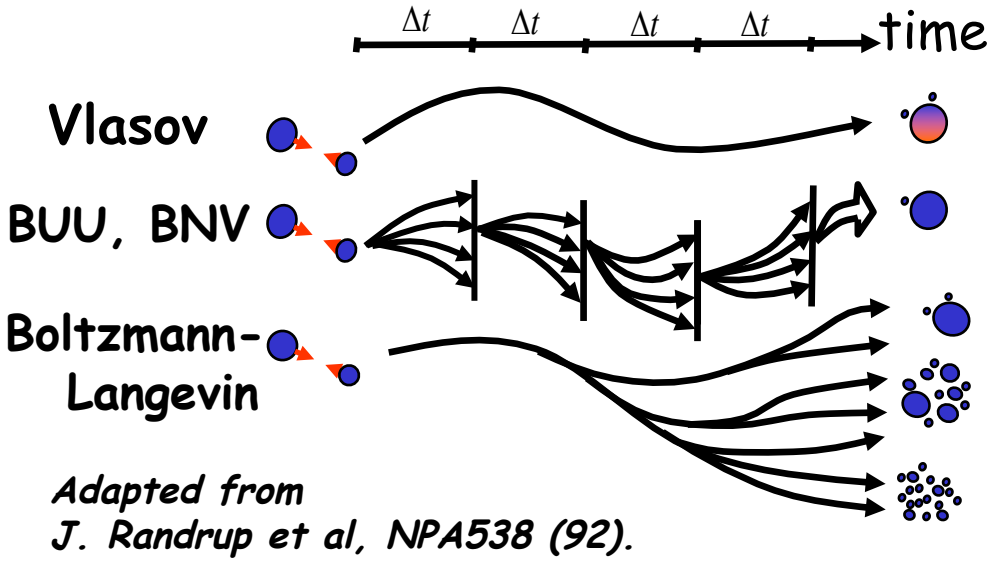
One possibility is to use Time-Dependent Generator Coordinate method (beyond adiabatic, number of DOFs, …)

Our objective: use the stochastic mean-field approach to describe fission

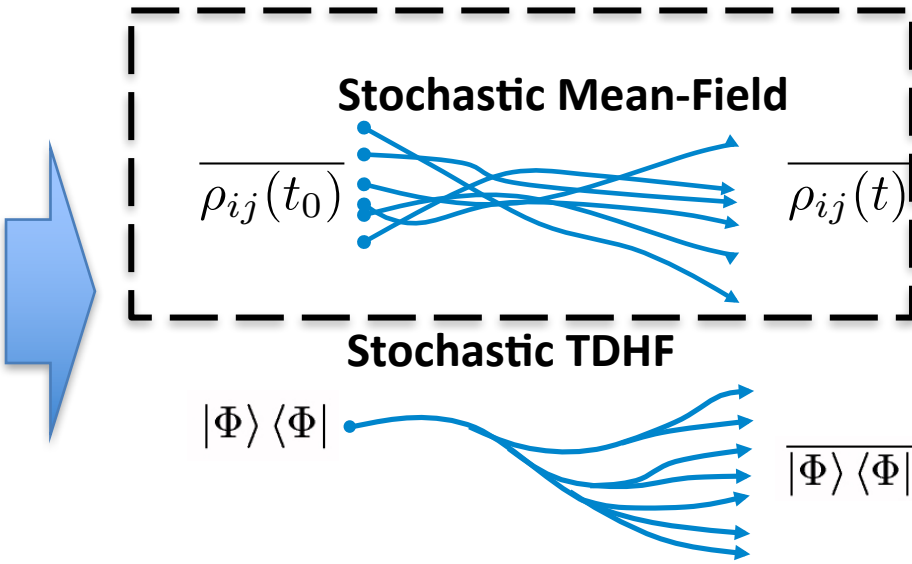
Lacroix, Ayik, EPJA (Review) 50 (2014)

Fermi energy

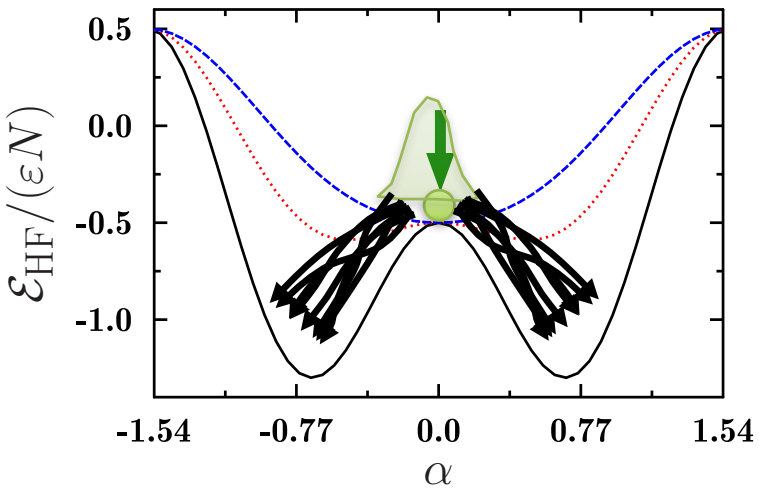
Coulomb barrier energy

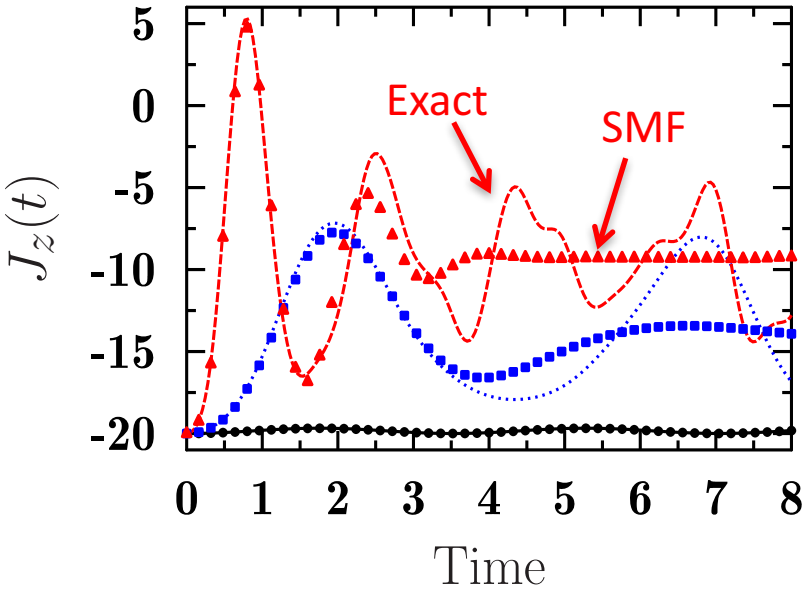


Adapted from J. Randrup et al, NPA538 (92).



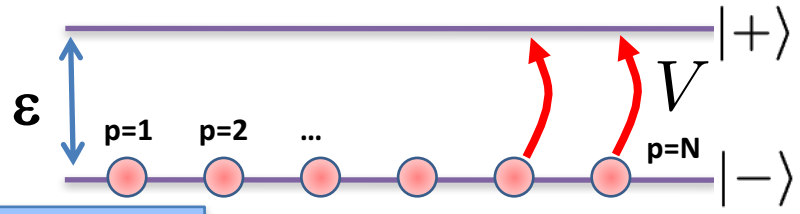
N=40 particles





Lacroix, Ayik, Yilmaz, PRC 85 (2012)

Two-Level Lipkin Model



Progress

$\chi = V/\varepsilon$

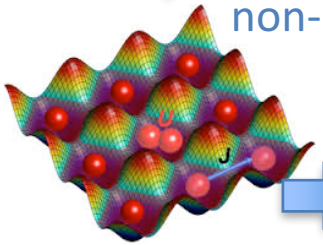
Extension to superfluid systems: TDHFB with fluctuations

Lacroix, Gambacurta, Ayik, Yilmaz, PRC C 87, 061302(R) (2013)

Mapping initial fluctuations with complex Initial correlations

Yilmaz, Lacroix, Curecal, PRC C 90, 054617 (2014).

Application to optical lattice: better than non-equilibrium 2-body green functions



Lacroix, Hermanns, Hinz, Bonitz, PRB90 (2014)

Equivalent to simplified un-truncated BBGKY hierarchy

Lacroix, Tanimura, Ayik, EPJA52 (2016)

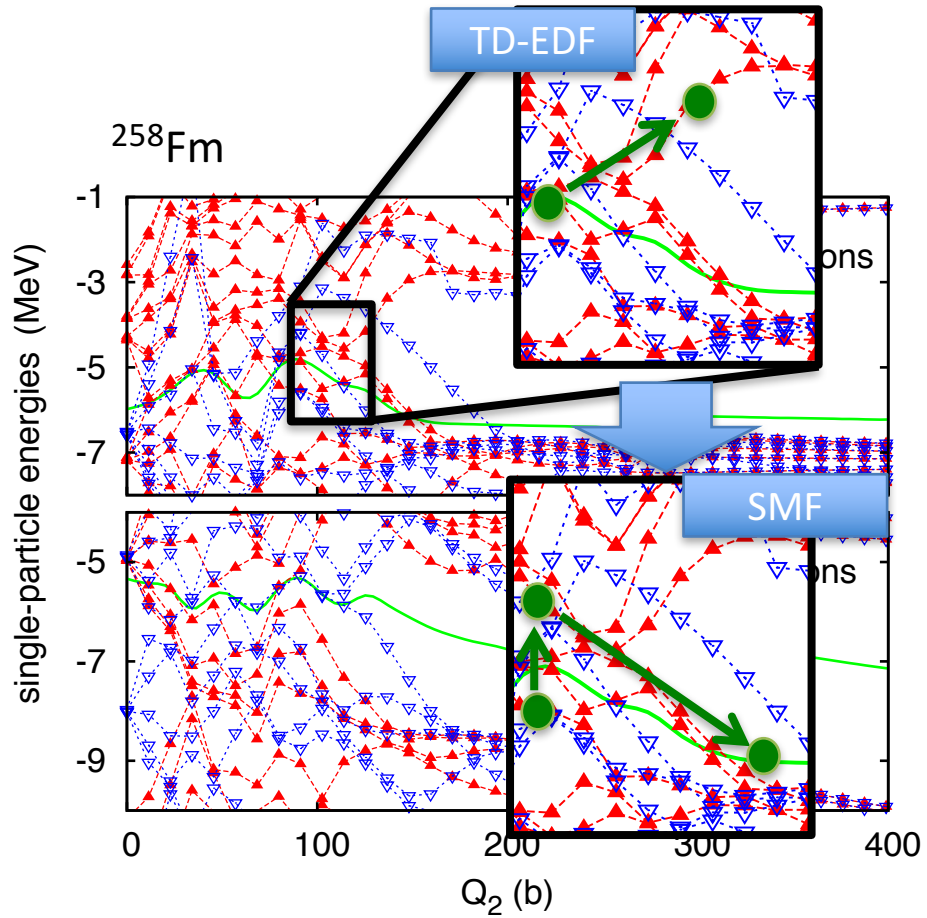
SMF in density matrix space

$$\rho(\mathbf{r},\mathbf{r}',t_0) = \sum_i \Phi_i^*(\mathbf{r},t_0) n_i \Phi_j(\mathbf{r}',t_0)$$

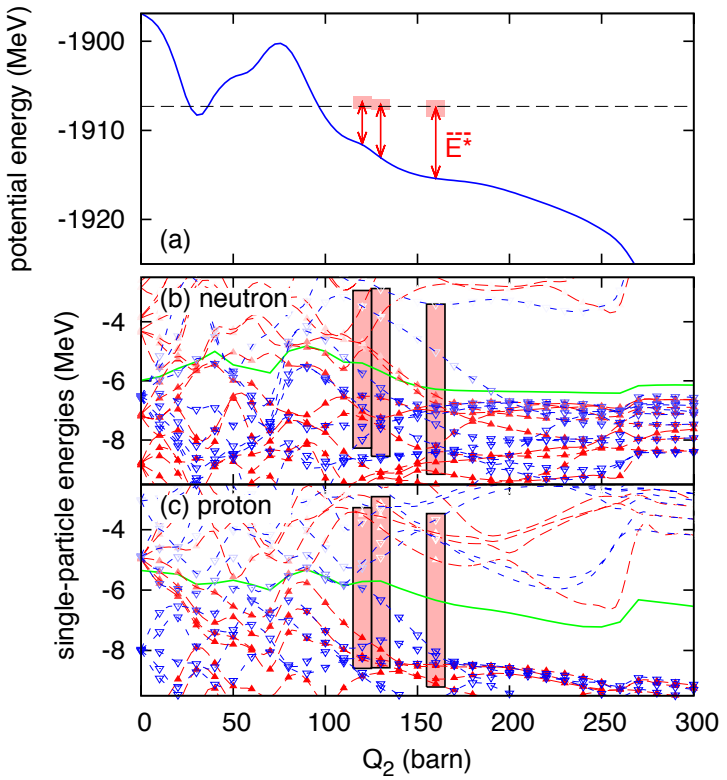
$$\rho^\lambda(\mathbf{r},\mathbf{r}',t_0) = \sum_{ij} \Phi_i^*(\mathbf{r},t_0) \rho_{ij}^\lambda \Phi_j(\mathbf{r}',t_0)$$

$$\overline{\rho_{ij}^\lambda} = \delta_{ij} n_i$$

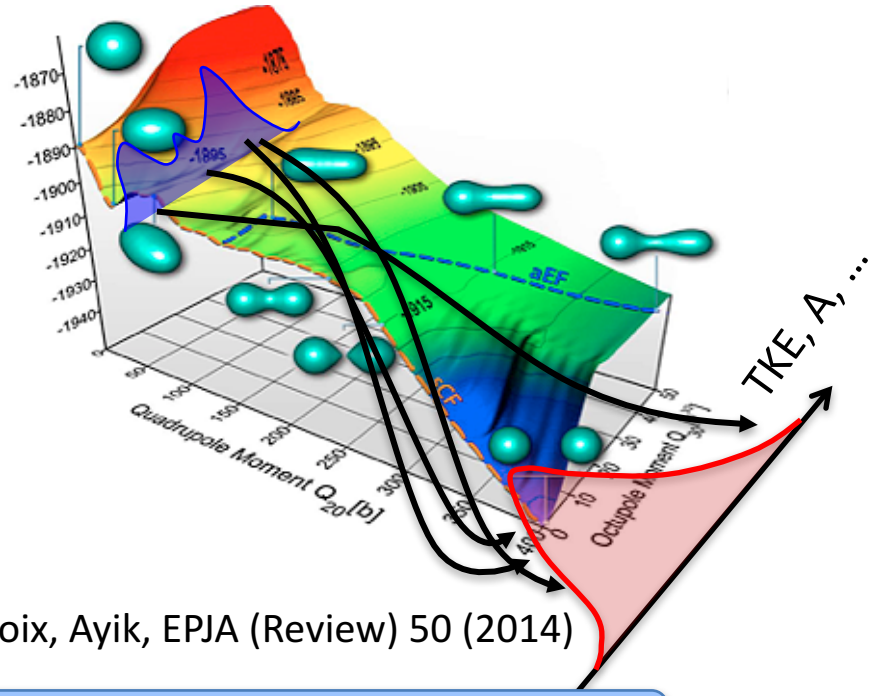
$$\overline{\delta\rho_{ij}^\lambda \delta\rho_{j'i'}^\lambda} = \frac{1}{2}\delta_{jj'}\delta_{ii'}\left[n_i(1-n_j)+n_j(1-n_i)\right].$$



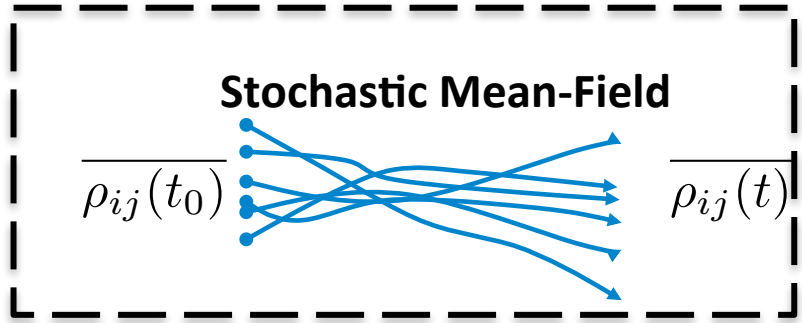
Range of fluctuation fixed by energy cons.



How to conceal microscopic deterministic approach and randomness ?



Lacroix, Ayik, EPJA (Review) 50 (2014)

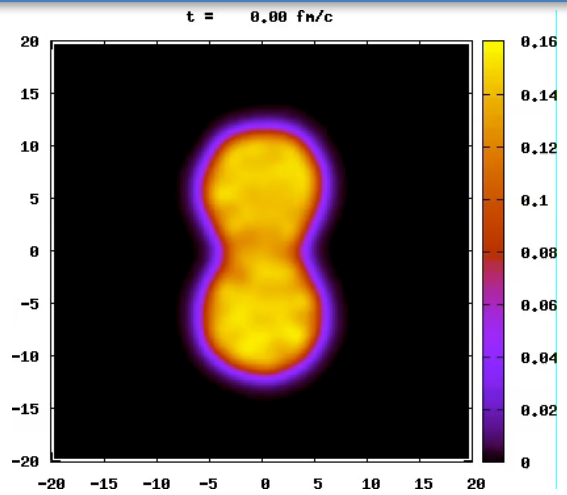


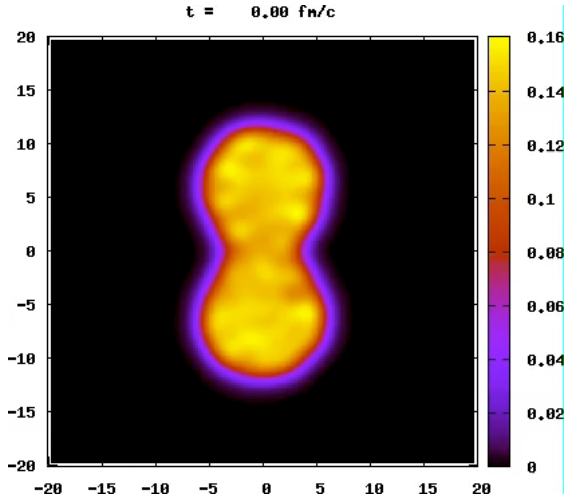
Constrains:

-Generates a sample of microscopic trajectories (typically 300)

-Each trajectory is 8-10 days CPU time

Some trajectories illustration





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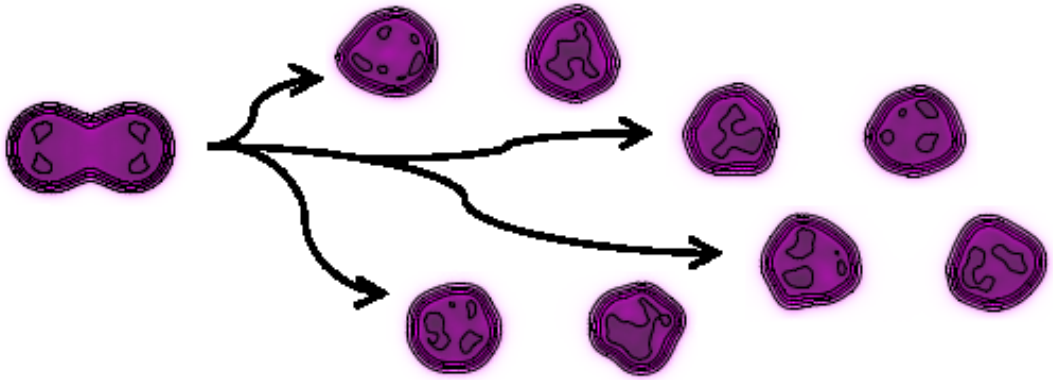
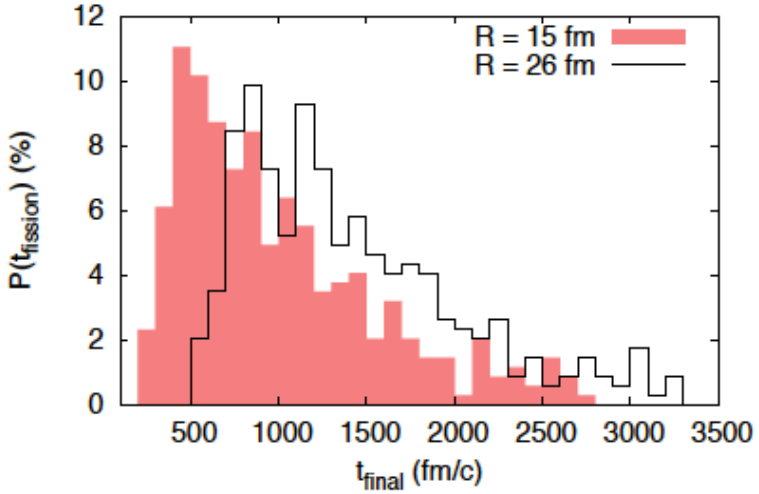


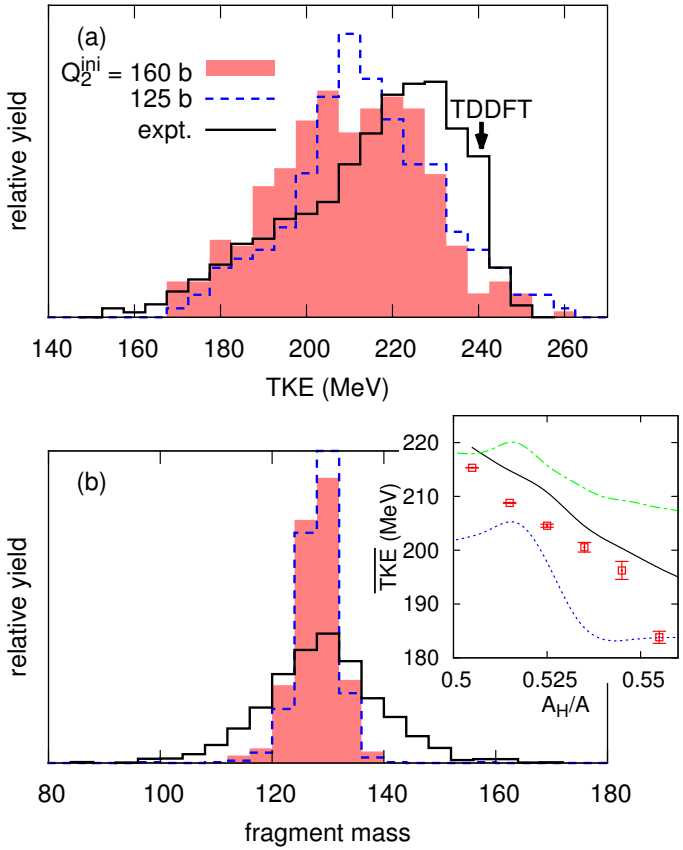
Tanimura, Lacroix, Ayik, submitted to PRL

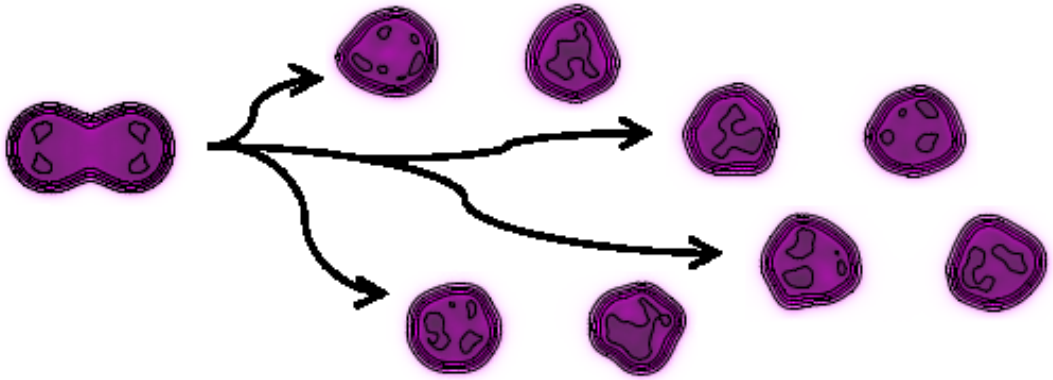
From deterministic to statistical approach

Distribution des temps de fission



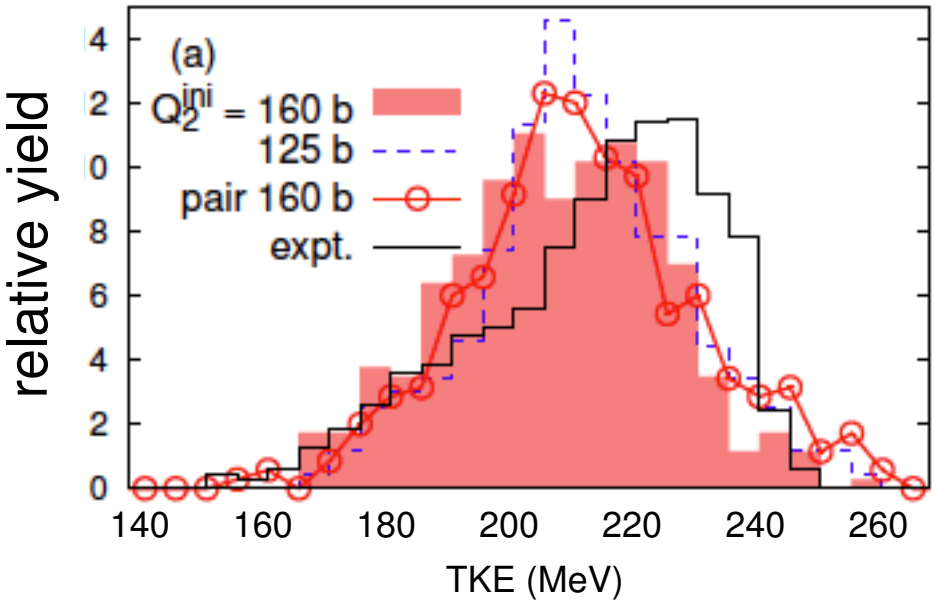
Experience vs Theory





Tanimura, Lacroix, Ayik, submitted to PRL

Quantum fluctuation versus dynamical pairing



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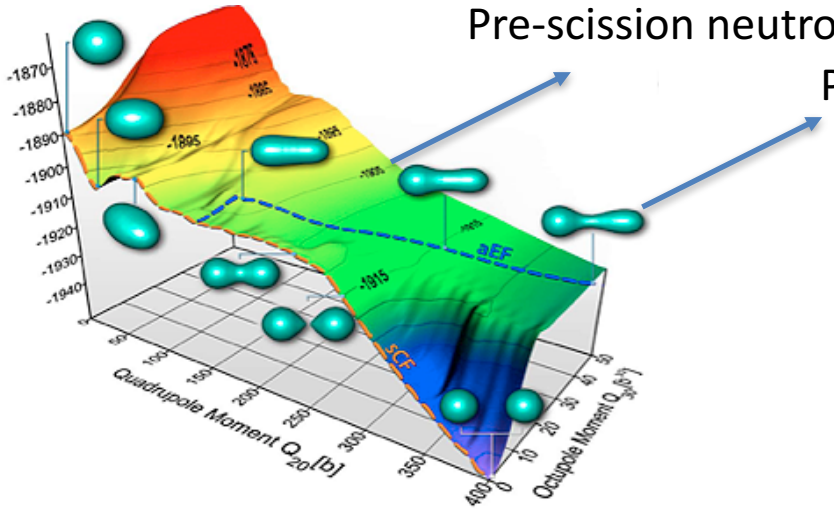
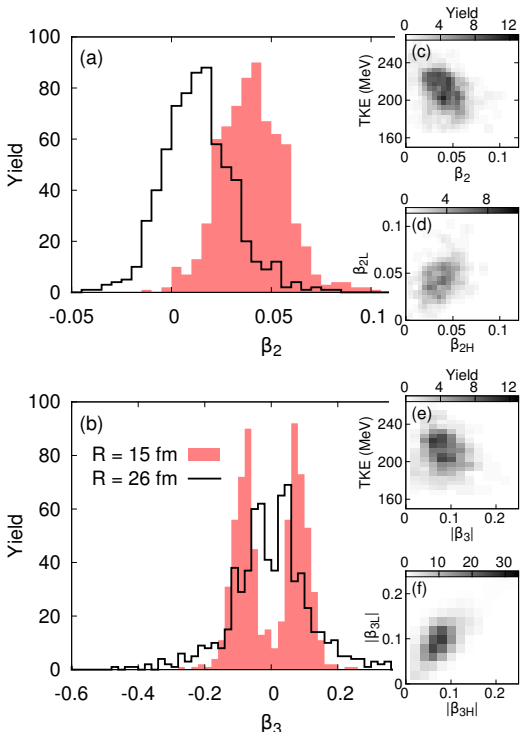
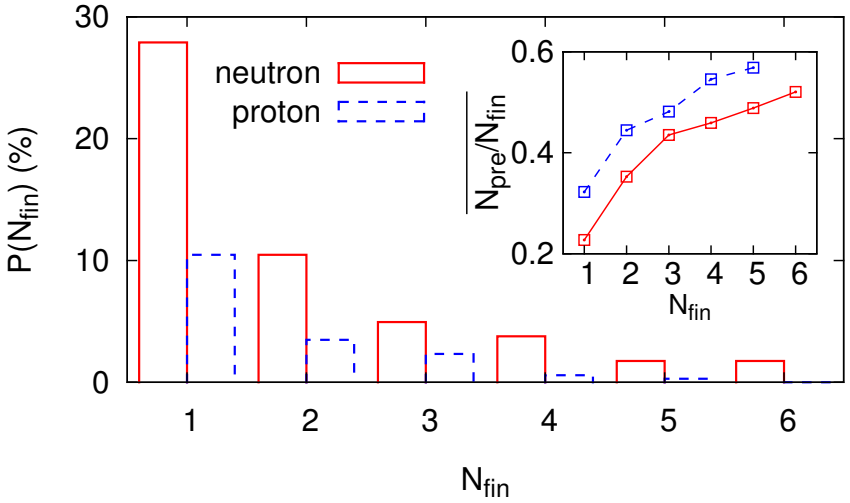


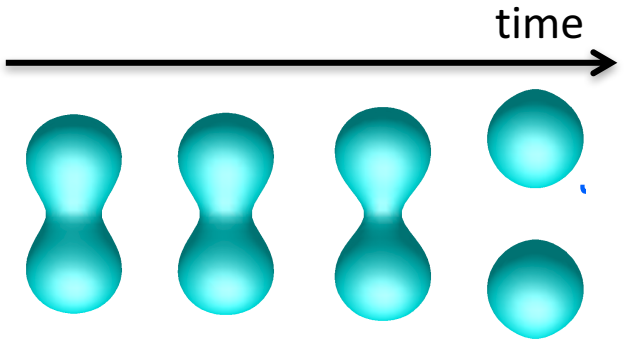
Internal deformation of fission fragments



Precission neutron emission

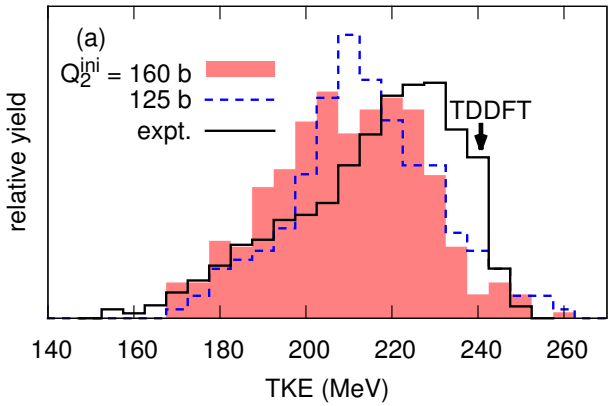


- TDDFT codes including pairing are now developed
- This open new applications perspectives



Applications to fission

- Fission of superfluid nuclei
- Collective mass and dissipation
- Fission time-scale



Beyond mean-field with quantum fluctuations

- First application with sampling of initial phase-space in TD-EDF
- TKE and mass distribution of 258Fm
- Towards a systematic study of spontaneous and induced fission