Recent progress in the microscopic description of nuclear reactions

Denis Lacroix

INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

Outline:

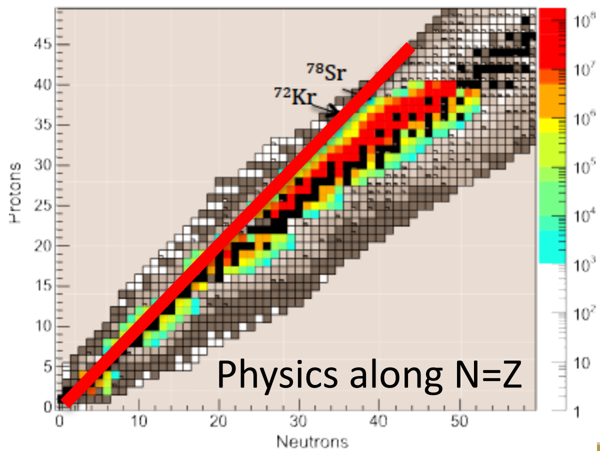
- Generalities on time-dependent approaches with pairing
- Highlights of recent applications
- Application to fission
- Collective aspects of Large Amplitude Collective motion
- Stochastic Mean-Field Theories for Large Amplitude Motion

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

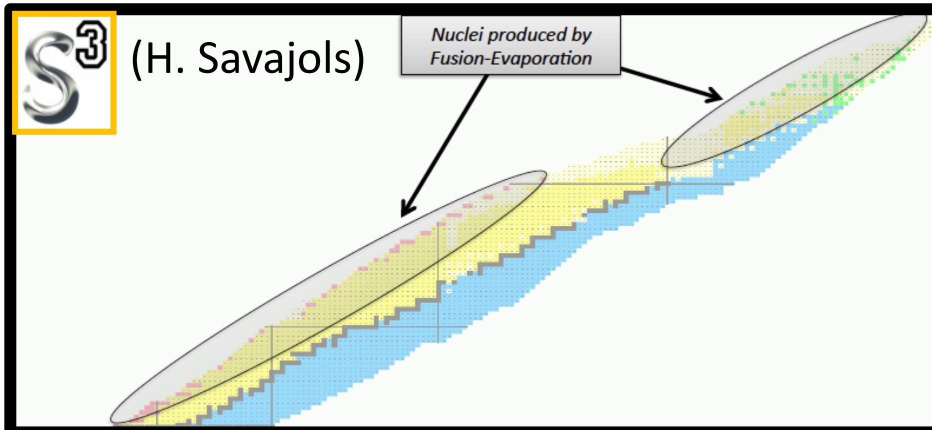
Nuclear Physics (in France) within 10 years

Nuclei at the frontiers

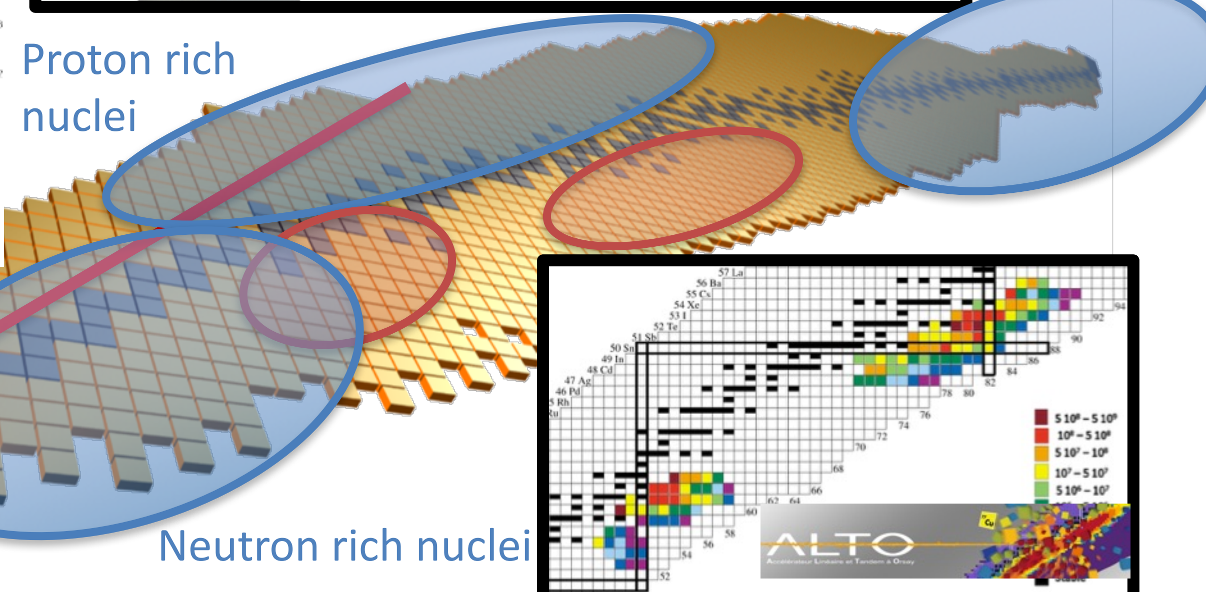
Spiral 1 upgrade (P. Delahaye)

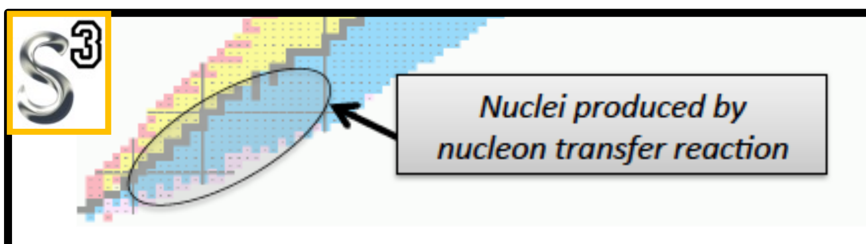


SPIRAL: Expected production from Nb target

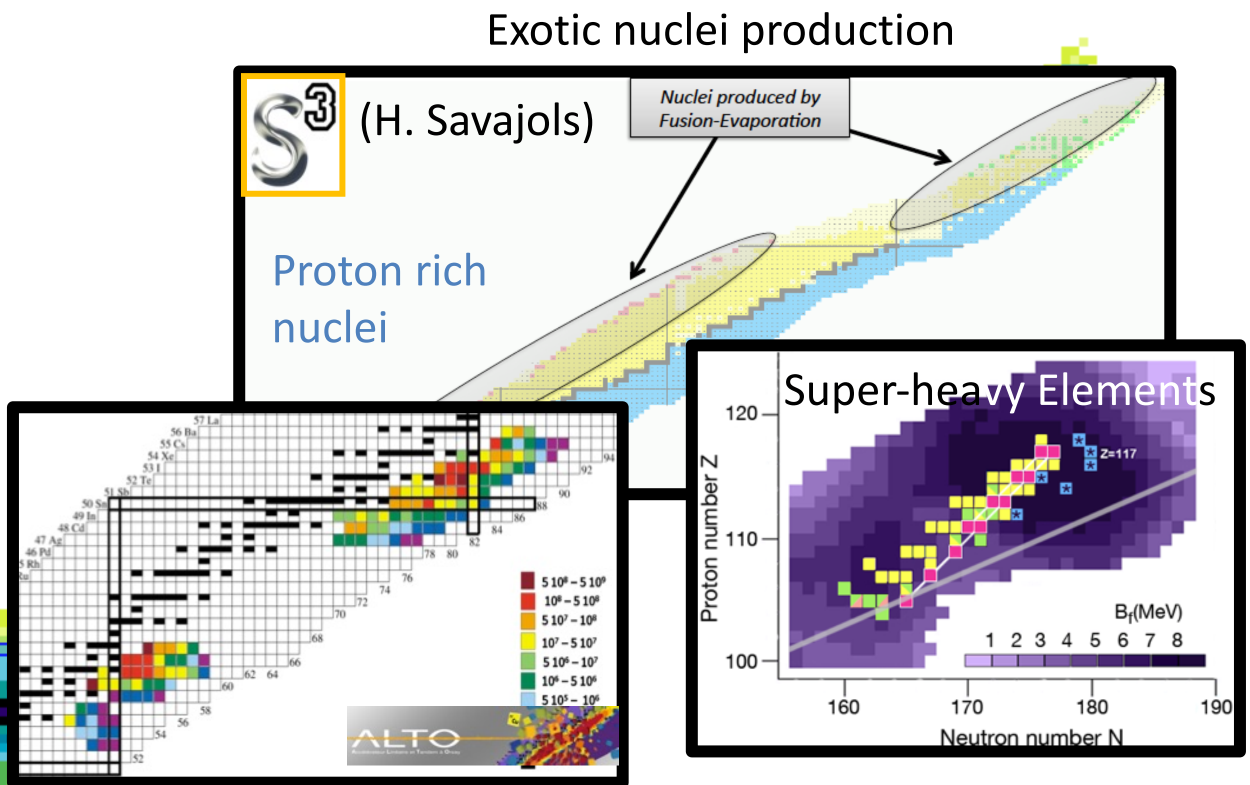


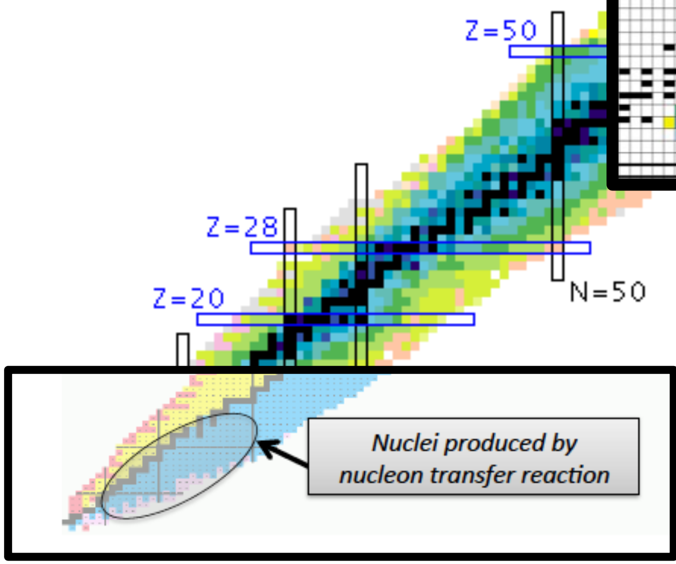
Nuclei at the extreme of mass





Spiral2 EURISOL Spiral2 DESIR ALTO Accélérateur Linéaire et Tandem à Orsay S3





Low energy beam (E/A < 10 MeV)

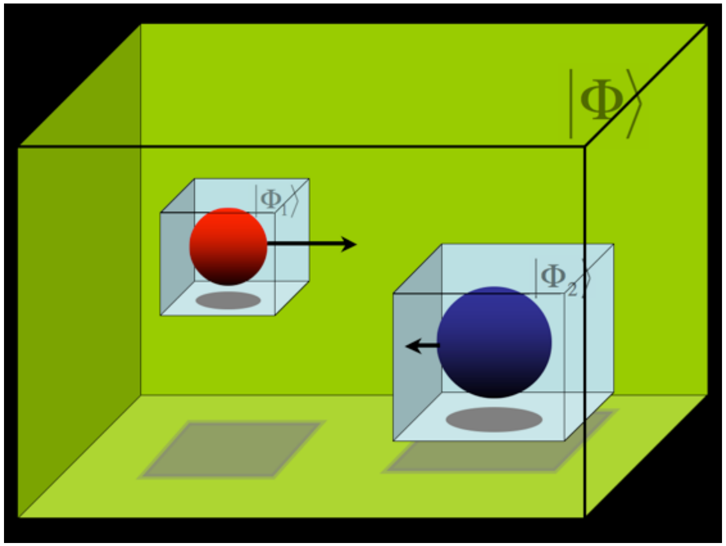
Competition between transfer reaction, Deep inelastic, fusion, quasi-fission and fission

Some recent theoretical progress

Dynamical description of superfluid nuclei

Recent progress

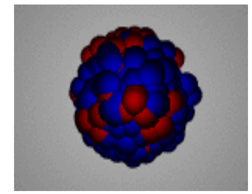
Nuclear motion of superfluid nuclei on a mesh (here within TDHF+BCS)



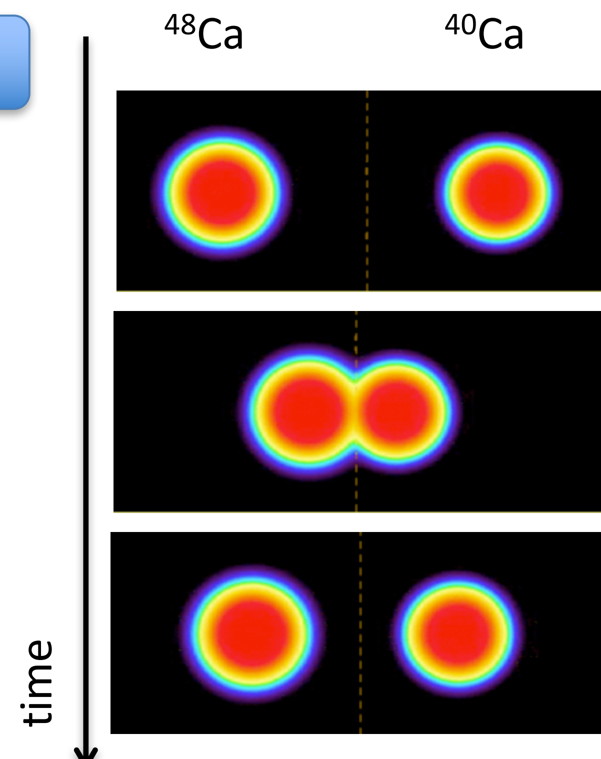
Scamps, Tanimura, Lacroix (2012-2017)

Applied to a number of physical process

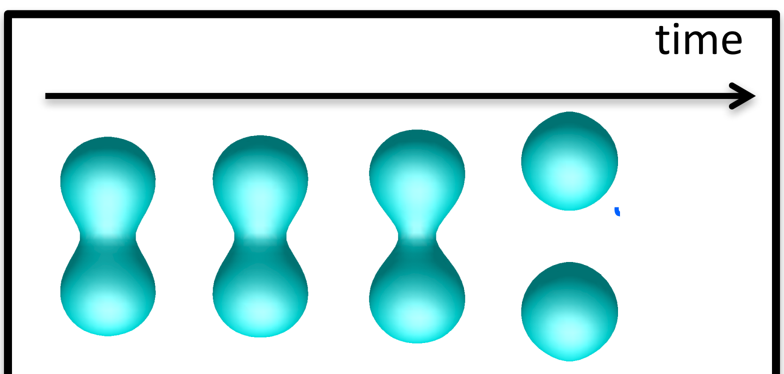
Vibrations



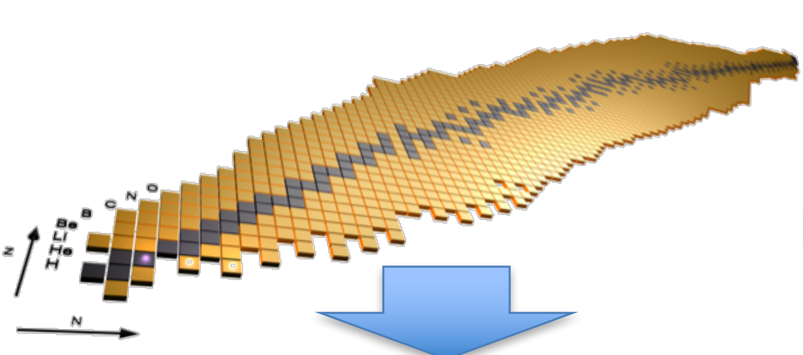
Fusion/Transfert

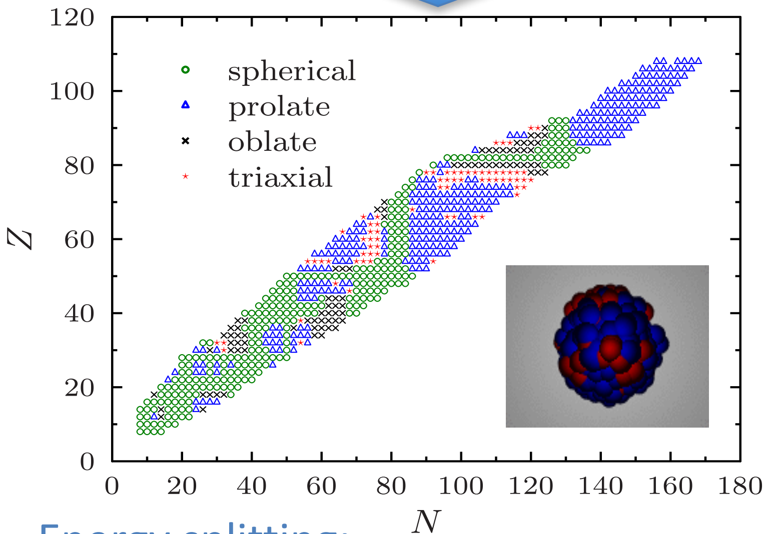


Fission



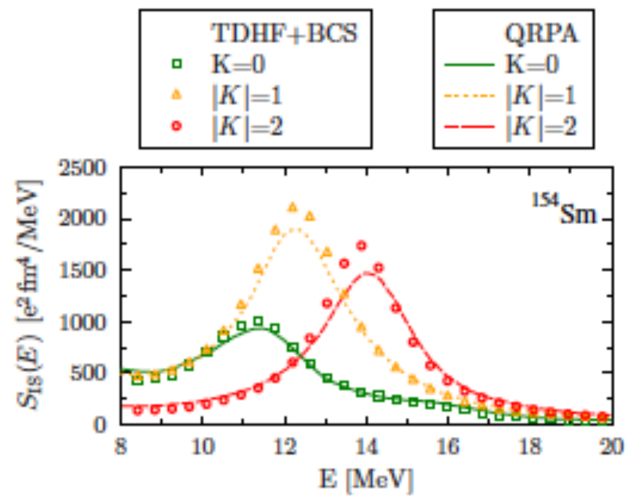
Large scale study of giant quadrupole resonances



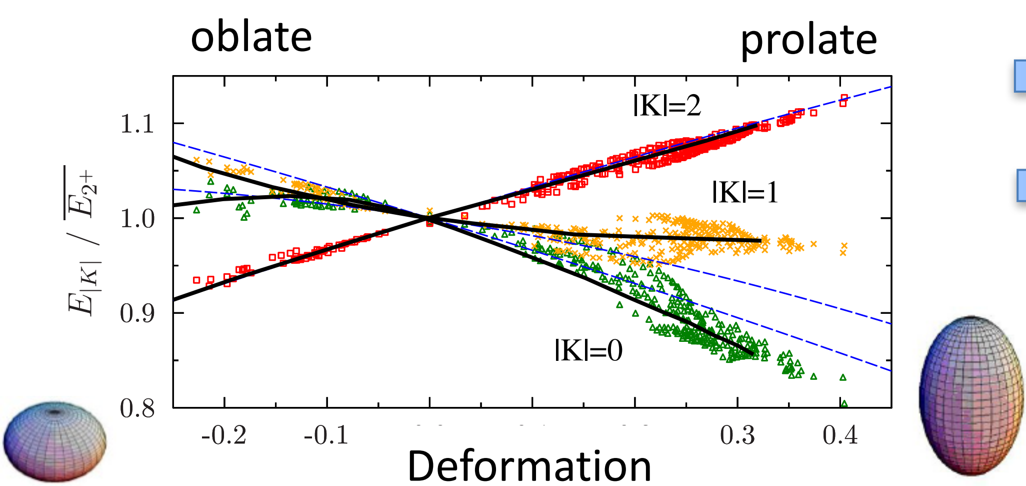


- Systematic study of isoscalar and isovector GQR in
  - (I) Spherical
  - (II) Axially deformed nuclei
  - (III) Triaxial nuclei

Example



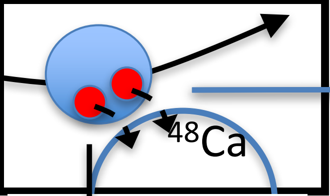
Energy splitting:



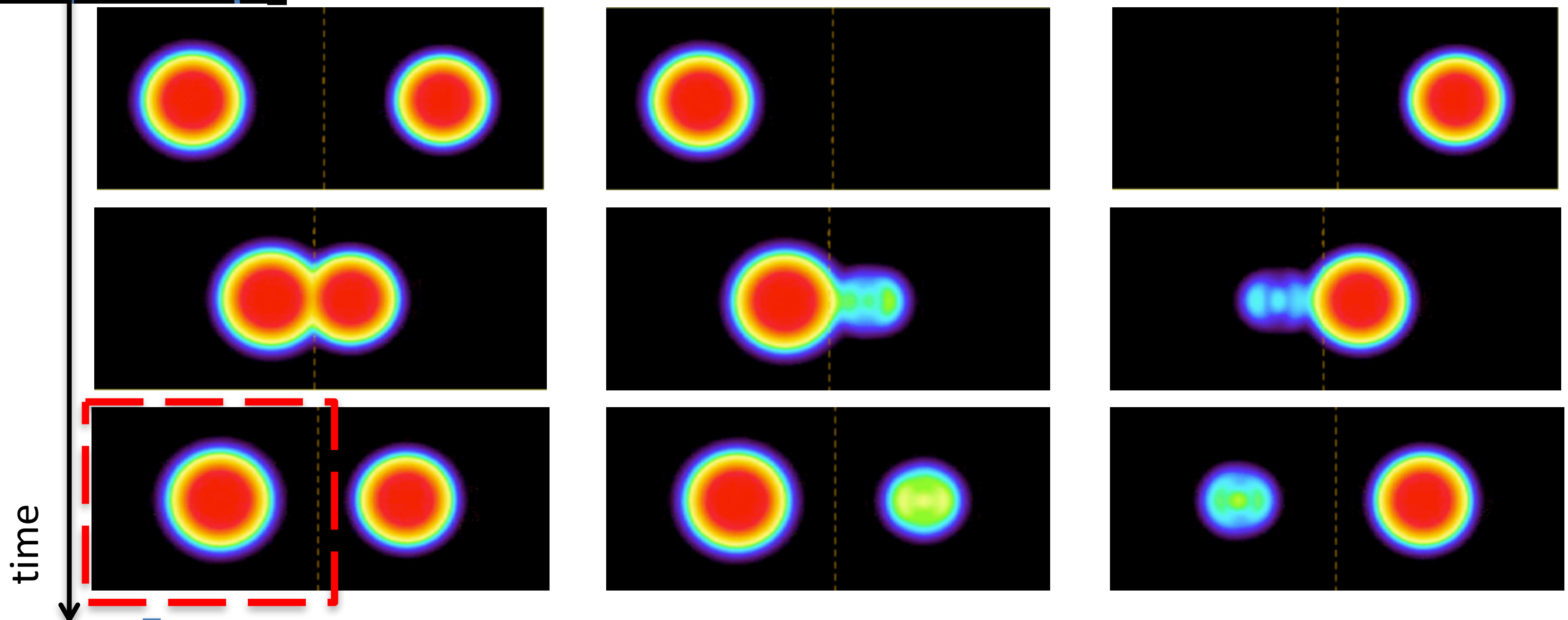
- Good reproduction of average energy
- Damping (fluctuations) is still Severely estimated but improves In deformed nuclei

Scamps, Lacroix, PRC88 (2013)
Scamps, Lacroix, PRC89 (2014)

Transfer reaction below the Coulomb barrier

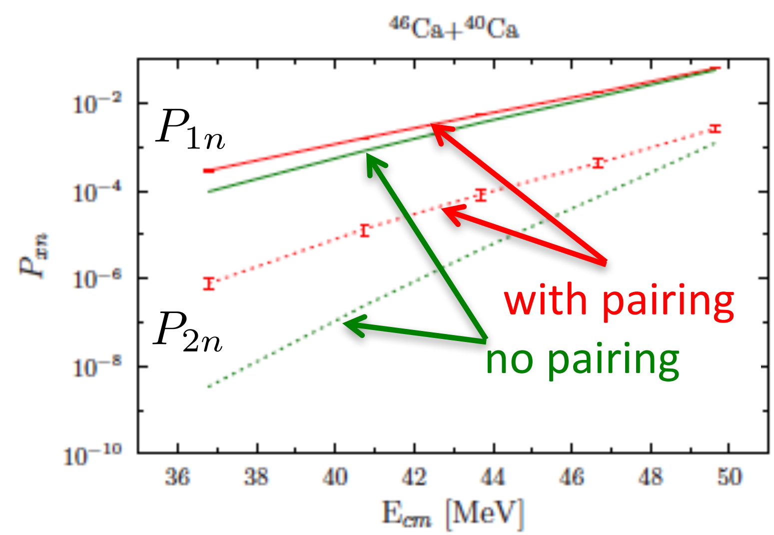


^{48}Ca ^{40}Ca ^{48}Ca ^{40}Ca



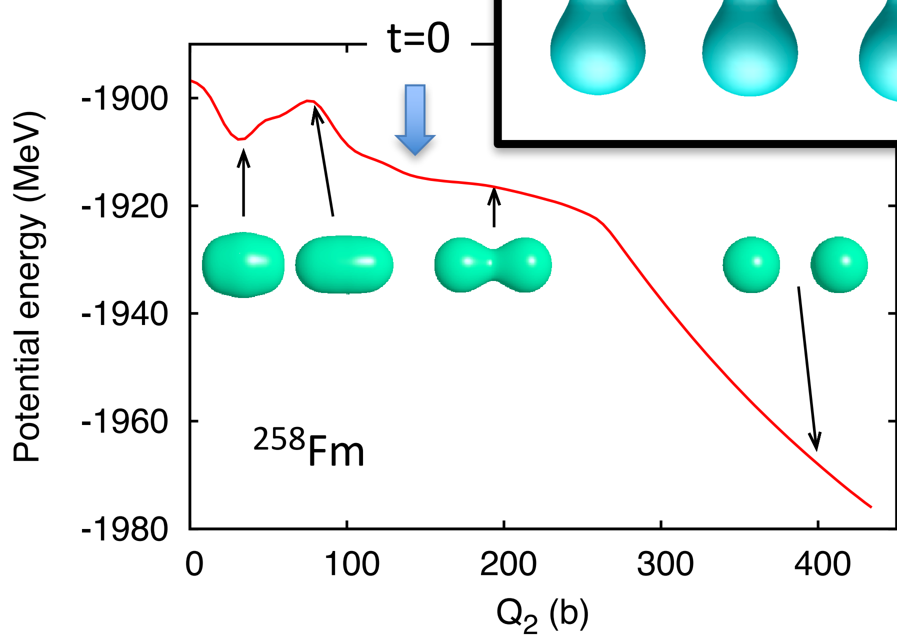
Extract one, two, … nucleons transfer probabilities $P_{1n},\ P_{2n},\ldots$

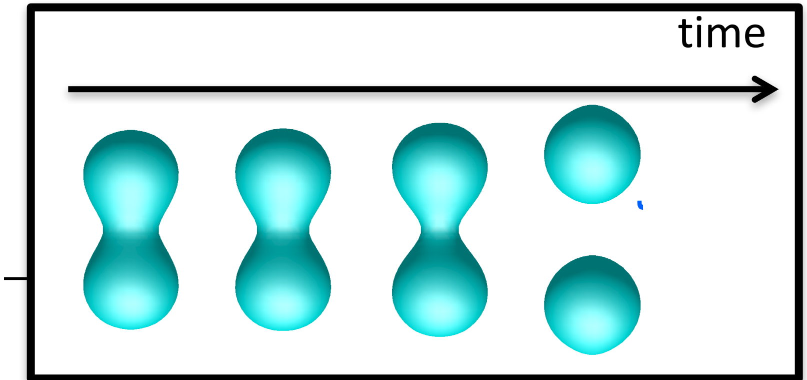
Scamps, Lacroix, PRC 87 (2013).

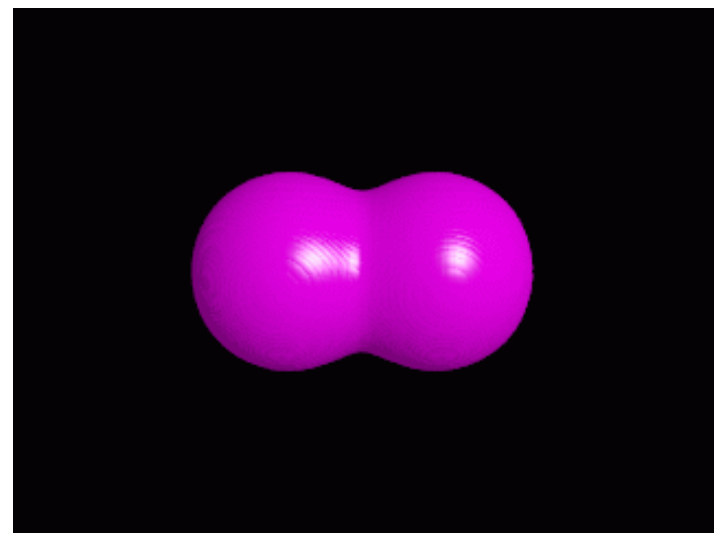


Fission with TD-EDF with pairing

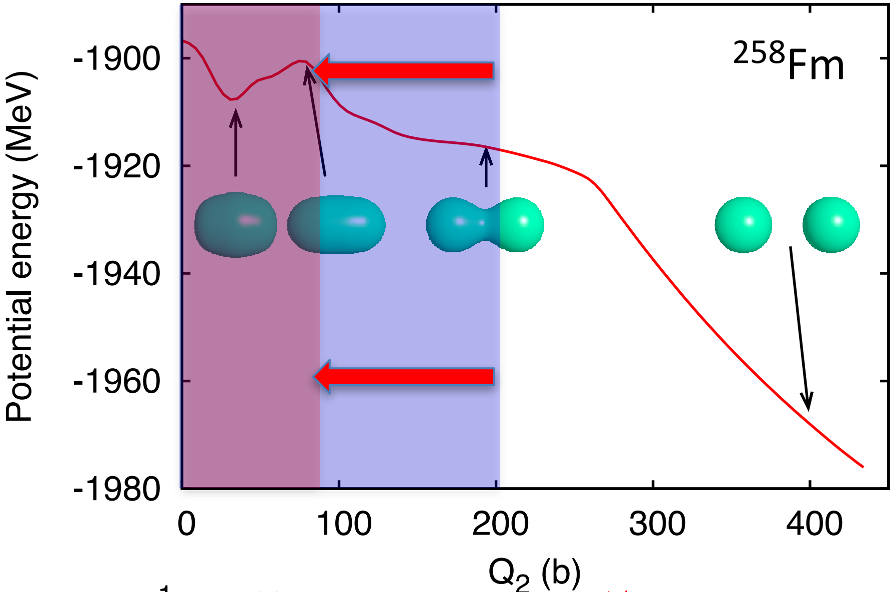
From static EDF

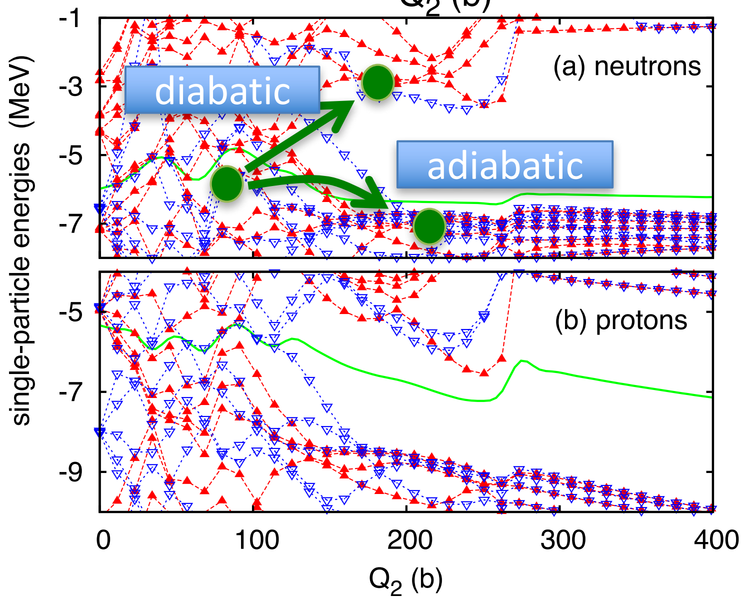






(courtesy Y. Tanimura)





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

Fission with TD-EDF without pairing

→ Threshold anomaly

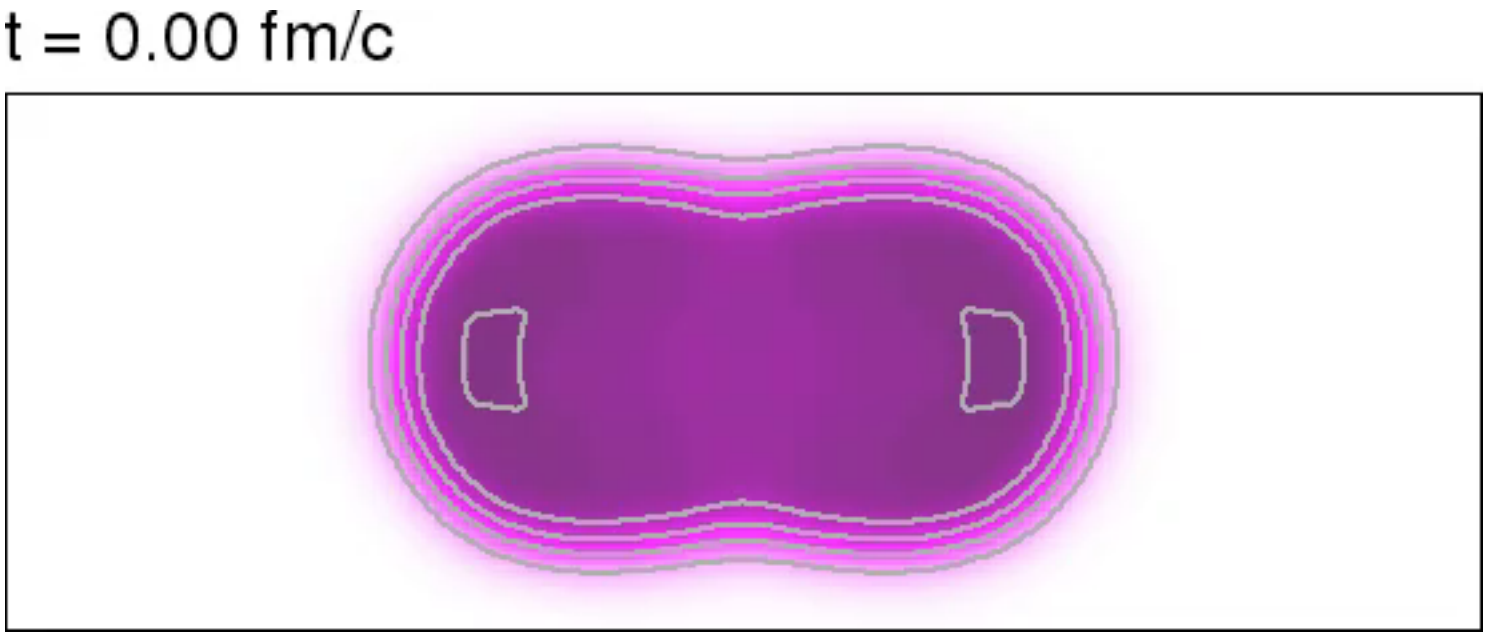
Simenel, Umar, PRC C89 (2014).
Goddard, Stevenson, Rios, PRC 92 (2015), 93 (2016)

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

→ Dynamical pairing is important

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

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)

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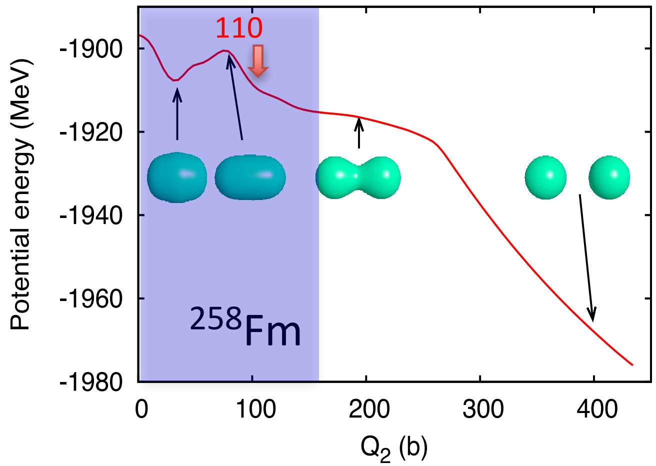


Fast fission

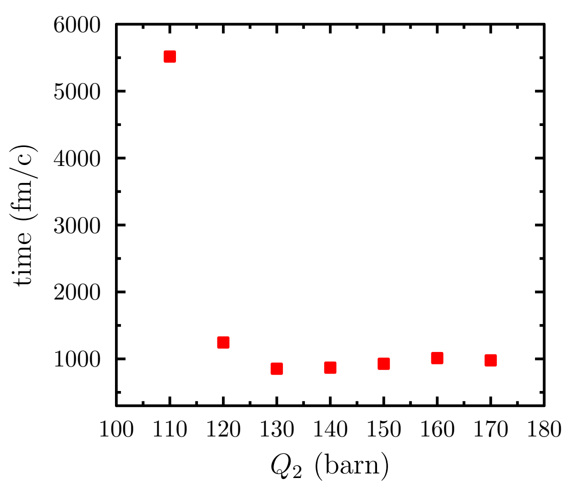
Time (fm/c)

1000 2000 3000 4000 5000 5300 5500 5600

Extremely slow pairing/dissipation dominated motion

Coulomb boost

Fission time with TDHF+BCS



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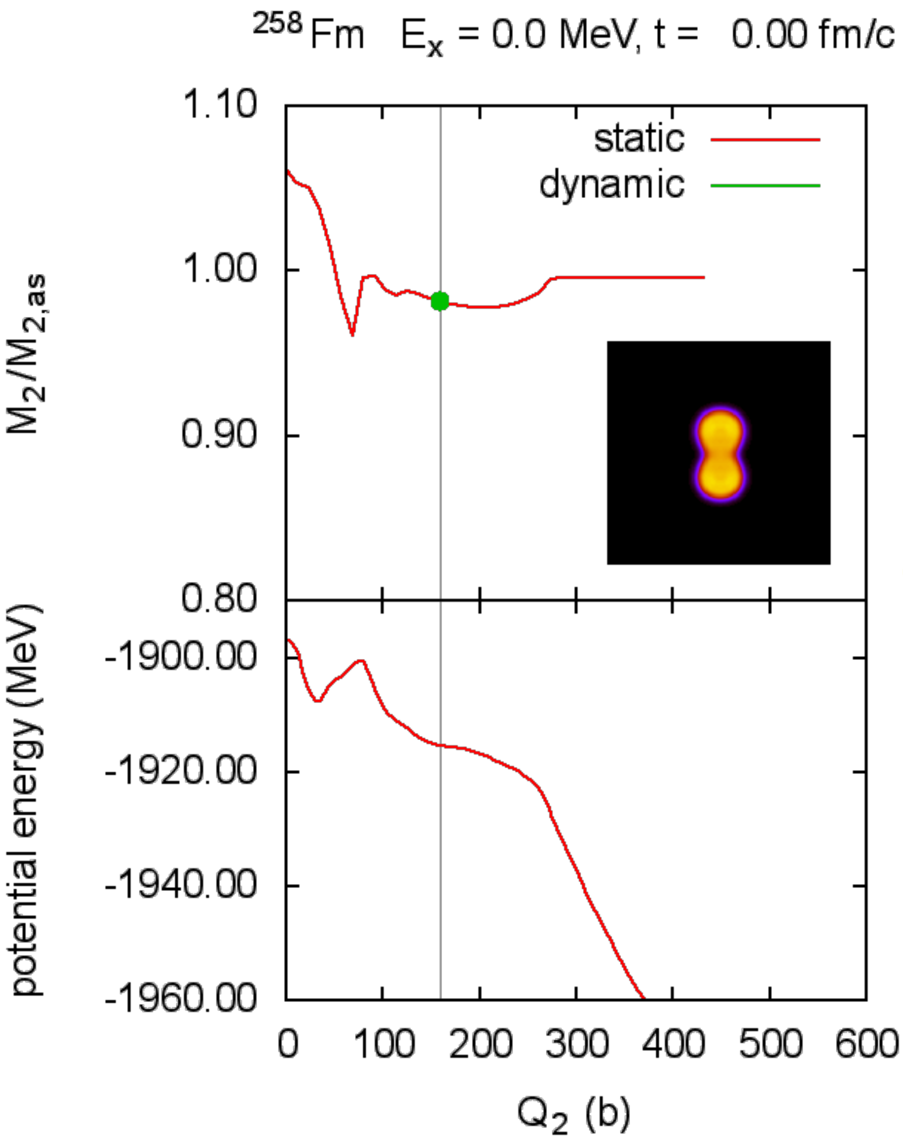
Tanimura, Lacroix, Scamps, PRC 92 (2015)



Microscopic dynamic

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

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

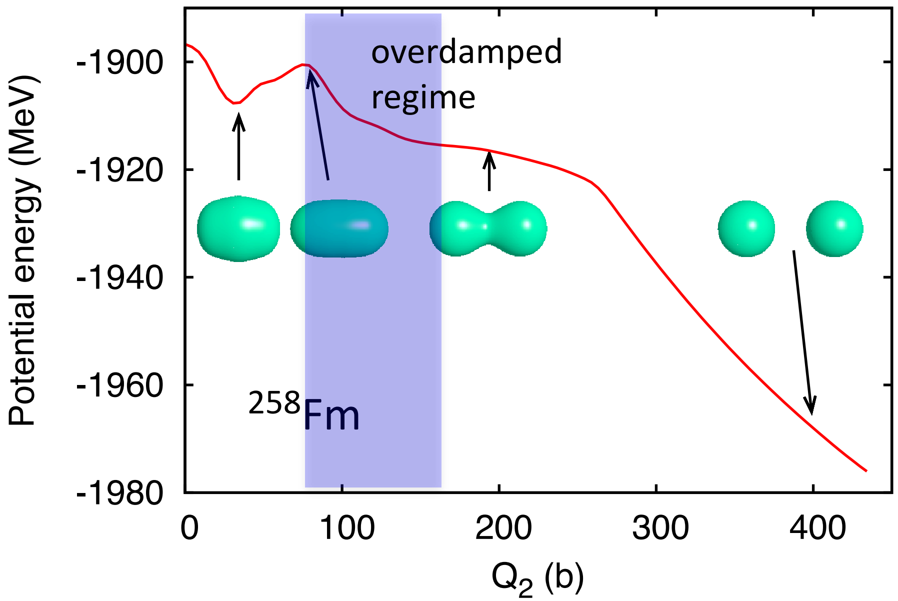
$$\langle[\hat{Q}_\alpha, \hat{P}_\alpha]\rangle = i\hbar, \Rightarrow \frac{1}{M_\alpha(t)} = \frac{1}{m}\mathrm{Tr}[\rho(t)\nabla Q_\alpha \cdot \nabla Q_\alpha],$$

Macroscopic evolution:
Dissipation, non-adiabatic effects…

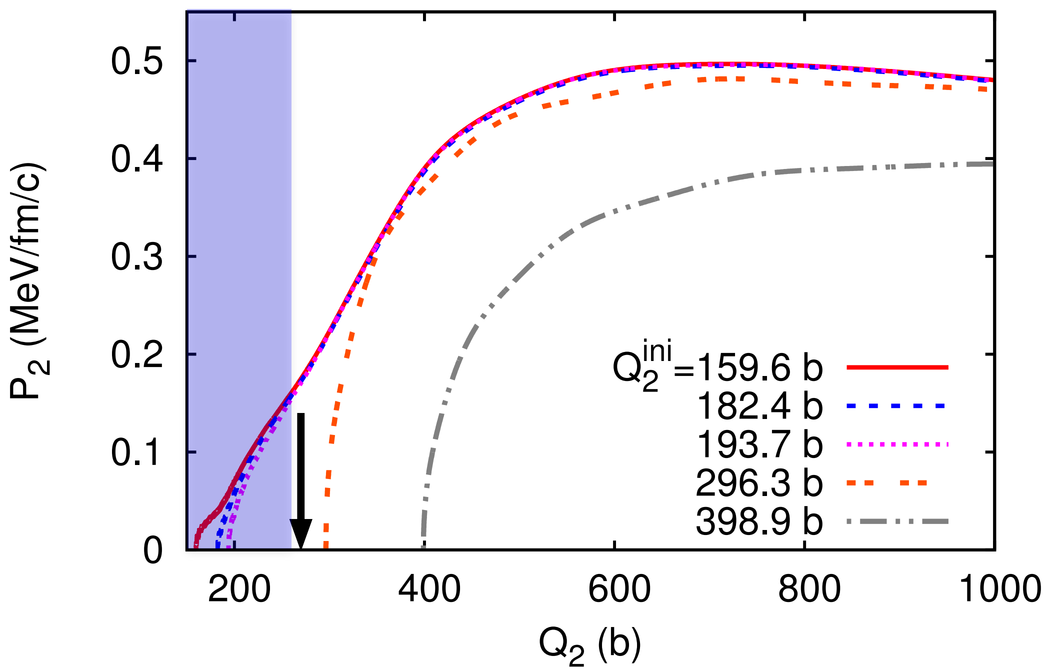
- The system first follows the adiabatic limit
- Around scission, dynamic is faster and Becomes non-adiabatic

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

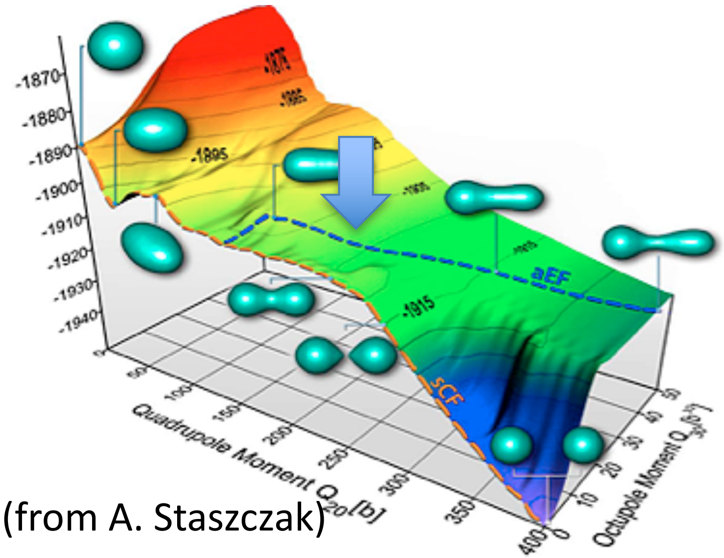
Dissipative regime in TDDFT



Collective momentum evolution



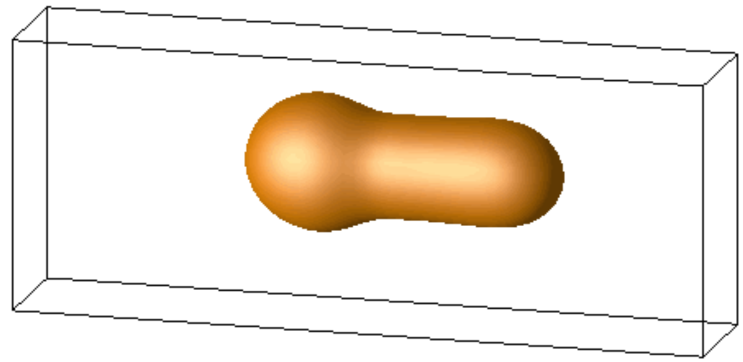
- More or less we confirm the overdamped regime before scission
- Still open : Precise values of dissipative transport coefficients



(from A. Staszczak)

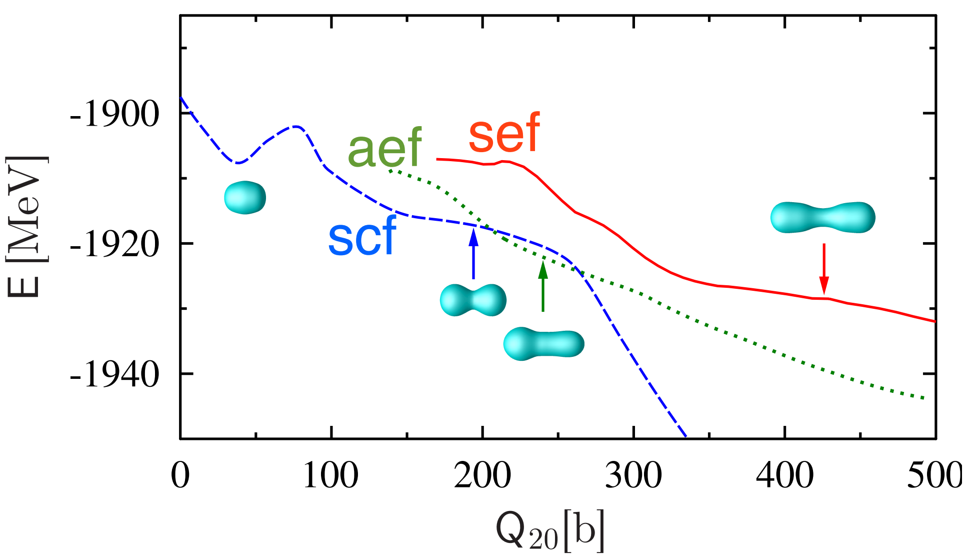
Time-dependent picture of fission

Scamps, Simenel, Lacroix, PRC92 (2015)



(courtesy G. Scamps/C. Simenel)

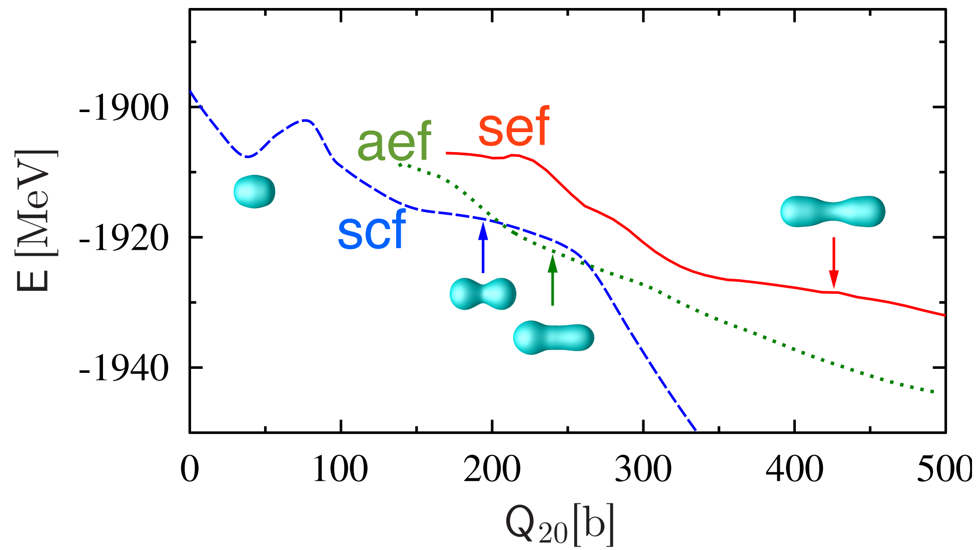
Fission along different paths



scf: symmetric compact fission

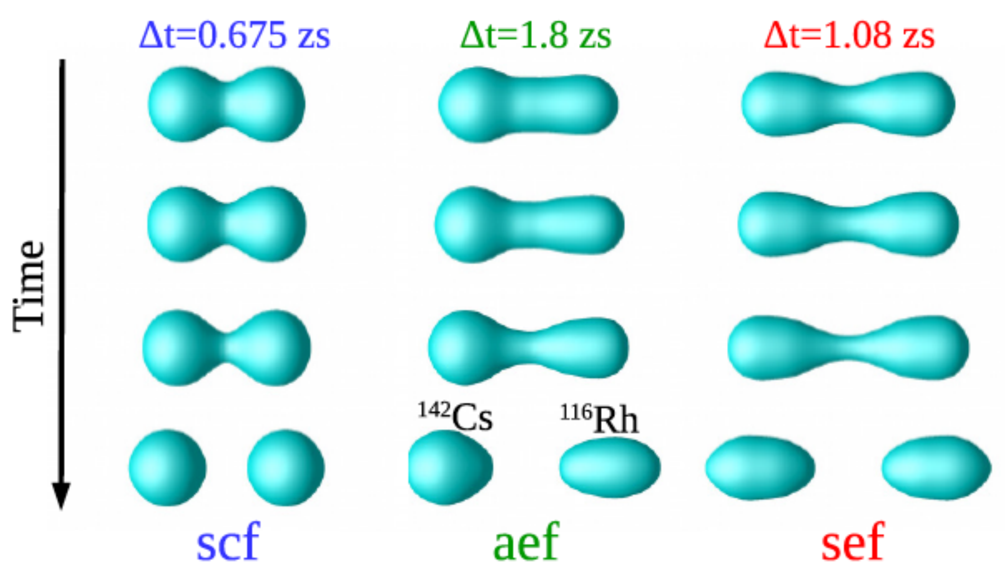
sef: symmetric elongated fission

aef: asymmetric elongated fission

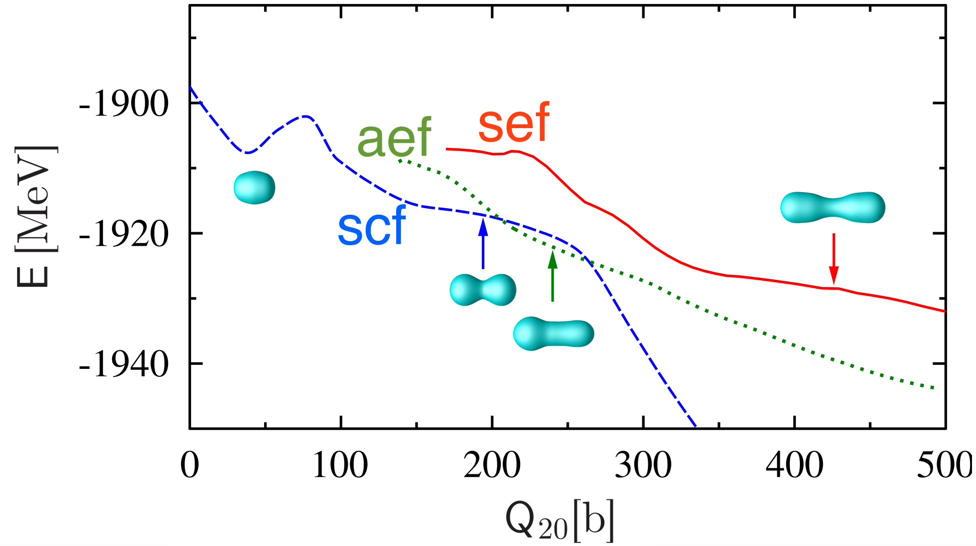


Time-scale

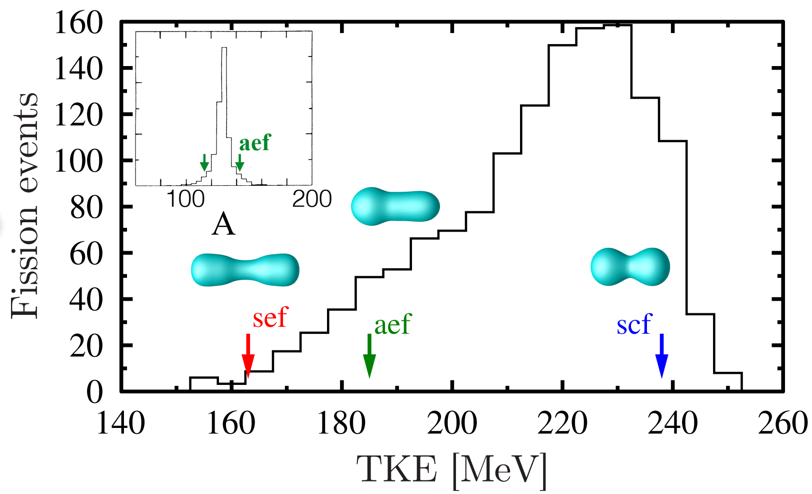
1 zs = 10^{-21} s



Fission of superfluid ^{258}Fm



Total Kinetic Energy



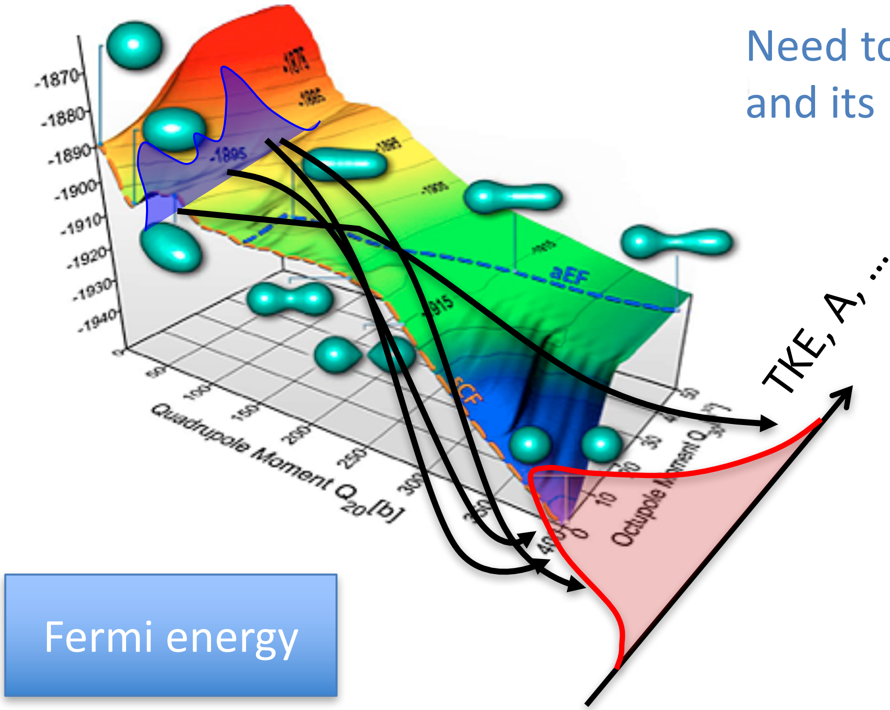
Scamps, Simenel, Lacroix, PRC 92 (2015)

Some conclusions

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

Remaining problem

- Fluctuations are underestimated
- Weight of each paths?



Need to describe configuration mixing and its propagation

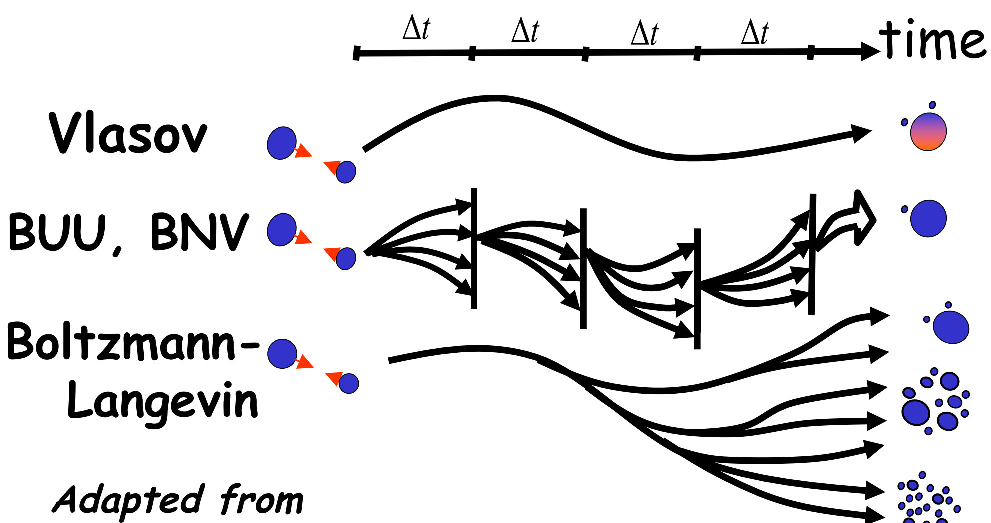
One possibility is to use Time-Dependent Generator Coordinate method (beyond adiabatic, number of DOFs, …)

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

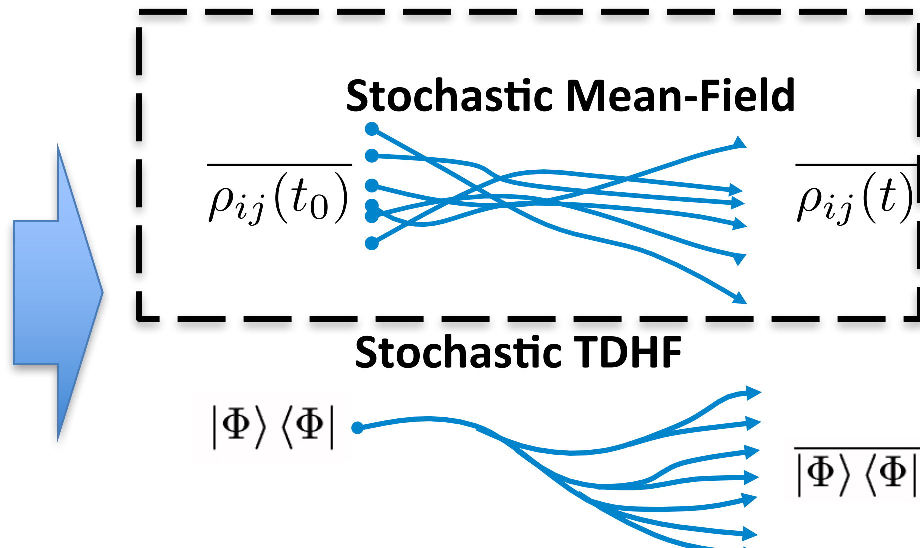
Lacroix, Ayik, EPJA (Review) 50 (2014)

Fermi energy

Coulomb barrier energy

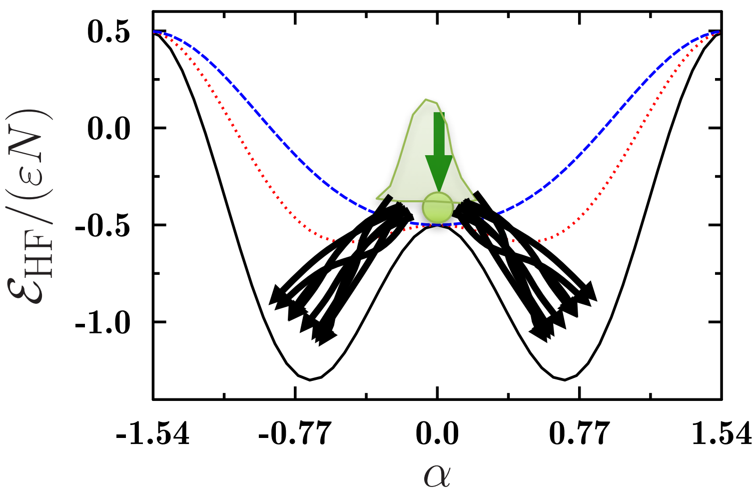


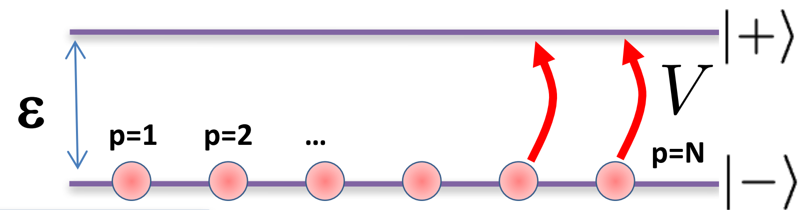
Adapted from J. Randrup et al, NPA538 (92).



Two-Level Lipkin Model

N=40 particles





$$\chi = V/\varepsilon$$

Progress

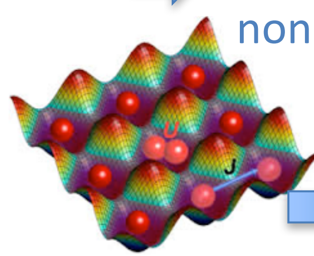
- Extension to superfluid systems: TDHFB with fluctuations

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).

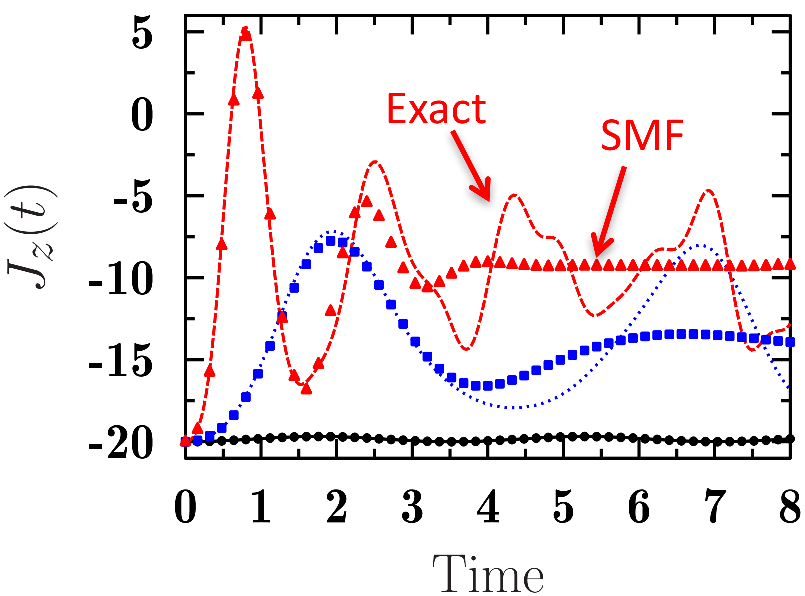
- Application to optical lattice: better than non-equilibrium 2-body green functions



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

- Equivalent to simplified un-truncated BBGKY hierarchy

Lacroix, Tanimura, Ayik, EPJA52 (2016)



Lacroix, Ayik, Yilmaz, PRC 85 (2012)

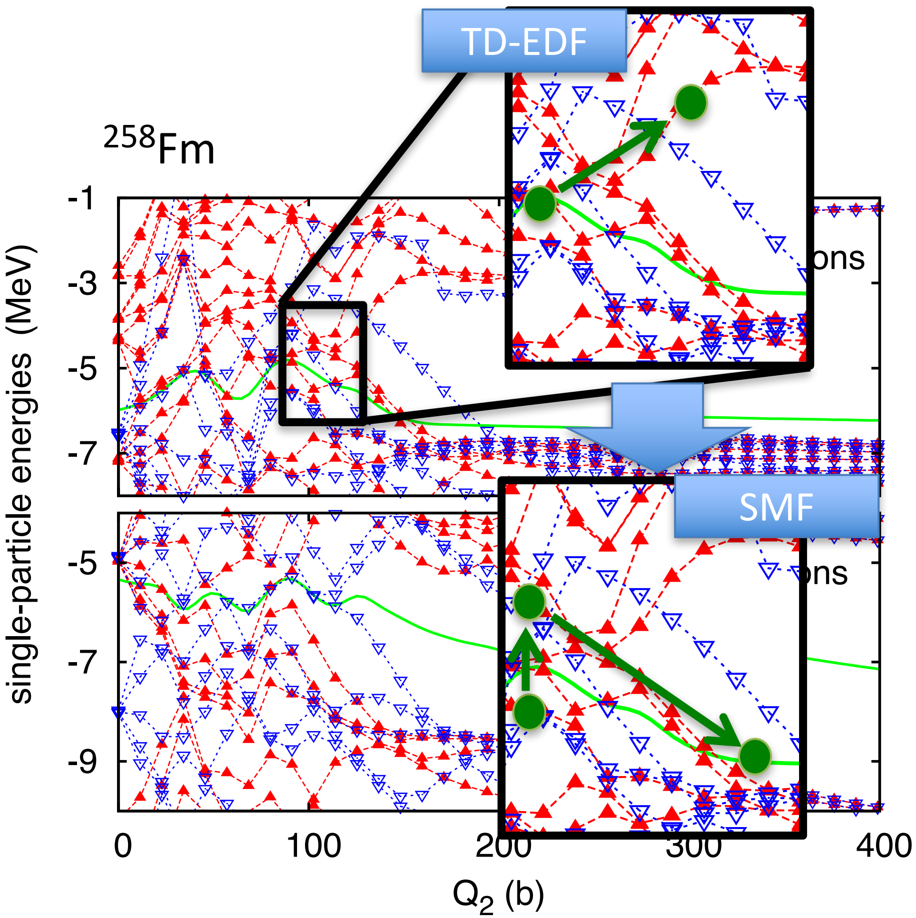
SMF in density matrix space

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

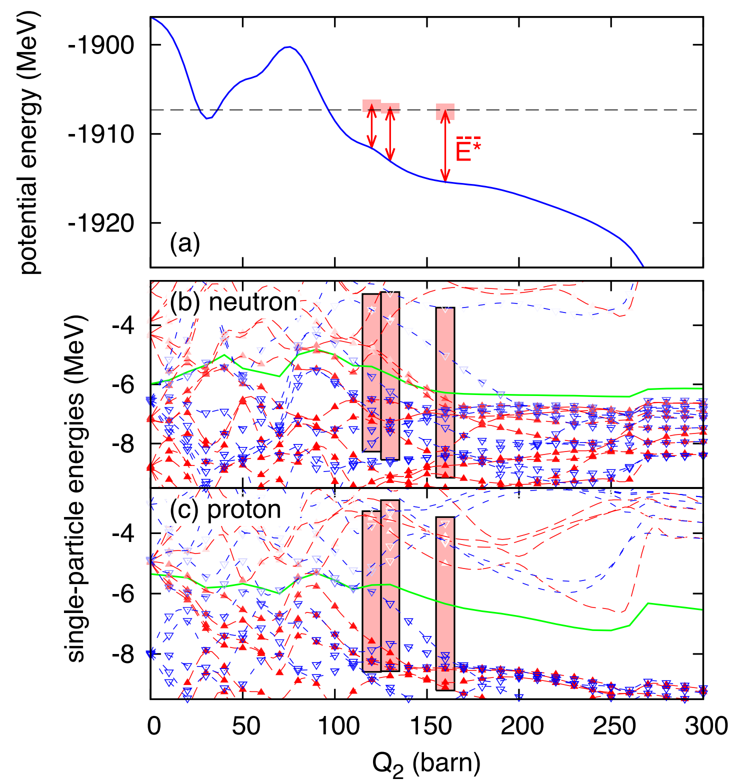
$$\rho^\lambda(\mathbf{r},\mathbf{r}',t_0) = \sum_{ij} \Phi_i^*(\mathbf{r},t_0) \rho_{ij}^\lambda \Phi_j(\mathbf{r}',t_0)$$

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

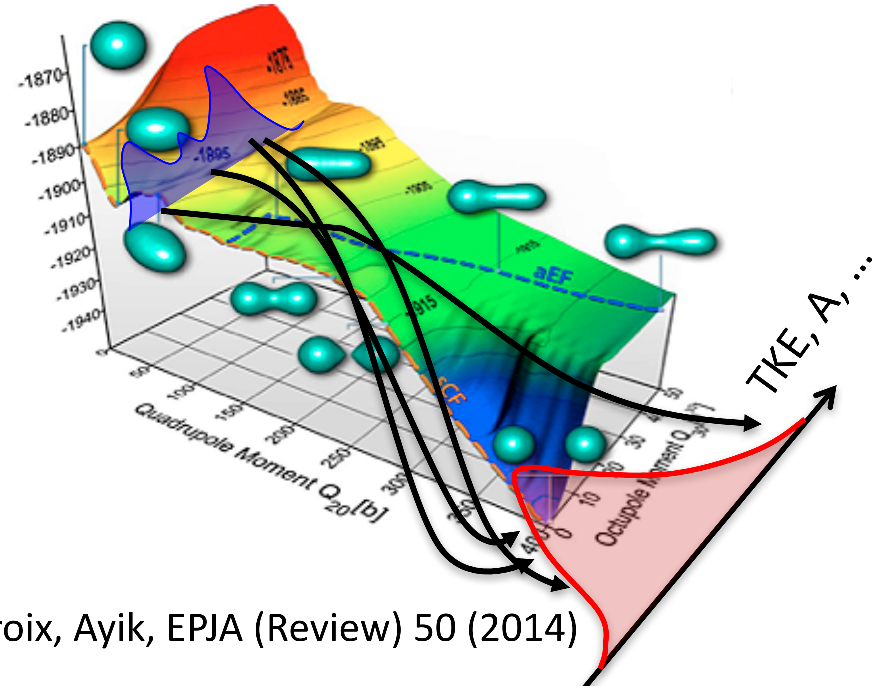
$$\overline{\delta\rho_{ij}^\lambda \delta\rho_{j'i'}^\lambda} = \frac{1}{2}\delta_{jj'}\delta_{ii'}\left[n_i(1-n_j) + n_j(1-n_i)\right].$$



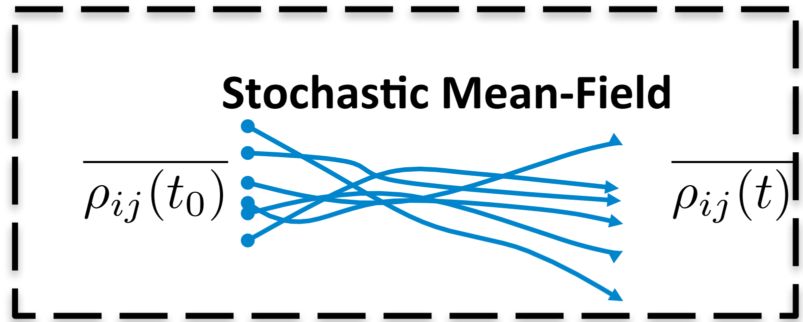
Range of fluctuation fixed by energy cons.



How to conceal microscopic deterministic approach and randomness ?

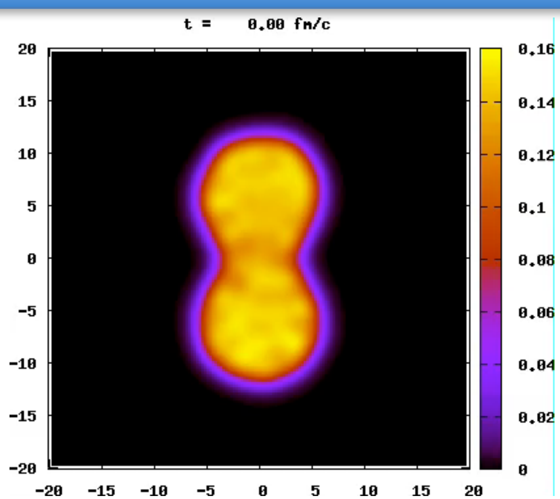


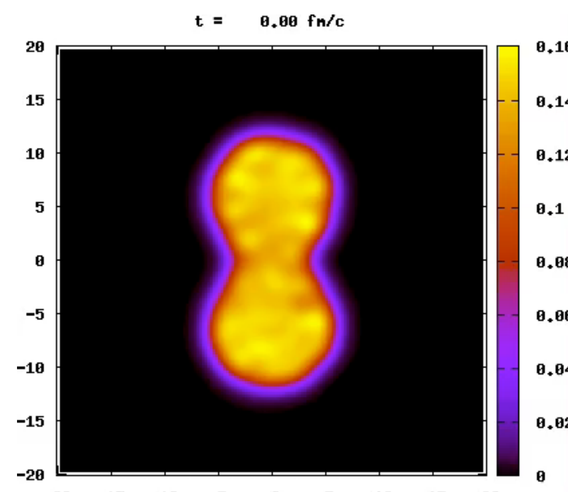
Lacroix, Ayik, EPJA (Review) 50 (2014)



Constrains:
- Generates a sample of microscopic trajectories (typically 300)
- Each trajectory is 8-10 days CPU time

Some trajectories illustration





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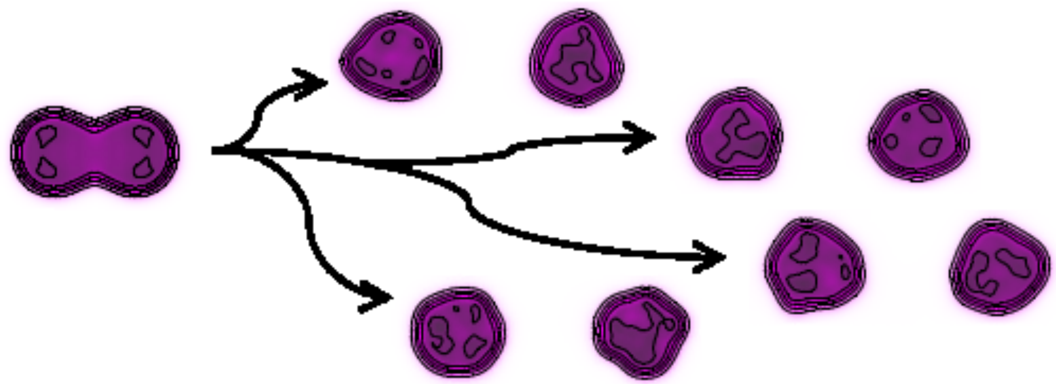
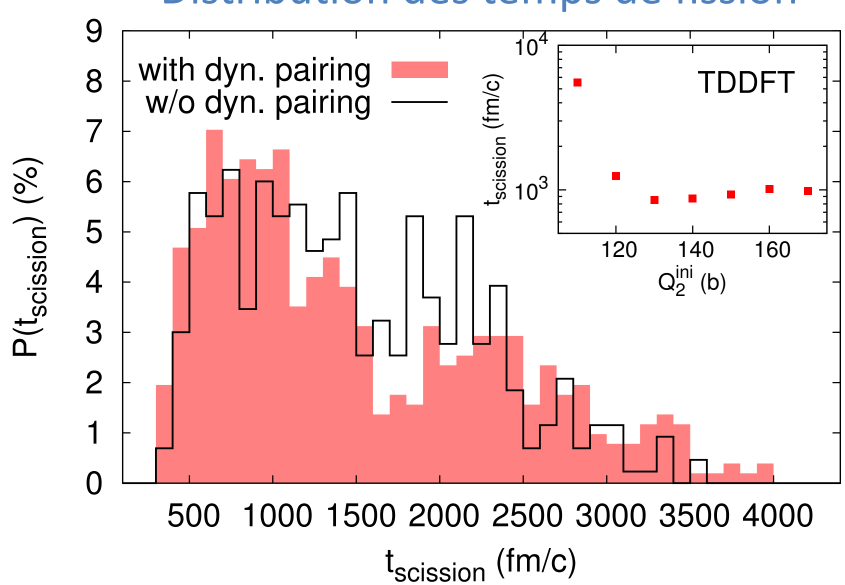


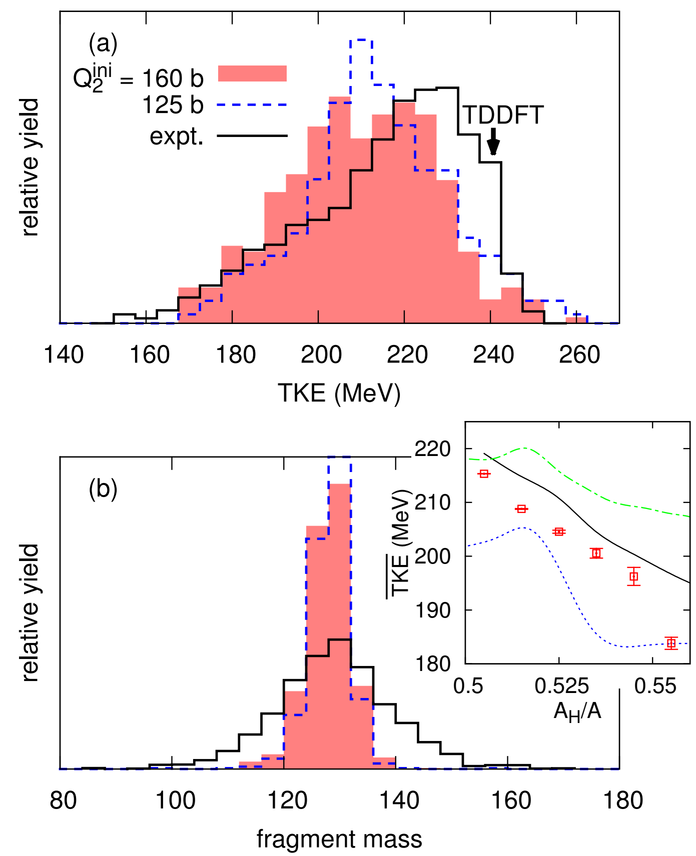
Tanimura, Lacroix, Ayik, PRL in press

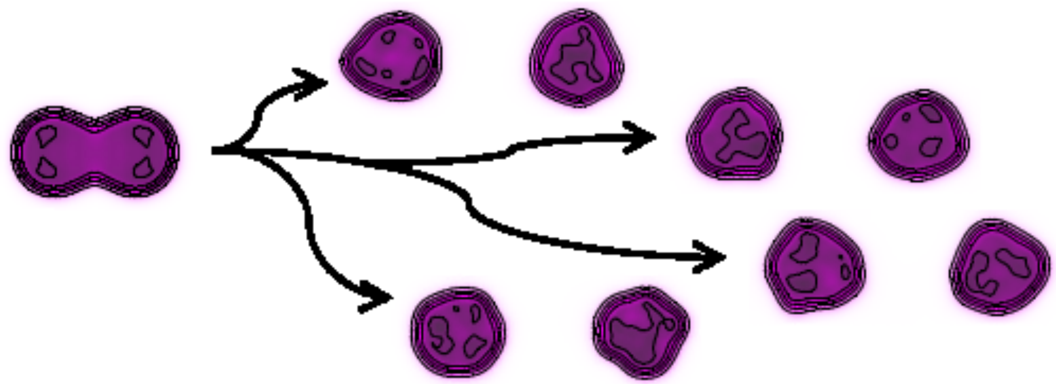
From deterministic to statistical approach

Distribution des temps de fission



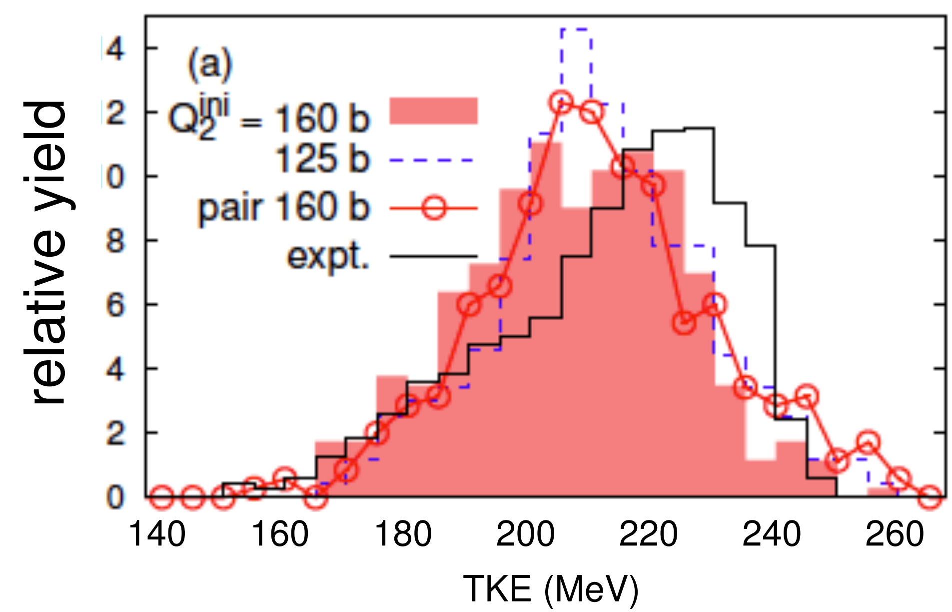
Experience vs Theory



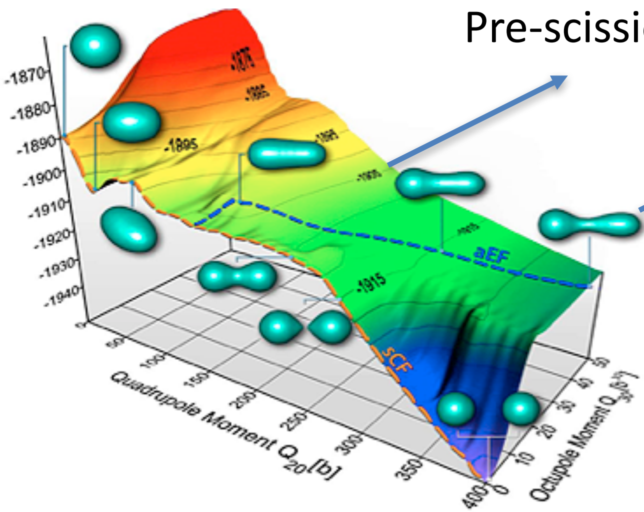


Tanimura, Lacroix, Ayik, PRL, in press

Quantum fluctuation versus dynamical pairing



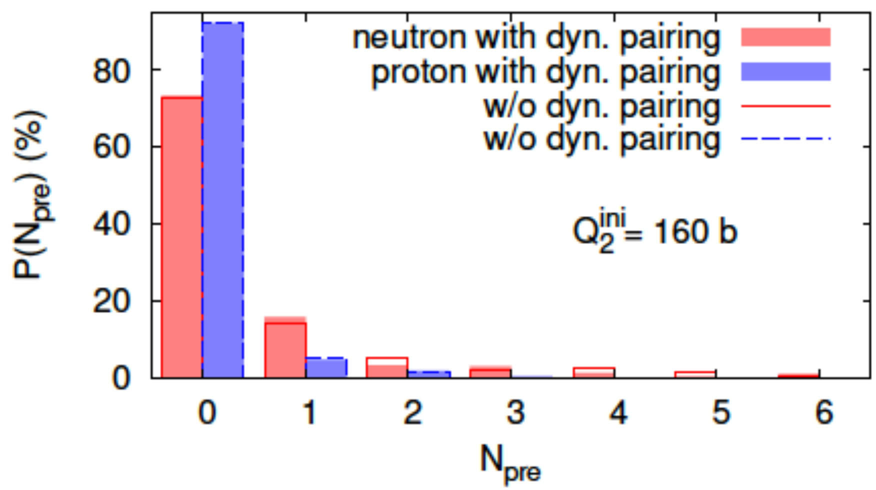
How to conceal microscopic deterministic approach and randomness ?



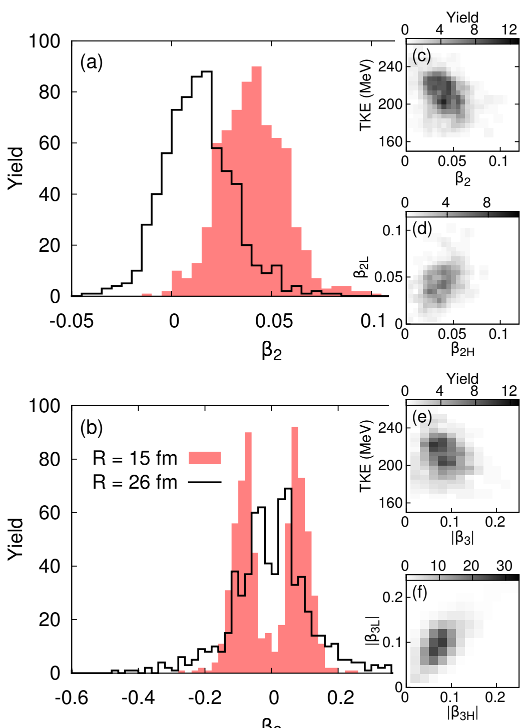
Pre-scission neutron?

Post-scission neutron ?

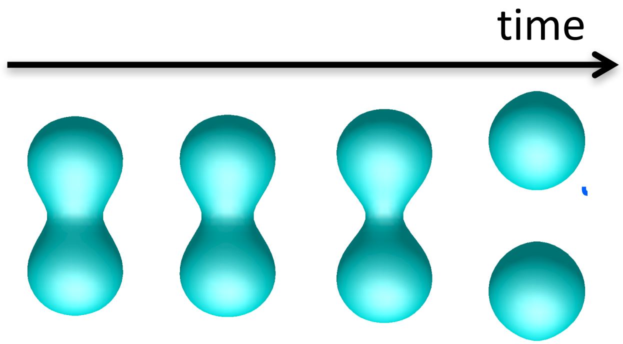
Precission neutron emission



Internal deformation of fission fragments

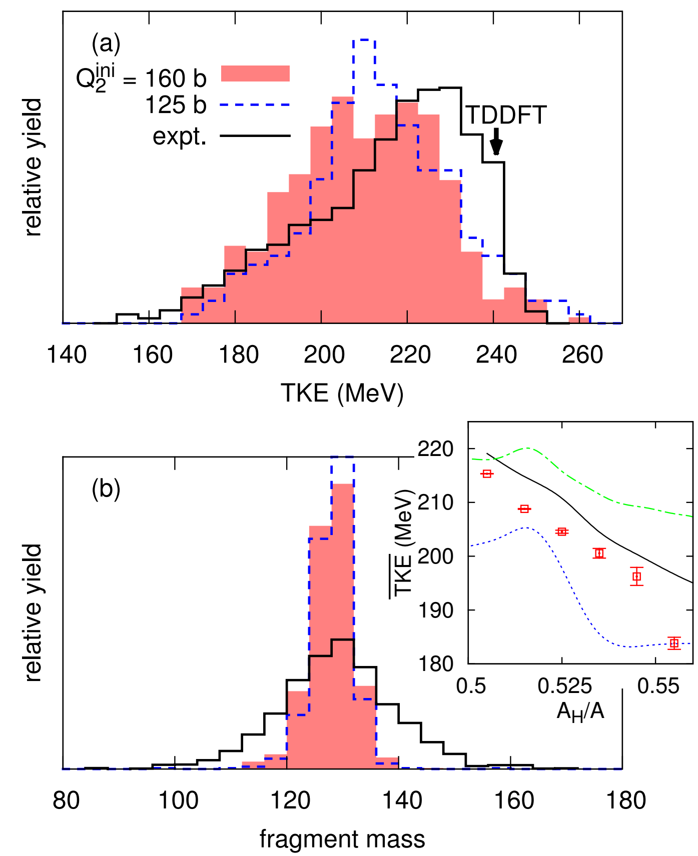


- TDDFT codes including pairing are now developed
- This open new applications perspectives



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