Superfluid effects in nuclear collective motion: applications to fission and other processes

Denis Lacroix

IPN 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

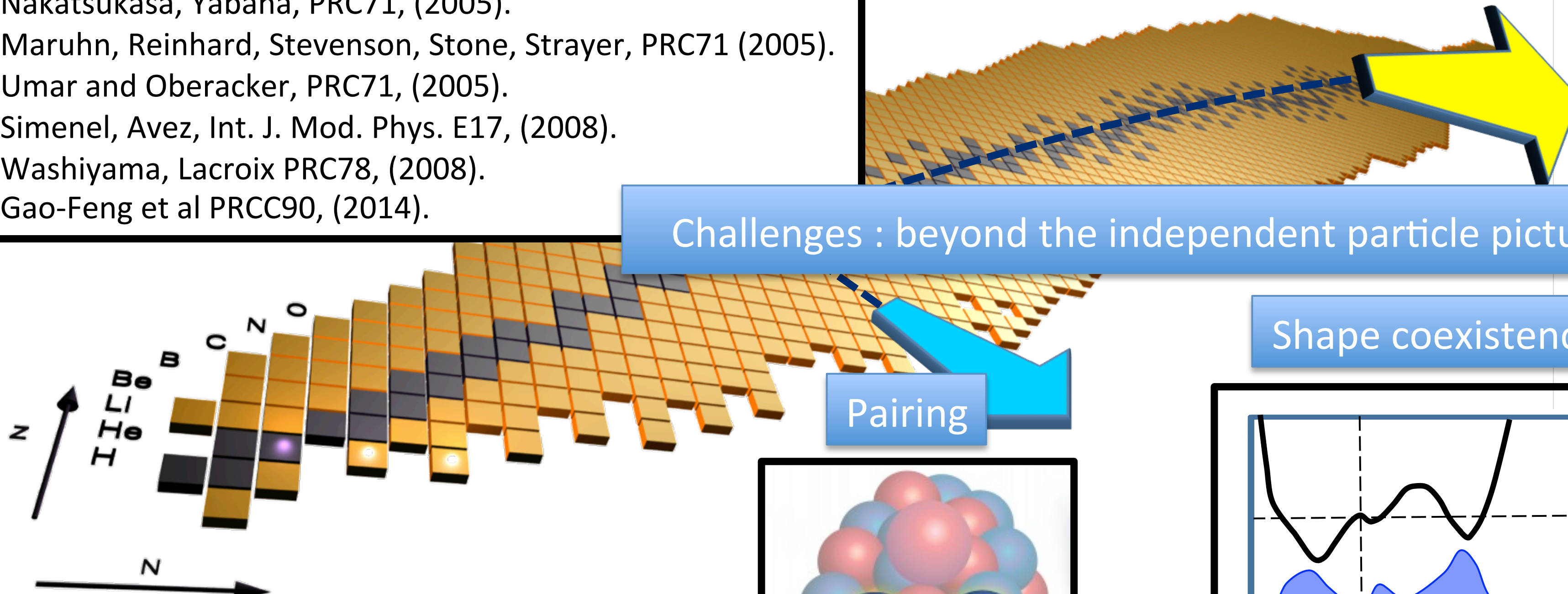
Coll: S. Ayik, B. Yilmaz, C. Simenel,
G. Scamps, Y. Tanimura

Ultimate Goals : give a unified description of nuclear structure and reactions
provide predictive theory in explored and unexplored region of nuclear chart

Status of TD-EDF

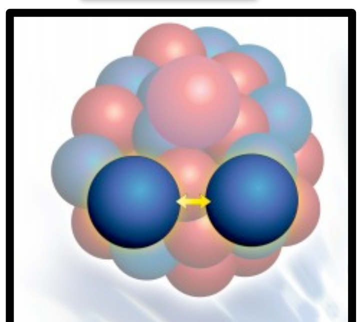
- Symmetry unrestricted simulations
- State of the art functional consistent with nuclear structure

Kim, Otsuka, Bonche, J. Phys.G23, (1997).
Nakatsukasa, Yabana, PRC71, (2005).
Maruhn, Reinhard, Stevenson, Stone, Strayer, PRC71 (2005).
Umar and Oberacker, PRC71, (2005).
Simenel, Avez, Int. J. Mod. Phys. E17, (2008).
Washiyama, Lacroix PRC78, (2008).
Gao-Feng et al PRCC90, (2014).

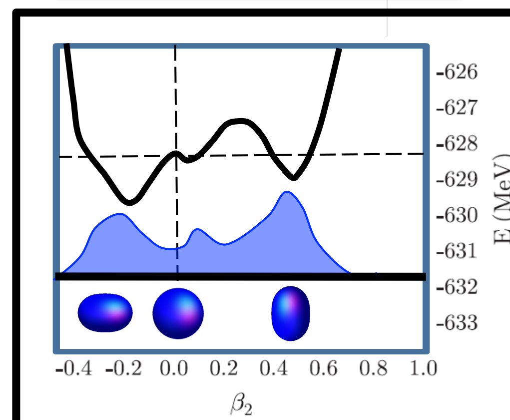


Challenges : beyond the independent particle picture

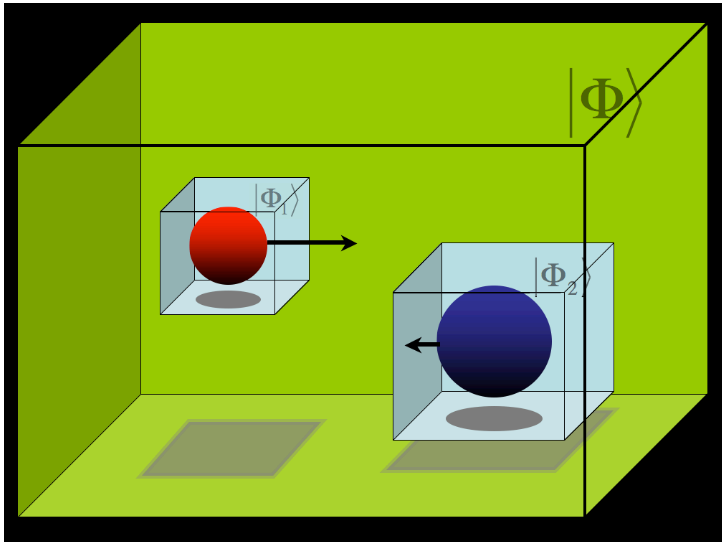
Pairing



Shape coexistence



Nuclear reaction on a mesh



TDHF is a standard tool $|\Phi_i\rangle$: Slater

$$i\hbar\frac{d\rho}{dt} = [h(\rho), \rho]$$

→ Single-particle evolution

Simenel, Lacroix, Avez, arXiv:0806.2714v2

Introduction of pairing: TDHFB

$$i\hbar\frac{d}{dt}\mathcal{R} = [\mathcal{H}(\mathcal{R}), \mathcal{R}] \qquad \mathcal{R} = \begin{pmatrix} \rho & \kappa \\ -\kappa^* & 1-\rho \end{pmatrix}$$

→ Quasi-particle evolution

(Active Groups: France, US, Japan…)

BCS limit of TDHFB (also called Canonical basis TDHFB)

TDHFB = 1000 * (TDHF)

Neglect Δ_{ij}

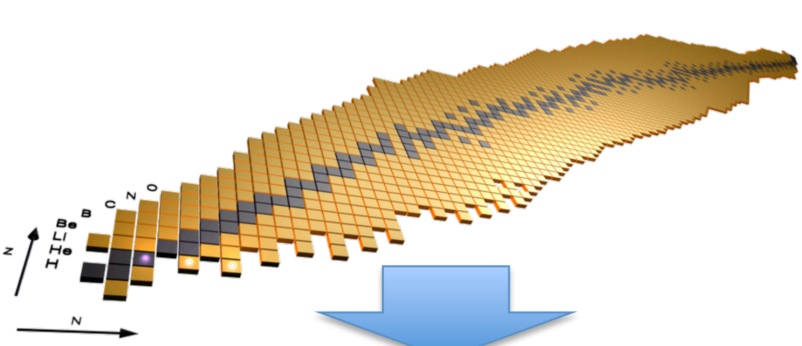
$$|\Phi(t)\rangle = \prod_{k>0}\left(u_k(t) + v_k(t)a_k^\dagger(t)a_{\bar{k}}^\dagger(t)\right)|-\rangle.$$

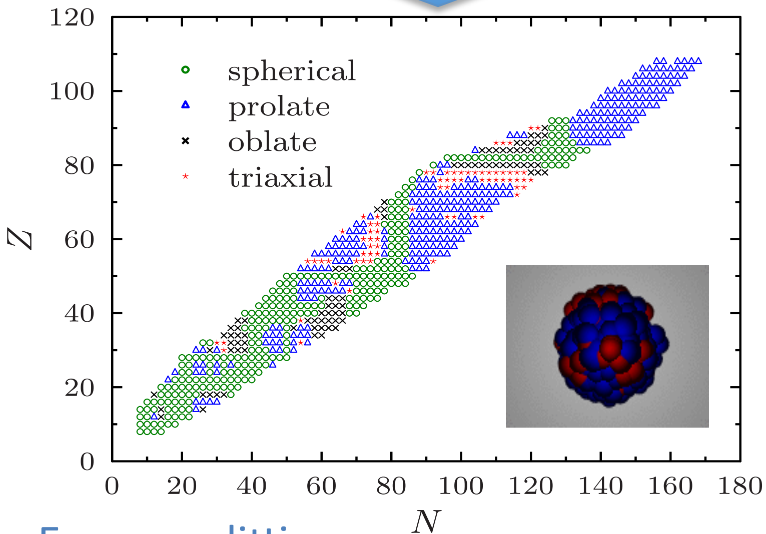
→ TDHFB is very demanding — Stetcu, Bulgac, Magierski, and Roche, PRC 84 (2011); *Hashimoto, Scamps, arXiv:1604.07494 (2016)*

→ Reasonable results for collective motion — Ebata, Nakatsukasa et al, PRC82 (2010)

→ Sometimes more predictive than TDHFB — Scamps, Lacroix, Bertsch, Washiyama, PRC85 (2012)

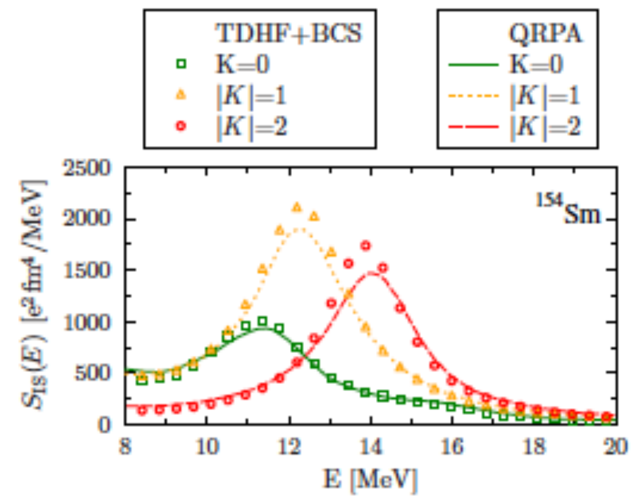
Large scale study of giant quadrupole resonances



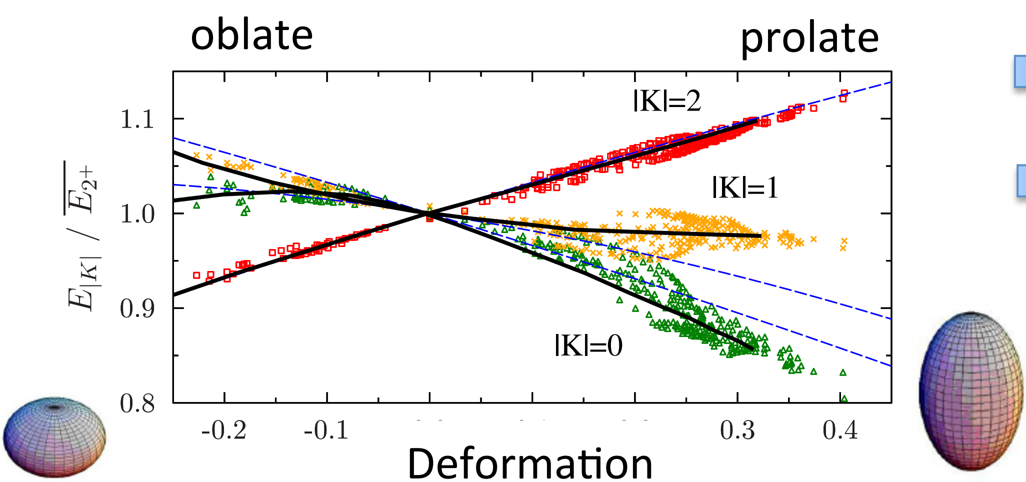


- Systematic study of isoscalar and isovector GQR in
  - (I) Spherical
  - (II) Axially deformed nuclei
  - (III) Triaxial nuclei

Example



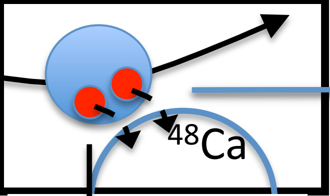
Energy splitting:

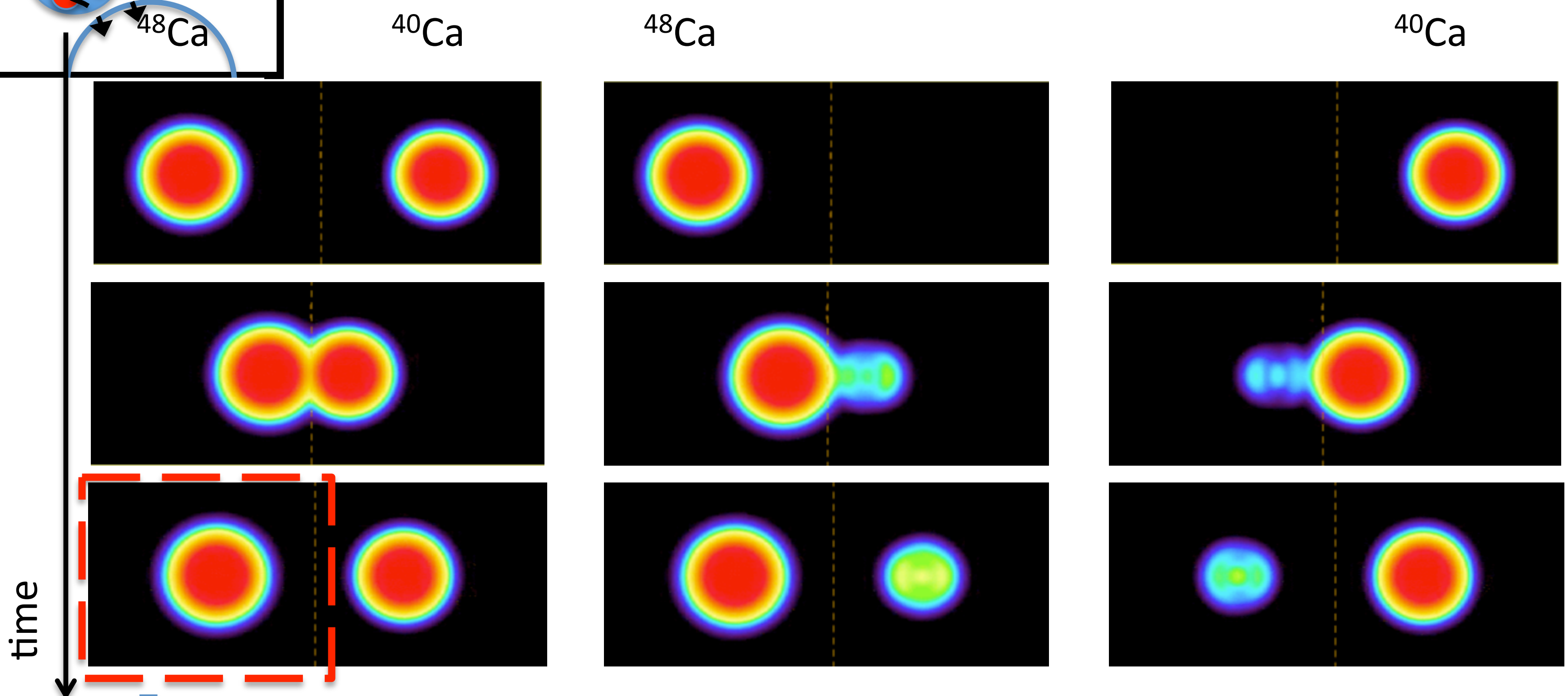


- Good reproduction of average energy
- Damping (fluctuations) is still Severely estimated but improves In deformed nuclei

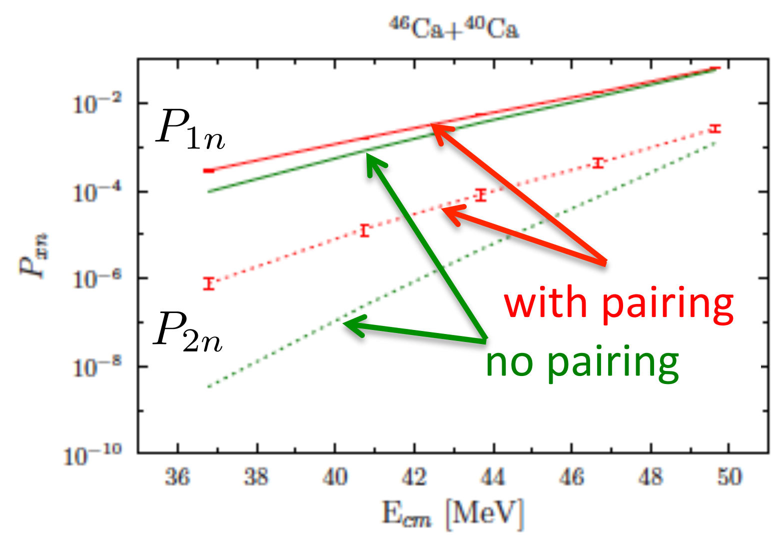
Scamps, Lacroix, PRC88 (2013)
Scamps, Lacroix, PRC89 (2014)

Transfer reaction below the Coulomb barrier





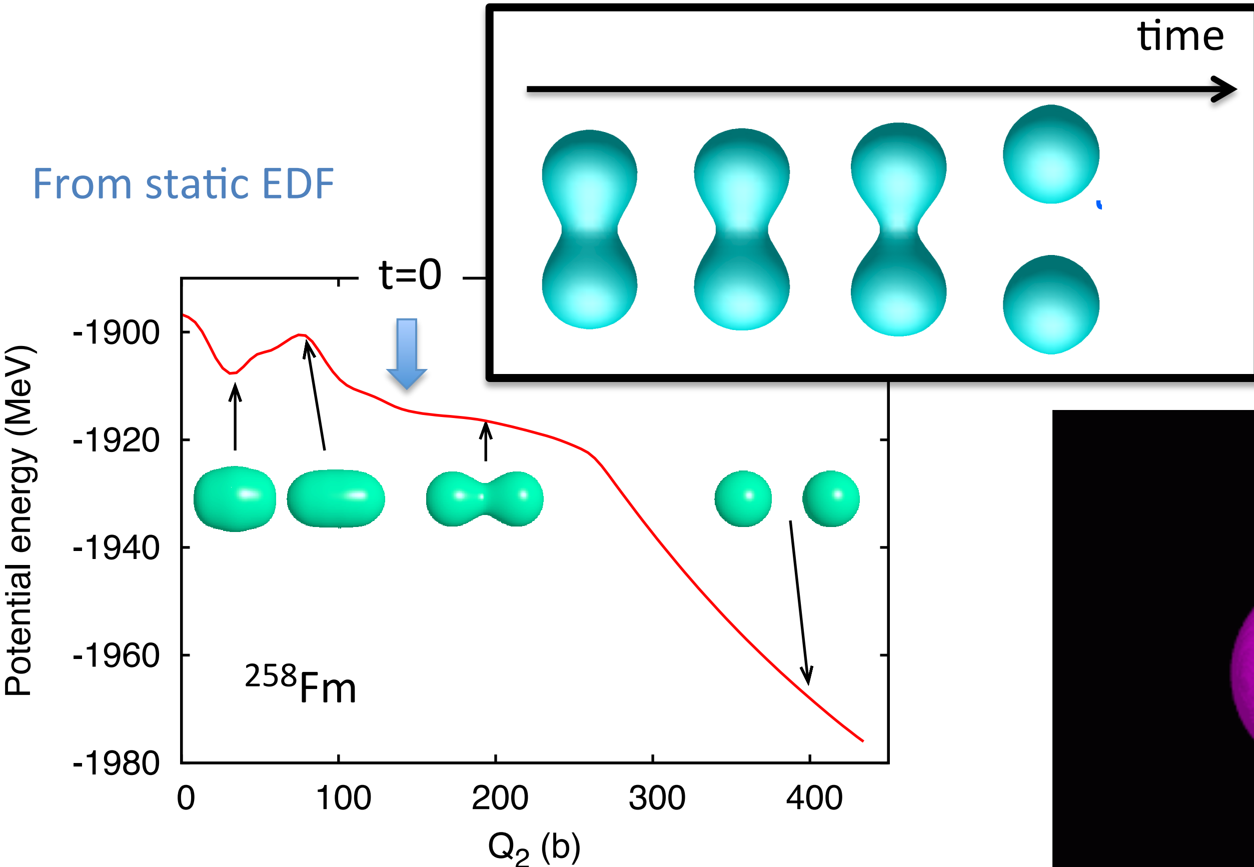
Extract one, two, …
nucleons transfer probabilities
$P_{1n},\ P_{2n}, \ldots$

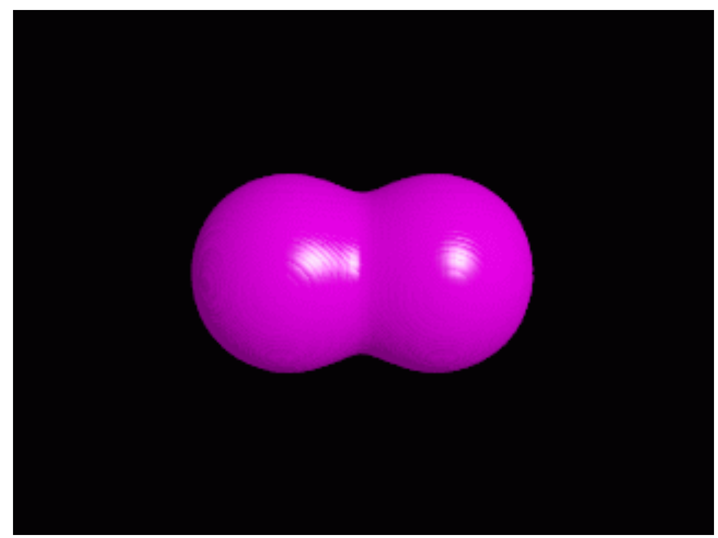


Scamps, Lacroix, PRC 87 (2013).

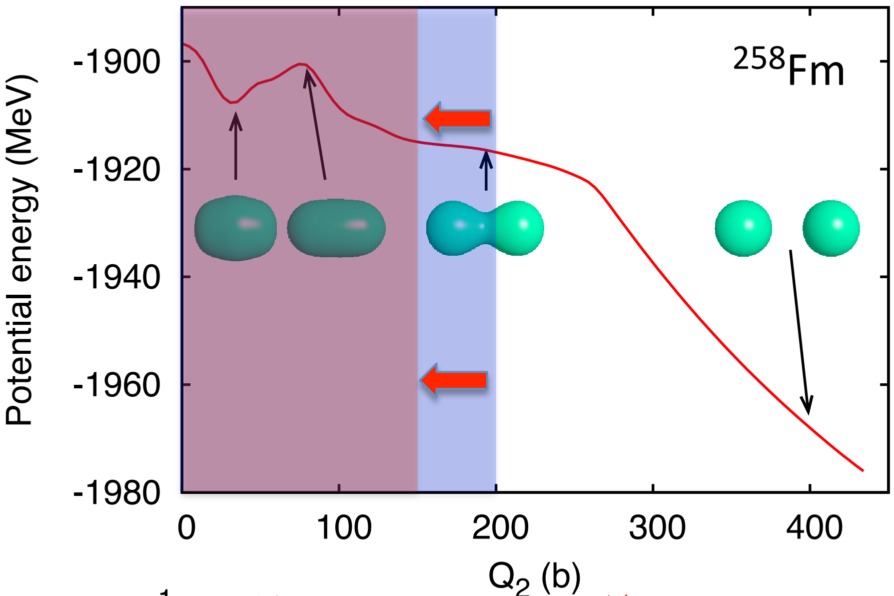
Fission with TD-EDF with pairing

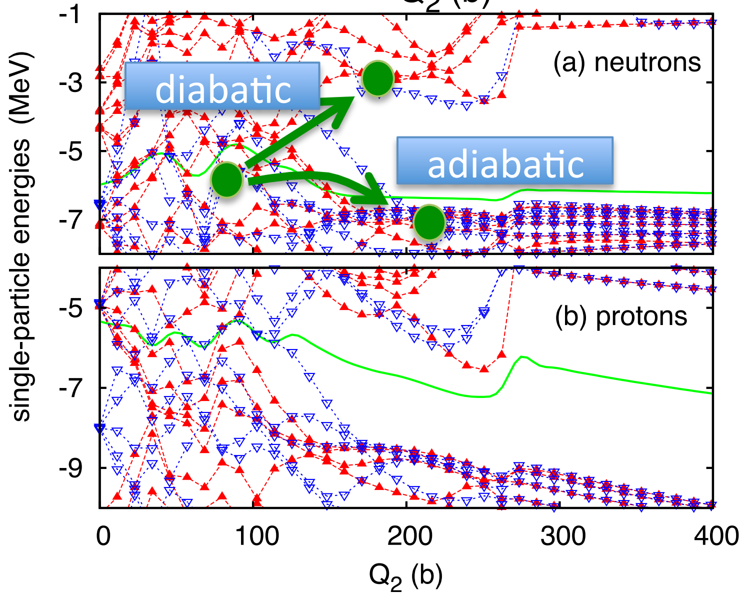
From static EDF





(courtesy Y. Tanimura)





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

Fission with TD-EDF without pairing

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

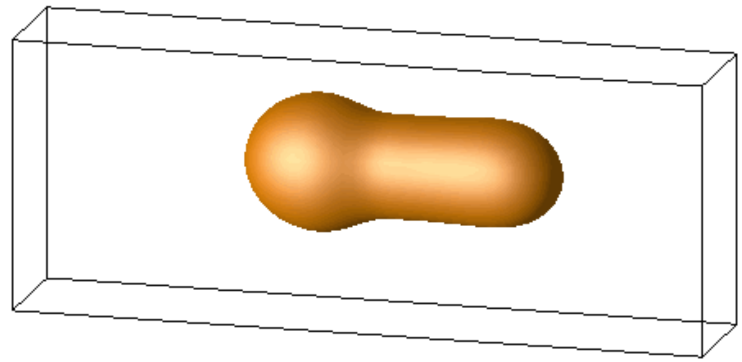
- Strong interplay between structure and dynamic
- TD-EDF does not follow the adiabatic path
- Existence of a spontaneous fission threshold at larger deformation than the fission barrier
- Still, information on fission can be obtained

Fission with TD-EDF with pairing

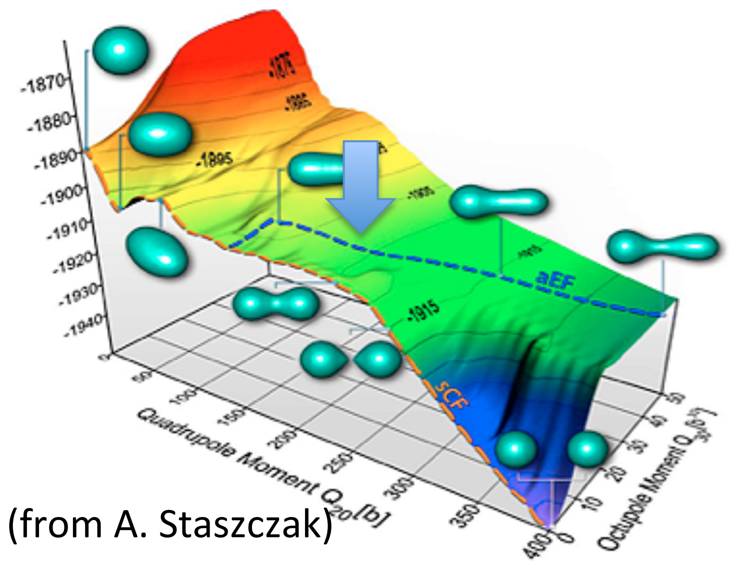
- Improve the threshold anomaly
- Allows to consider the fission of superfluid nuclei

Time-dependent picture of fission

Scamps Simenel, Lacroix, PRC92 (2015)

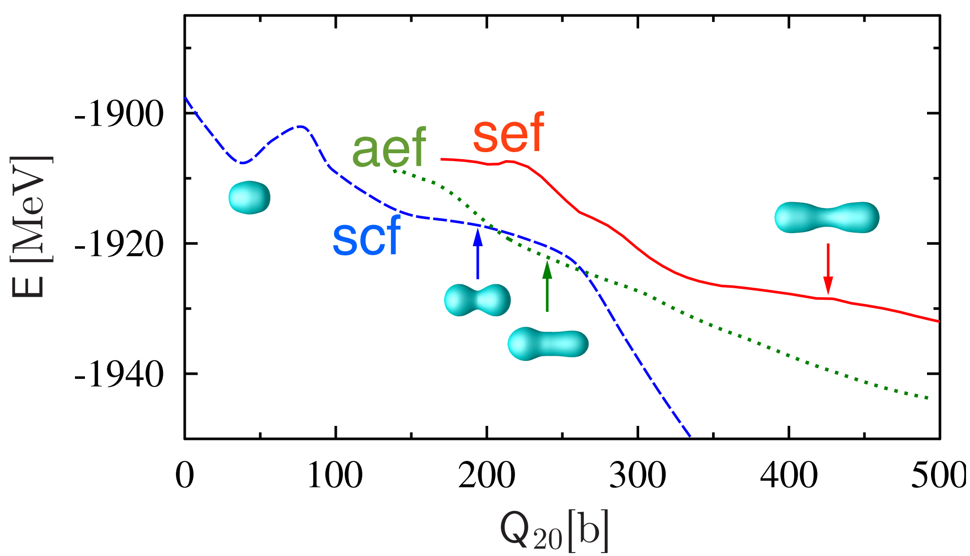


(courtesy G. Scamps/C. Simenel)



(from A. Staszczak)

Fission along different paths

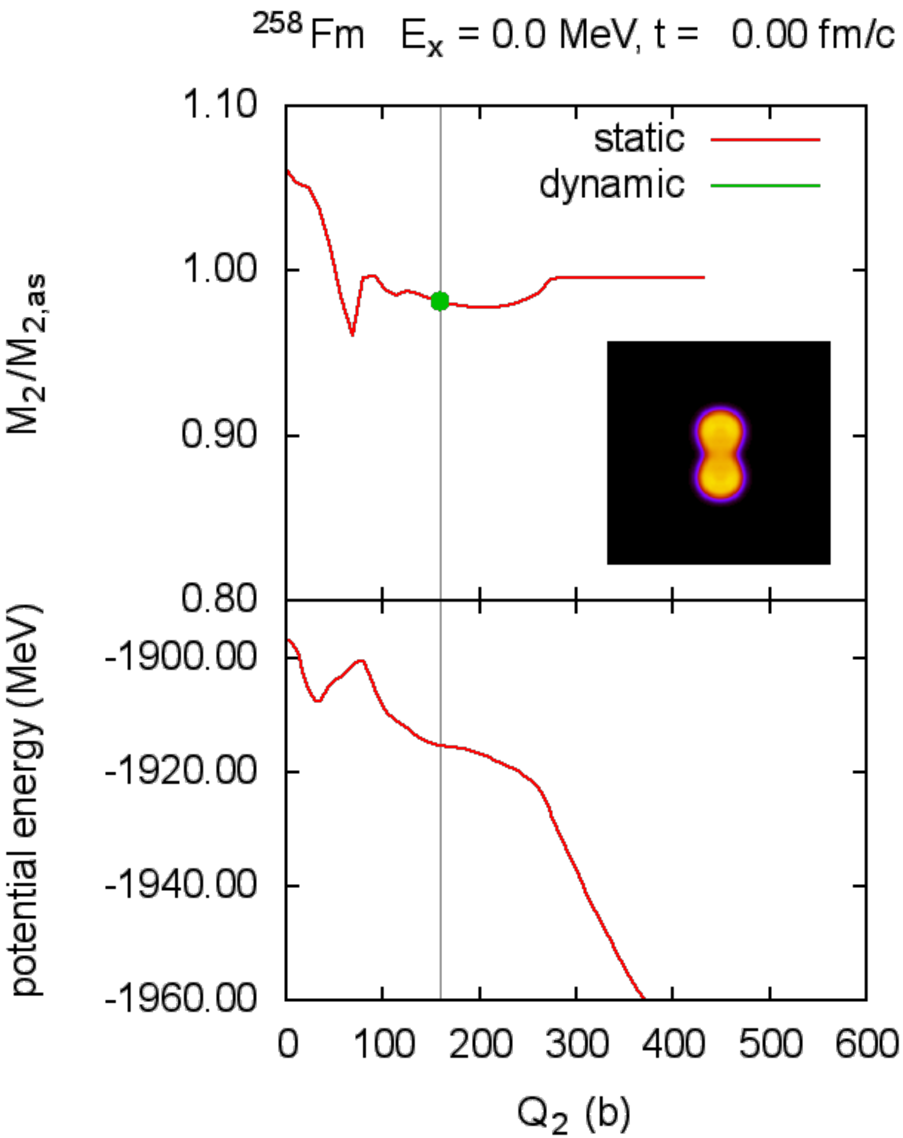


scf: symmetric compact fission

sef: symmetric elongated fission

aef: asymmetric elongated fission

Tanimura, Lacroix, Scamps, PRC 92 (2015)



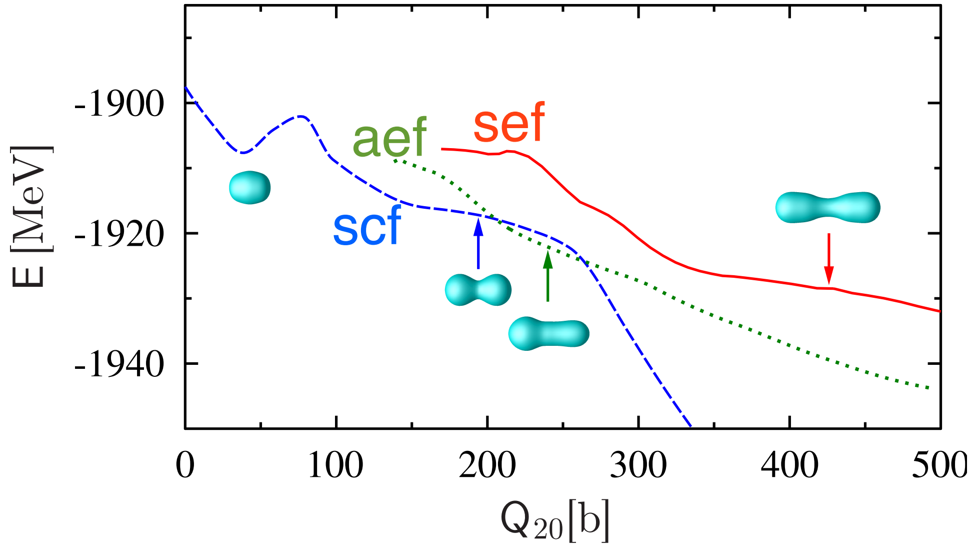
Microscopic dynamic

Collective mass, collective momentum

Macroscopic evolution:
Disspation, non-adiabatic effects…

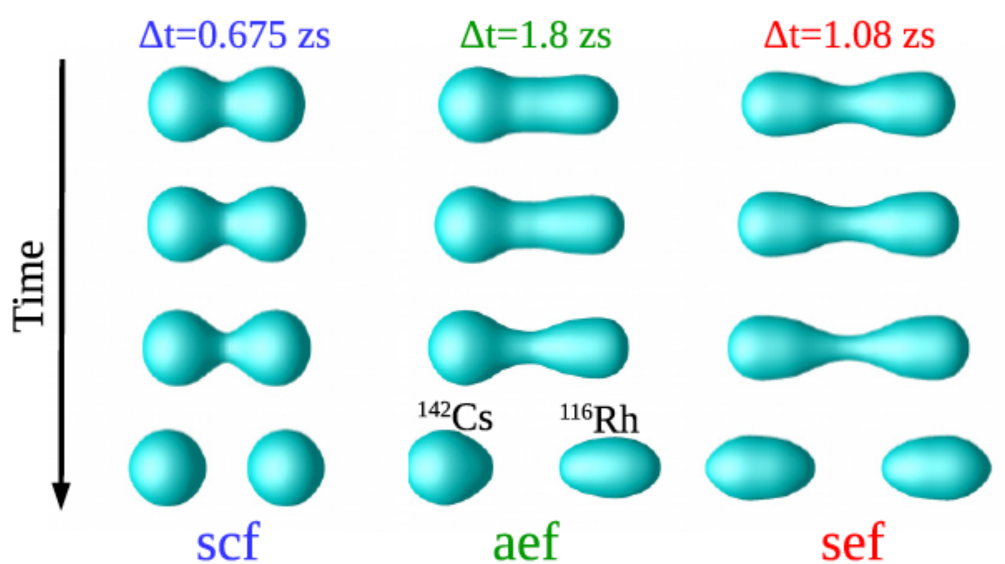
- The system first follows the adiabatic limit
- Around scission, dynamic is faster and Becomes non-adiabatic

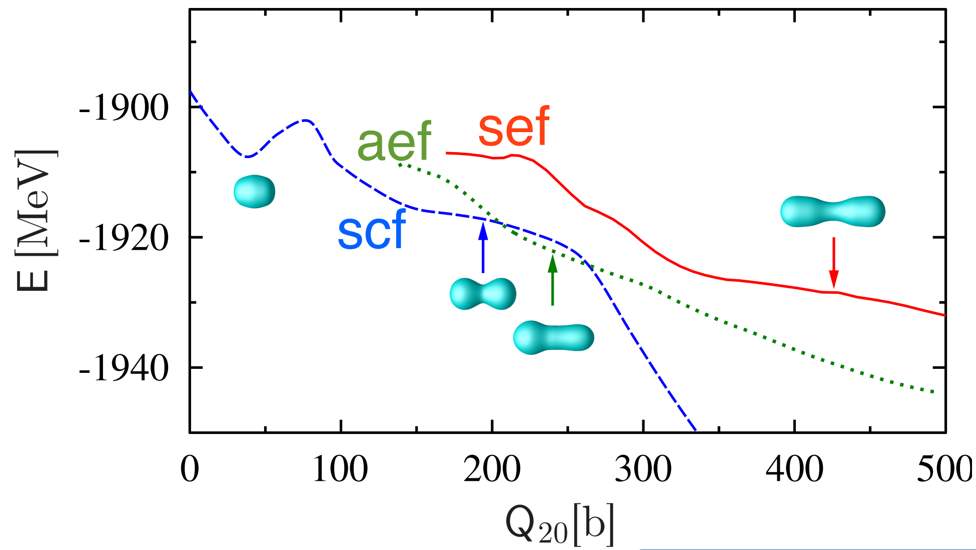
$E_{\rm diss} \simeq 20 \rm MeV$ $\rm TKE \simeq 250 MeV$



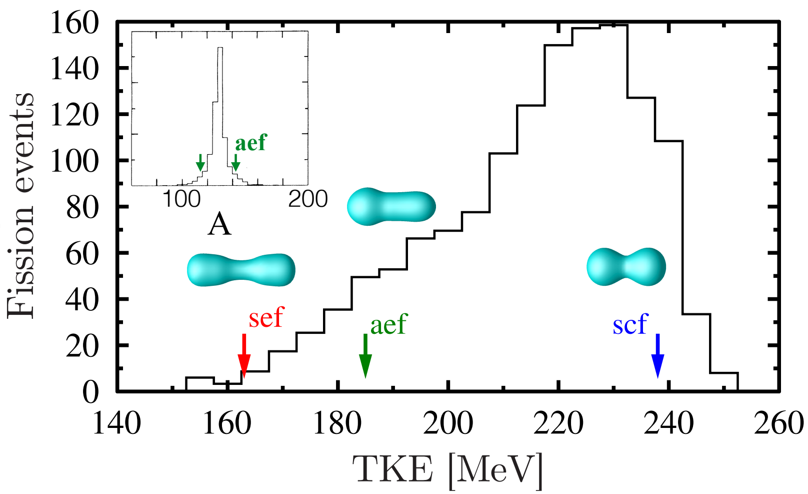
Time-scale

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

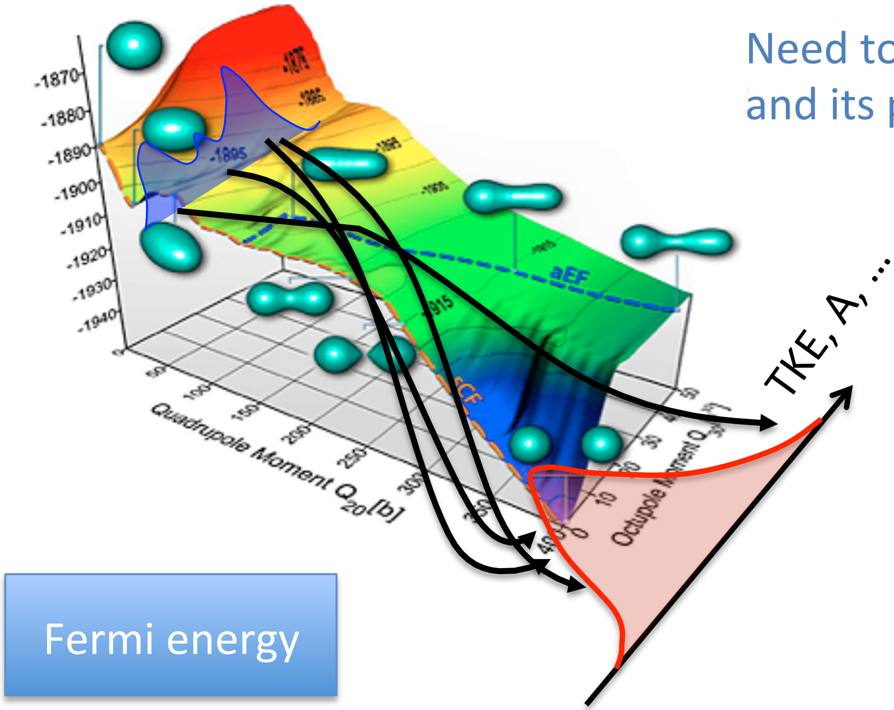
- Fluctuations are underestimated
- Weight of each paths?

Need to describe configuration mixing and its propagation

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

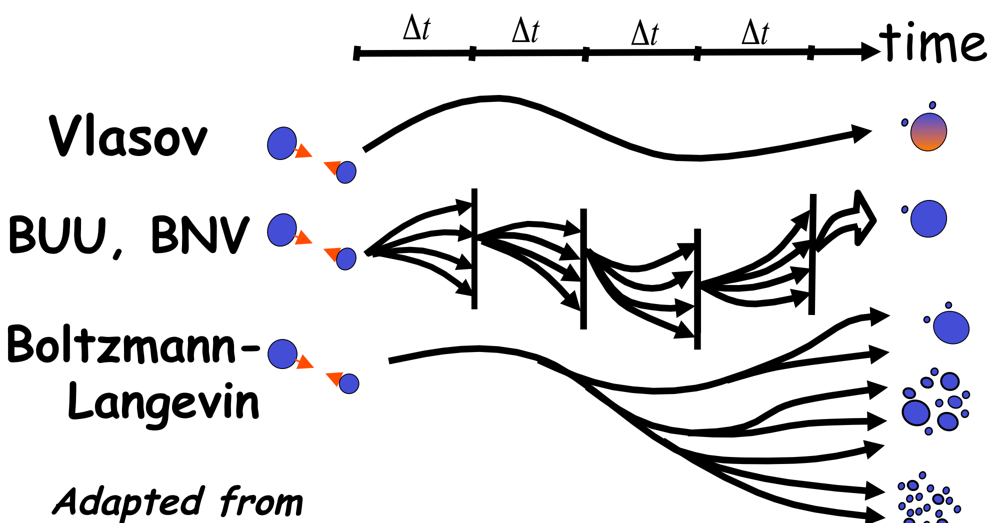
Our objective: use the stochastic mean-field approach to describe fission

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

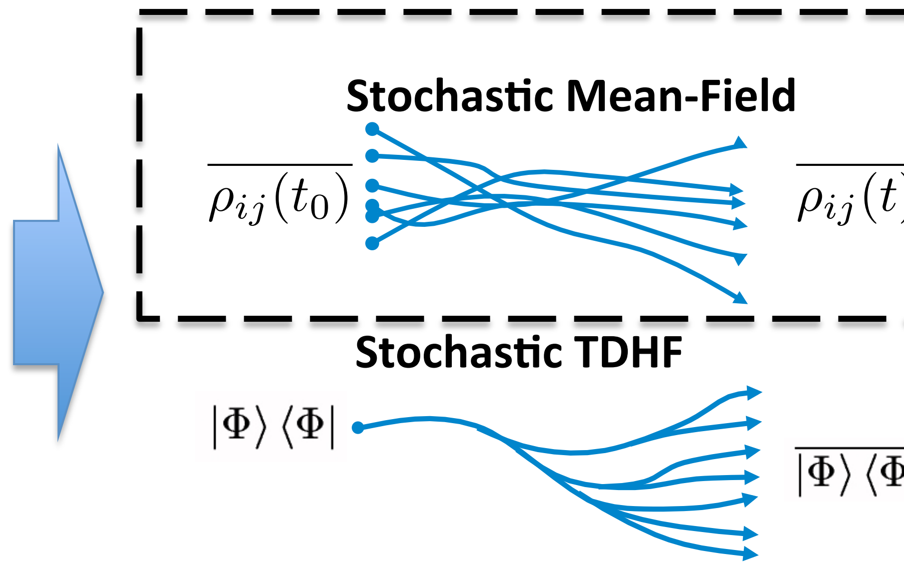


Fermi energy

Coulomb barrier energy

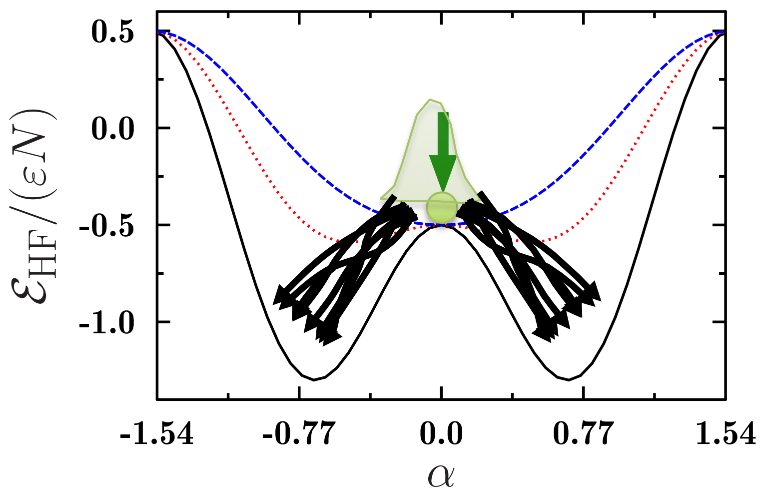


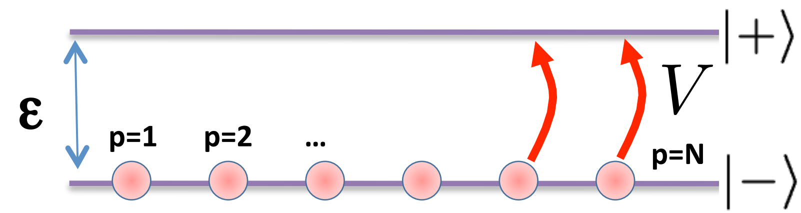
Adapted from J. Randrup et al, NPA538 (92).



Two-Level Lipkin Model

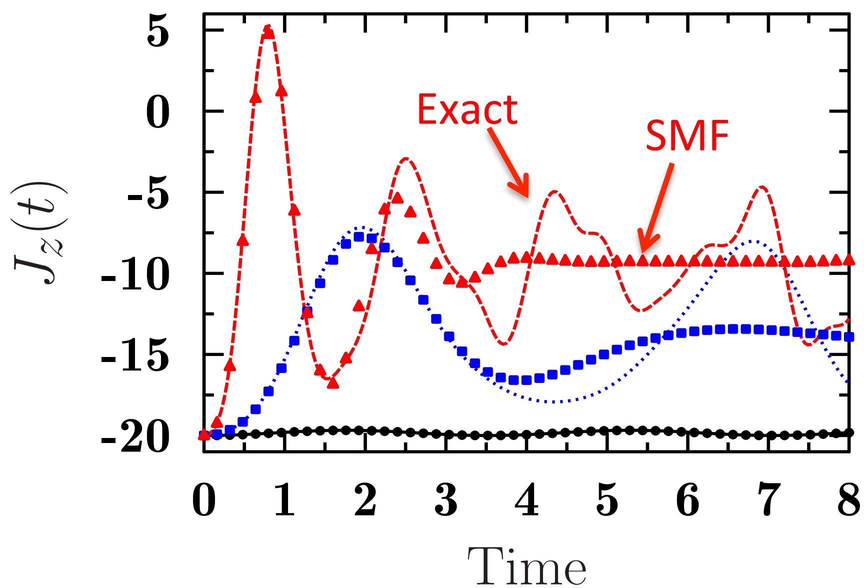
N=40 particles



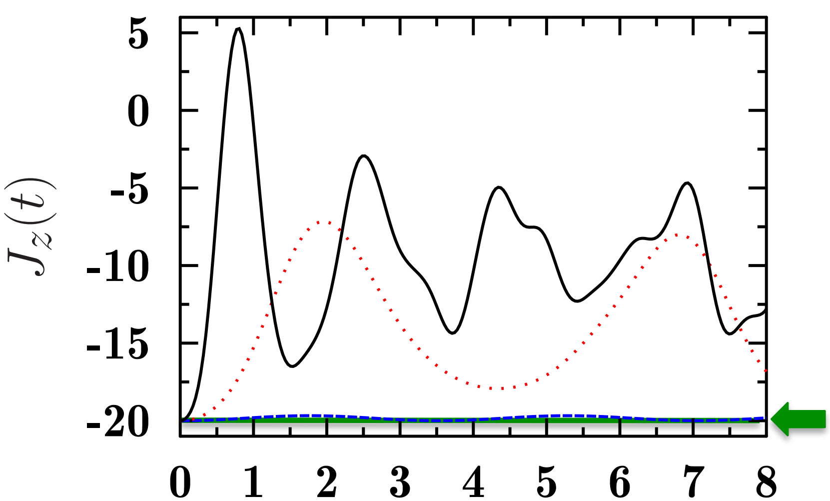


$\chi = V/\varepsilon$

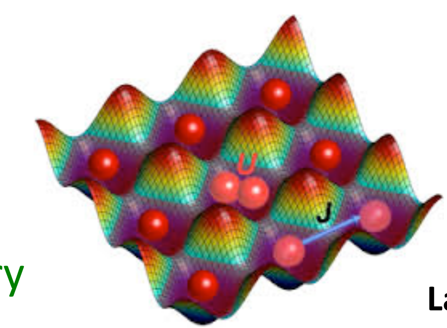
Exact dynamics



Lacroix, Ayik, Yilmaz, PRC 85 (2012)



Mean-field is stationary



Lacroix et al, PRB90 (2014)

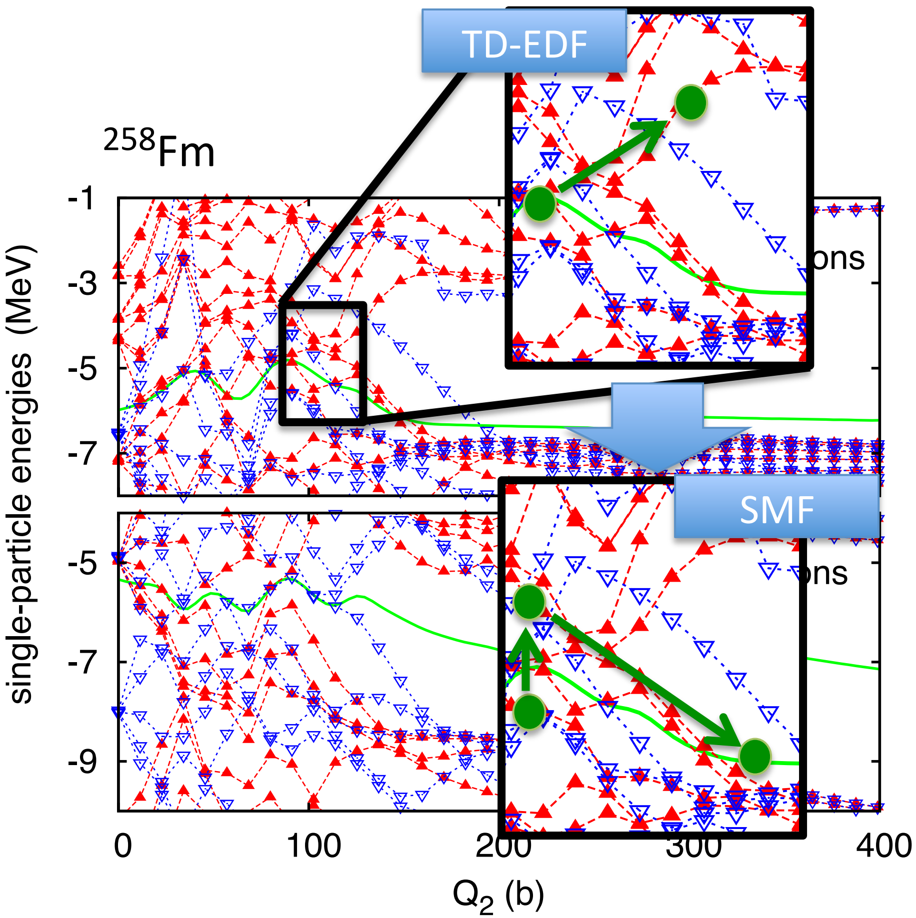
SMF in density matrix space

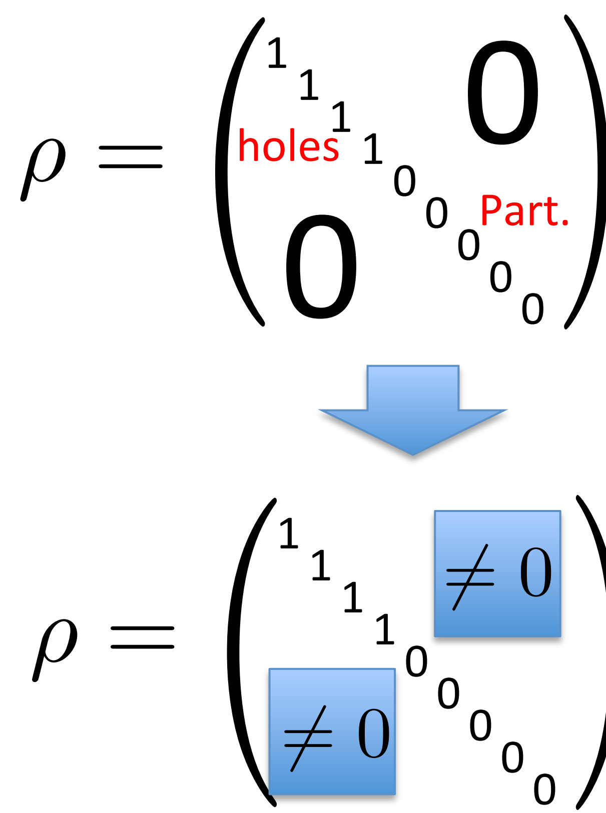
$$\rho(\mathbf{r},\mathbf{r}',t_0) = \sum_i \Phi_i^*(\mathbf{r},t_0) n_i \Phi_j(\mathbf{r}',t_0)$$

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

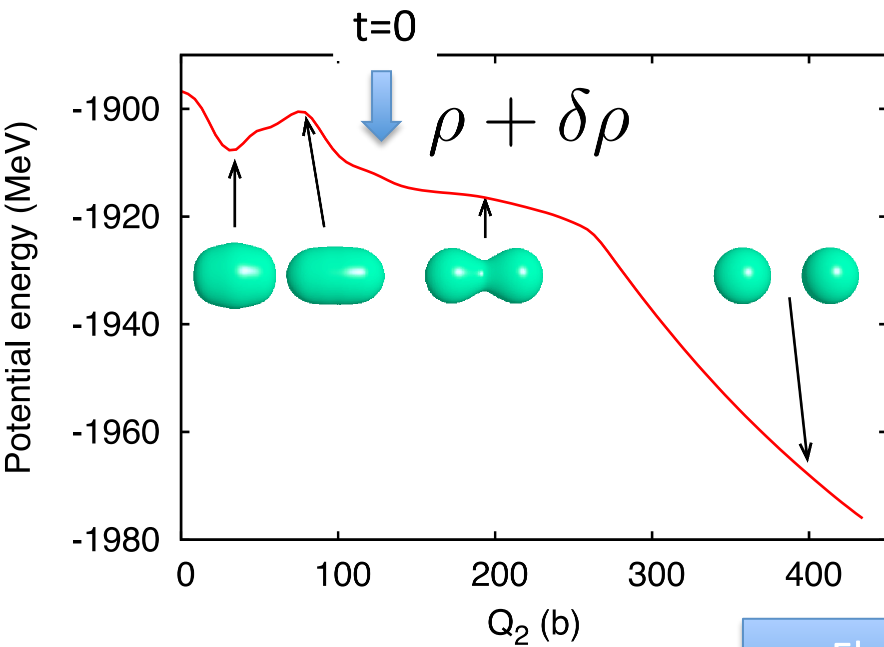
$$\overline{\rho_{ij}^\lambda} = \delta_{ij} n_i$$

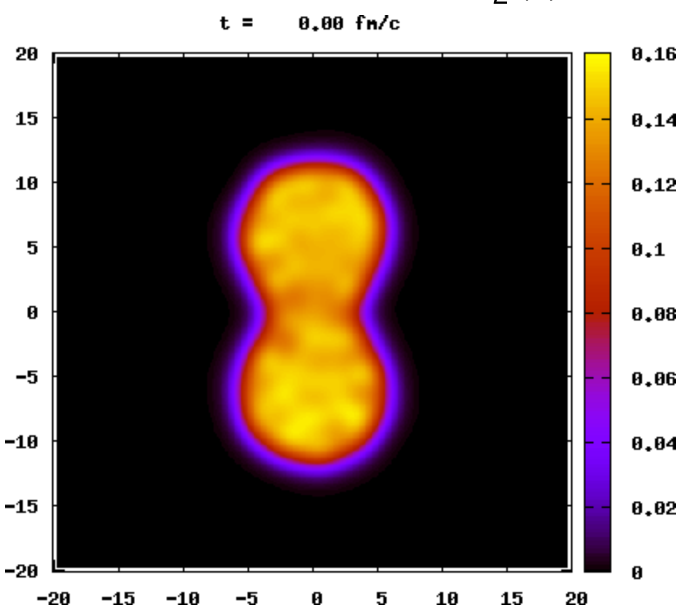
$$\overline{\delta\rho_{ij}^\lambda \delta\rho_{j'i'}^\lambda} = \frac{1}{2}\delta_{jj'}\delta_{ii'}\left[n_i(1-n_j)+n_j(1-n_i)\right].$$

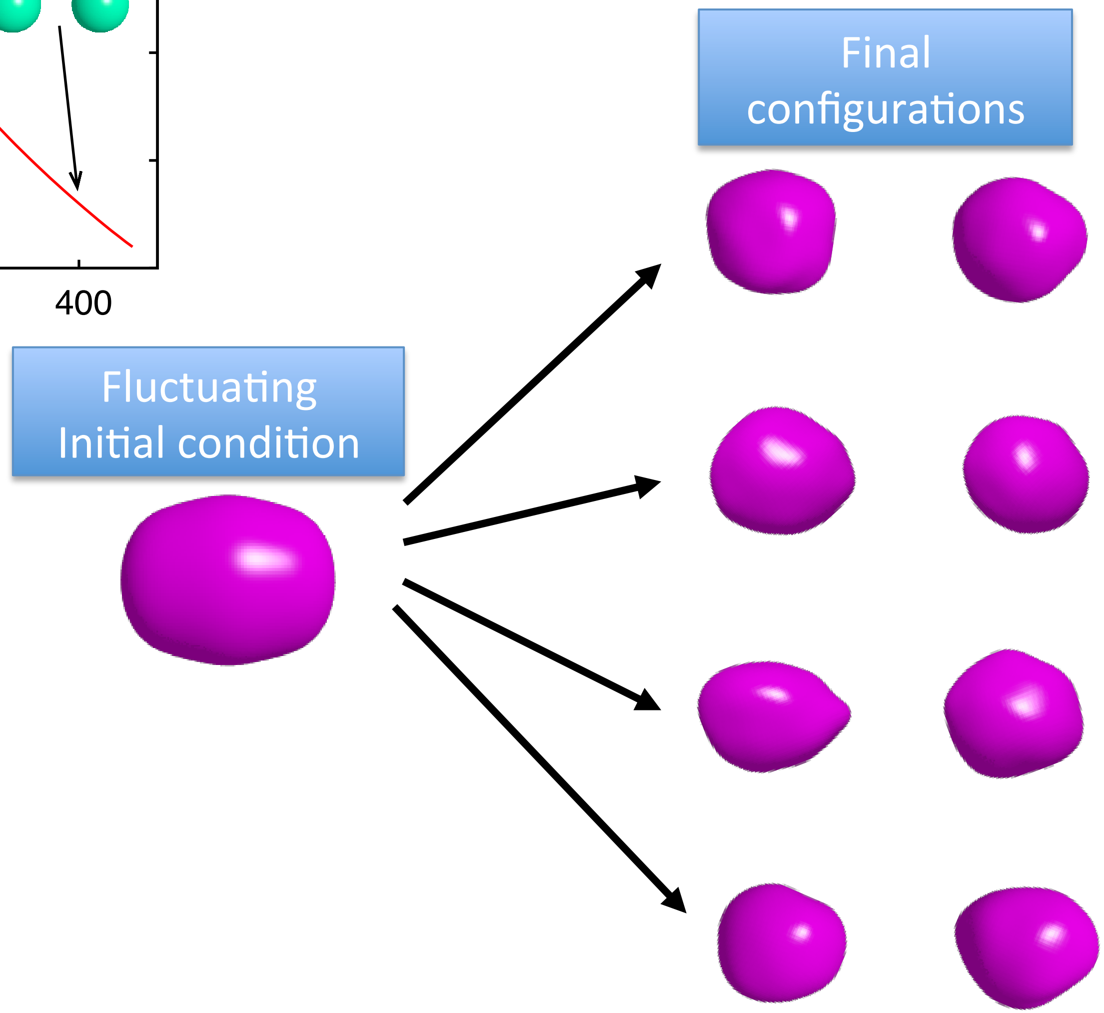




Density evolution with initial fluctuations

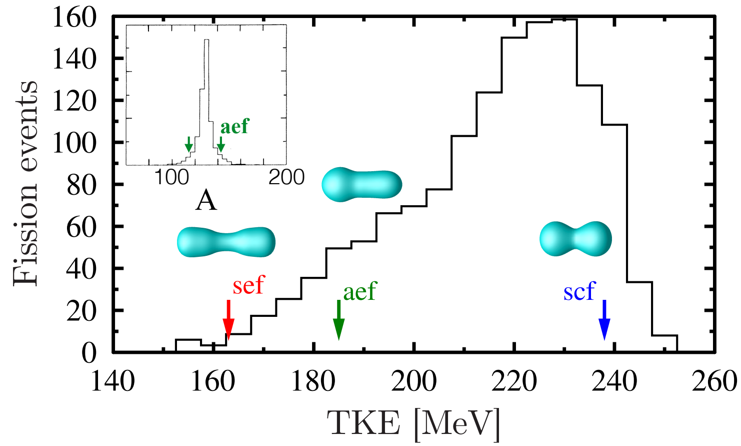




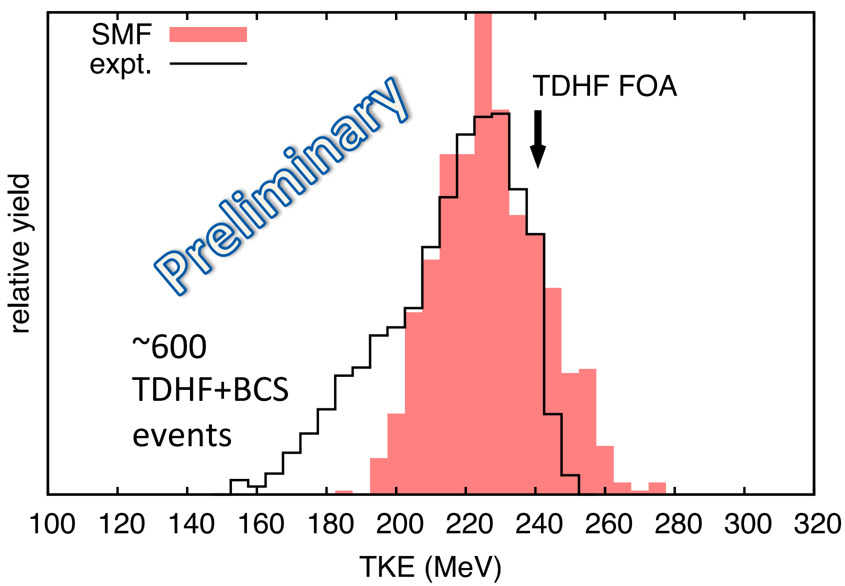


Total Kinetic energy

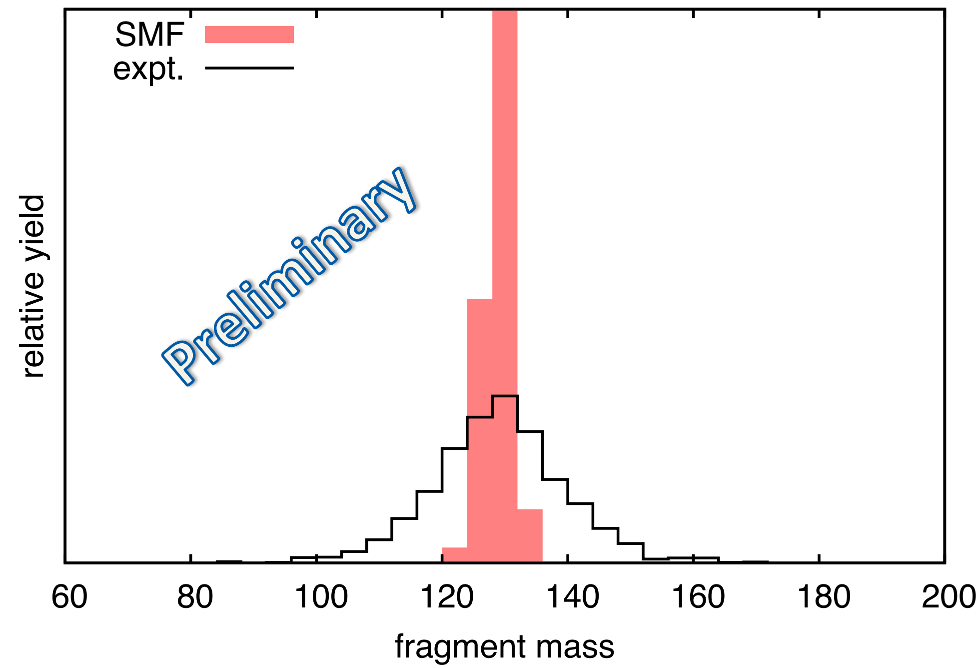
TDHF+BCS results



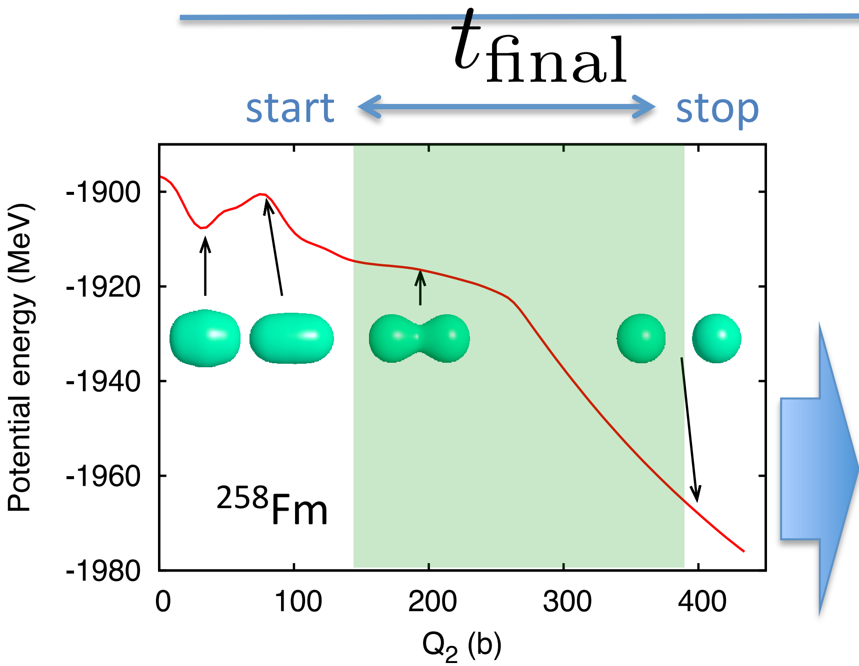
SMF results



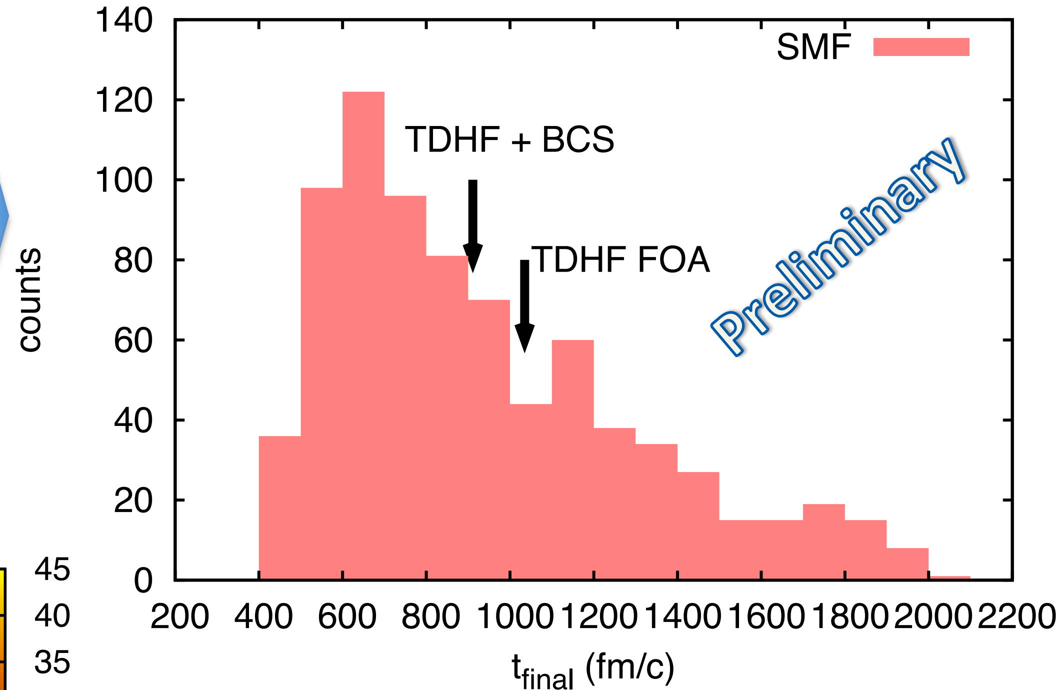
Mass distribution



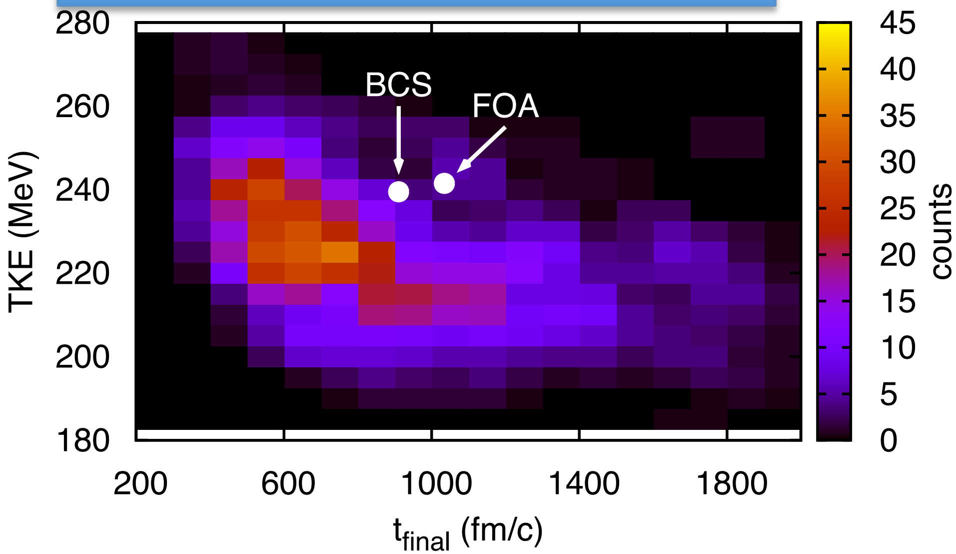
Y. Tanimura and D. Lacroix, in preparation

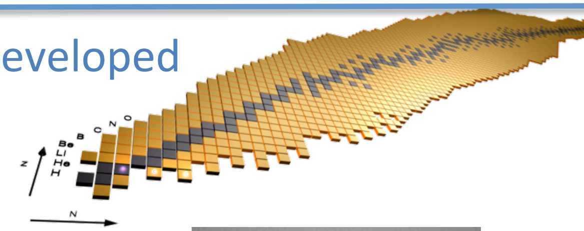


Fission time distribution



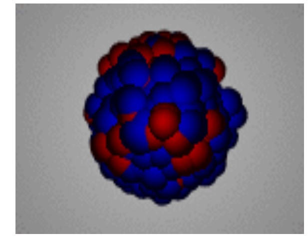
Time versus TKE



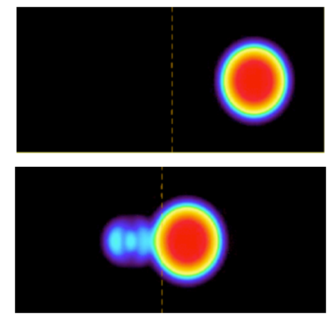


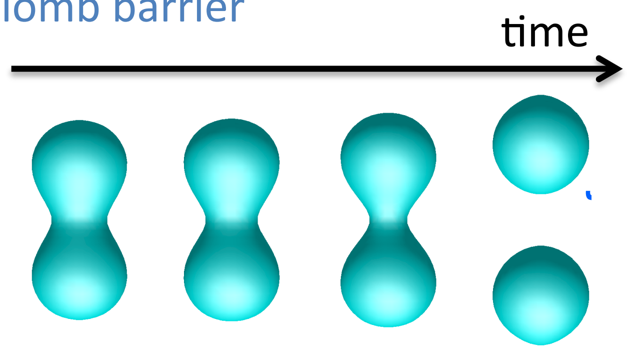
- New versatile TD-EDF codes including pairing are now developed
- This open new applications perspectives

Recent applications



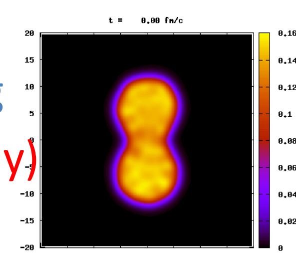
- Systematic of giant resonances in nuclei with various shapes
- Particle transfer below the Coulomb barrier
- Fission of superfluid nuclei

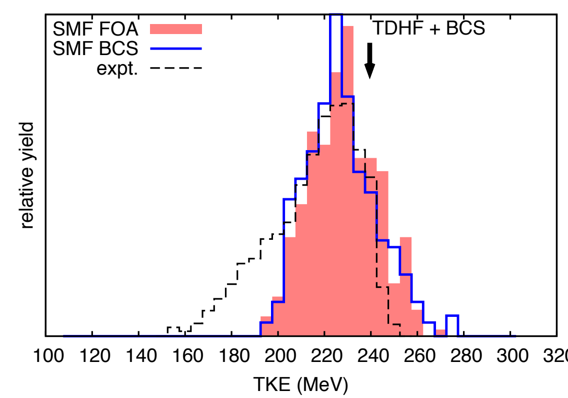




Stochastic Mean-Field application

- First application with sampling of initial phase-space in TD-EDF
- Preliminary results are encouraging





Emergent collaboration (LNS Catane-IPN Orsay)

ENSAR2