Current trends in the microscopic description of fission

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Ultimate goal:

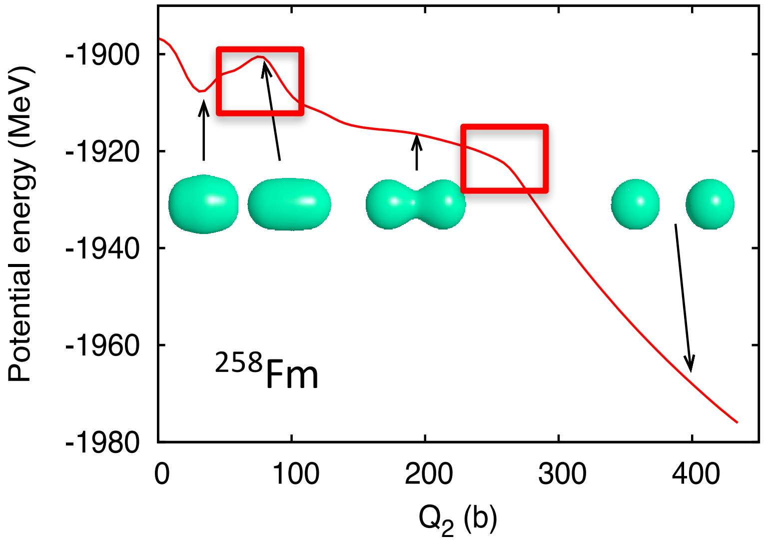
Provide a fully microscopic description of fission from compound nucleus to separated fragments

Outline:

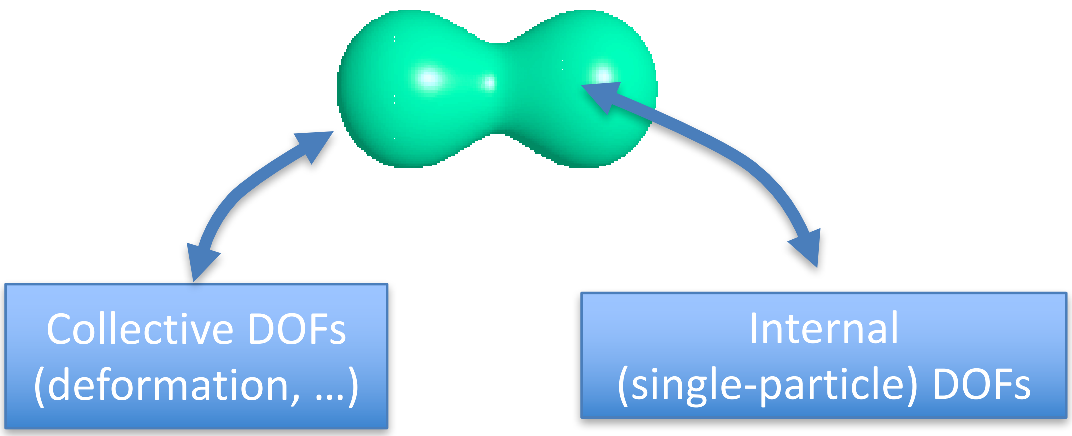
- Challenges in the description of fission
- Generalities on time-dependent approaches with pairing
- Recent application to fission
- Beyond quantum Mean-Field Theories: *deterministic* vs *stochastic* theories
- Applications and perspectives

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

Challenges in the fully microscopic description of fission

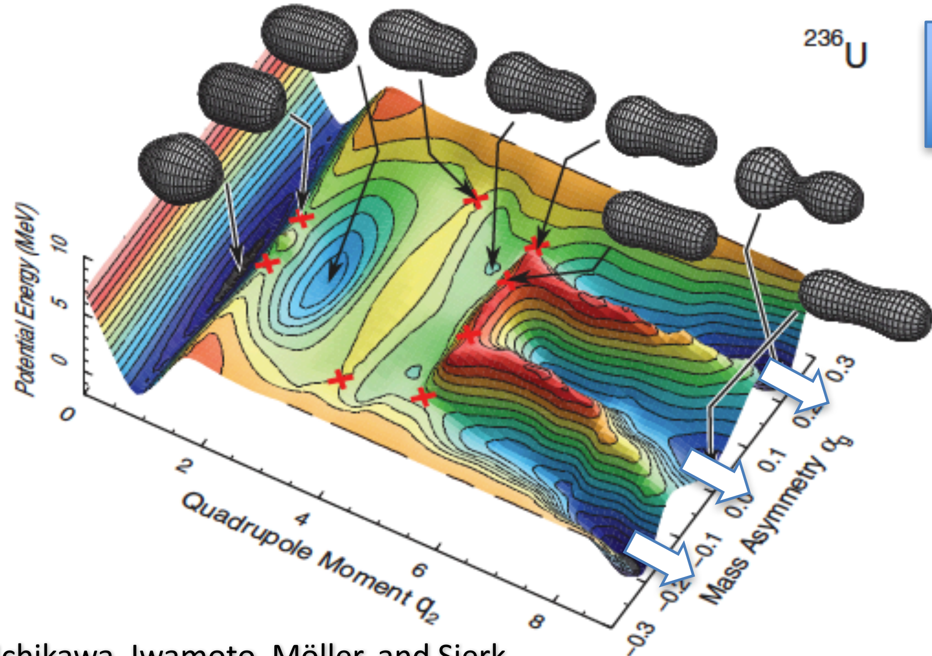


- Describe a large variety of degrees of freedom (DOFs) with different time-scales



- Quantum effect is important (both for collective and intrinsic): quantum tunneling, …
- The processus is not slow enough to be fully adiabatic in collective space (@scission).
- Superfluidity impact both quasi-static and dynamical effects (see later).
- Systems are big and the global time-scale can be very long (up to million of years)
- The number of DOFs might be very large.

From quasi-static to dynamical approach: the time-dependent GCM

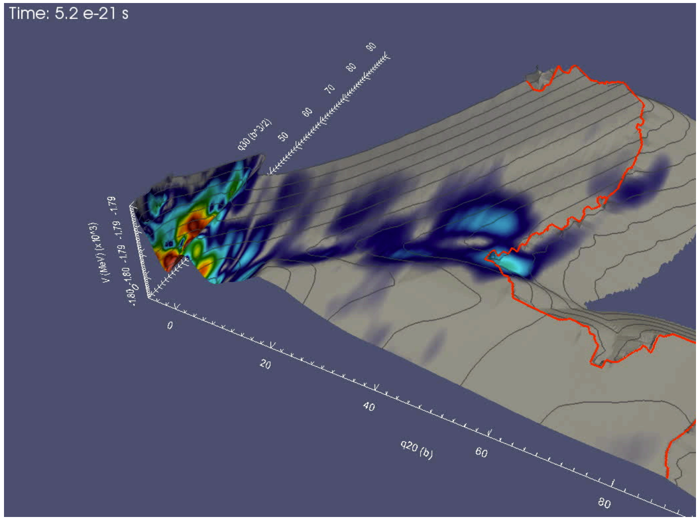


Ichikawa, Iwamoto, Möller, and Sierk,
Phys. Rev. C 86 (2012)

Solve quantum motion in collective space

$$|\Psi(t)\rangle = \int_{\mathbf{q}} g(\mathbf{q},t)|\xi(\mathbf{q})\rangle d\mathbf{q}$$

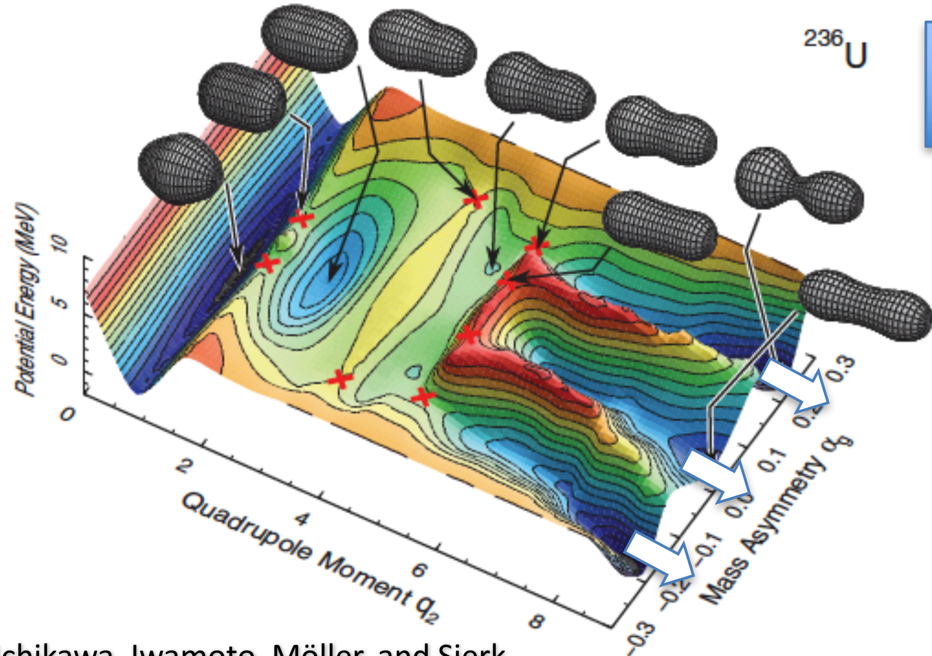
$$i\hbar \frac{\partial g(\mathbf{q},t)}{\partial t} = \hat{H}_{\mathrm{coll}}(\mathbf{q}) g(\mathbf{q},t).$$



(Courtesy D. Regnier)

Advantages

- Treat quantum effects in collective space: (quantum tunneling, interferences)
- As its counterpart in nuclear structure (static GCM)
- Works quite well for mass yields



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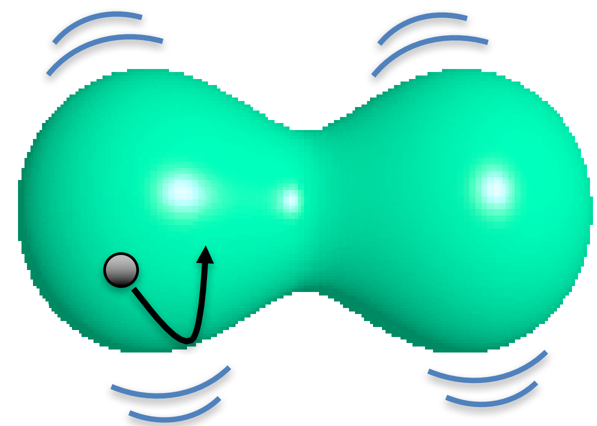


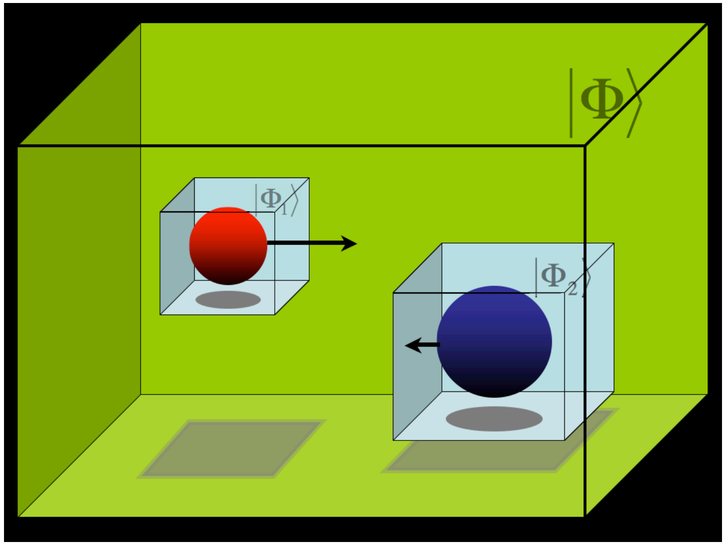
Difficulties

Some of this difficulties can be solved using Time-dependent EDF

- Dimensionality: number of collective DOFs. Proper mass require doubling the dimension.
- Energy landscape has discontinuities.
- Full GCM is not well defined within the EDF approach

  Lacroix et al, Phys. Rev. C79 (2009); Robledo J. Phys. G 37 (2010),...
- Motion can be non-adiabatic: onset of dissipation, fluctuations, non-Markovian effects.

Nuclear reaction with superfluid nuclei 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…)

TDHFB = 1000 * (TDHF)

→ Full TDHFB (Skyrme-spherical symmetry) — Avez, Simenel, Chomaz, PRC 78 (2008).

Full TDHFB (Skyrme-symmetry unrestricted) — Stetcu, Bulgac, Magierski, and Roche, PRC 84 (2011)

(Gogny-axial symmetry) — Y. Hashimoto, PRC 88 (2013).

→ Symmetry unrestricted TDBCS limit of TDHFB (also called Canonical basis TDHFB)

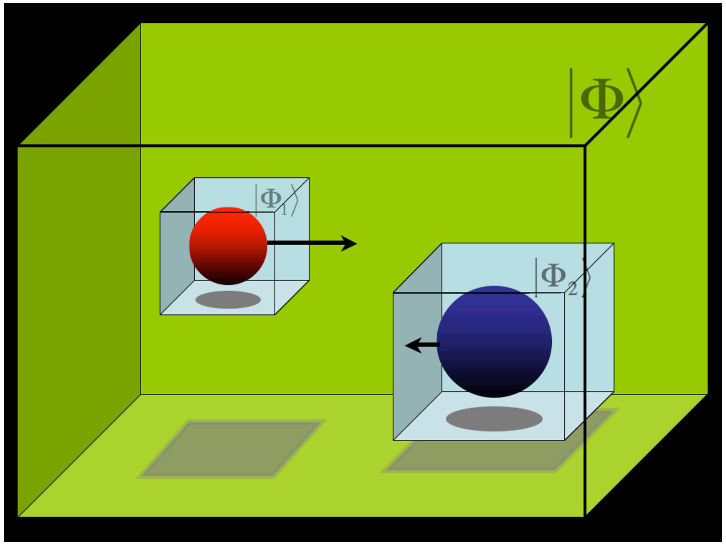
Neglect Δ_{ij} → $|\Phi(t)\rangle = \prod_{k>0} \left(u_k(t) + v_k(t) a_k^\dagger(t) a_{\bar{k}}^\dagger(t)\right) |-\rangle.$

TDBCS = 2-3 * (TDHF)

Ebata, Nakatsukasa et al, PRC82 (2010)
Scamps, Lacroix, PRC88 (2013).

→ Very good predictive power

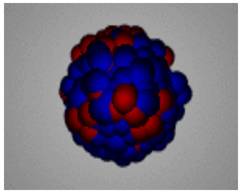
Nuclear reaction with superfluid nuclei on a mesh



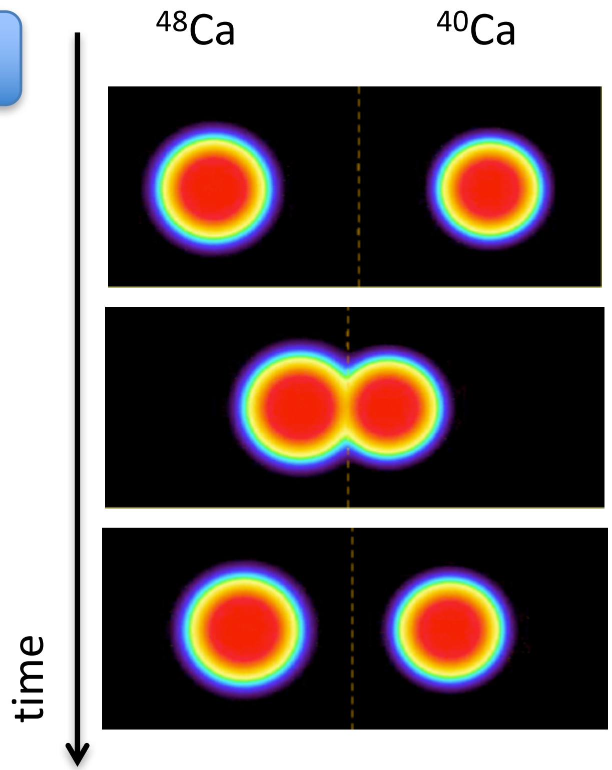
Scamps, Tanimura, Regnier, Lacroix (2012-2017)

Applied to a number of physical process

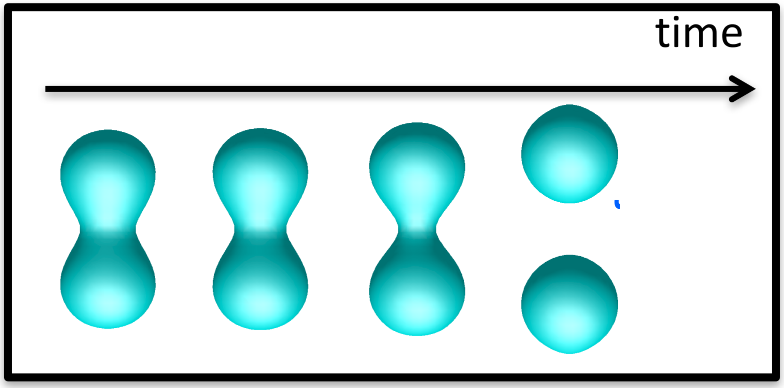
Vibrations



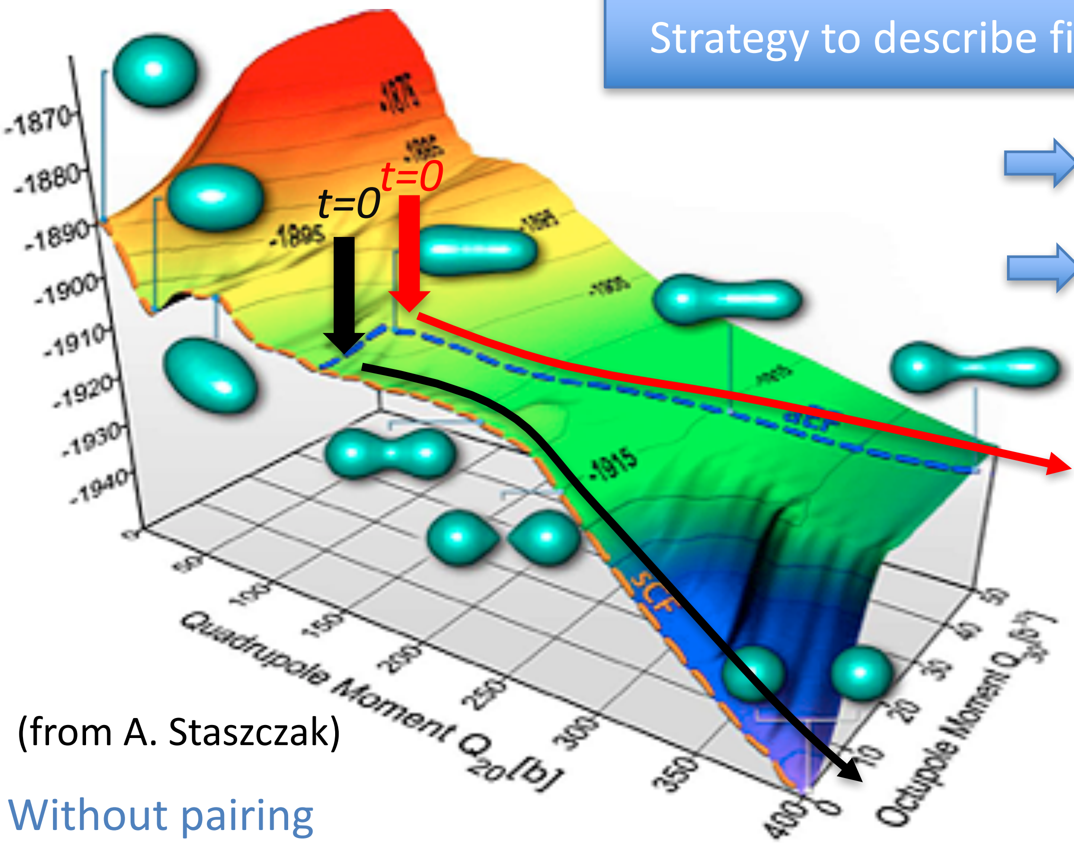
Fusion/Transfert



Fission



Description of fission in a time-dependent mean-field framework



(from A. Staszczak)

Strategy to describe fission in mean-field

- Choose an initial condition
- Follow the system in time until something happen (fission)

Advantages

-fully microscopic time-dependent

-non-adiabatic theory

-symmetry unrestricted

(however with no spontaneous symmetry breaking)

Drawback

-almost classical in collective space

(fluctuations are underestimated,

no quantum tunneling, interferences …)

Without pairing

Simenel, Umar, PRC C89 (2014).

Goddard, Stevenson, Rios, PRC 92 (2015), 93 (2016)

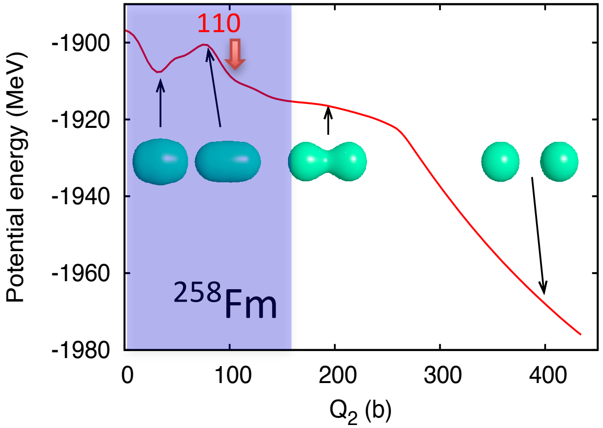
With pairing

Scamps Simenel, Lacroix, PRC92 (2015)

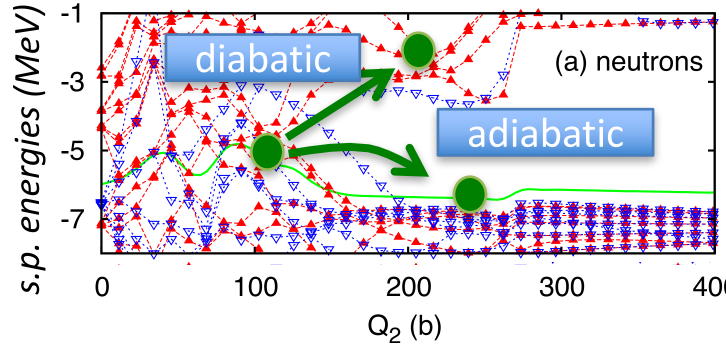
Tanimura, Lacroix, Scamps, PRC 92 (2015)

Bulgac, Magierski, Roche, and Stetcu, PRL 116, 122504 (2016)

Time-dependent mean-field with pairing
Accounting for non-adiabaticity



Without pairing the system do not fission: Mean-field without pairing is too diabatic!

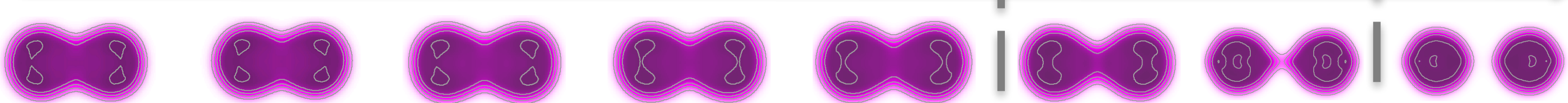


TDHFB or TDHF+BCS solve this problem

Time (fm/c)

Fast fission

1000 2000 3000 4000 5000 5300 5500 5600

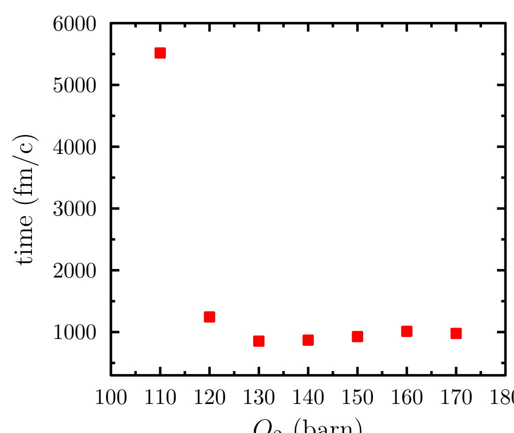


Extremely slow pairing/dissipation dominated motion

Coulomb boost

Fission time with TDHF+BCS

Scamps, Simenel, DL PRC 92 (2015)
Tanimura, DL, Ayik, PRL 118 (2017)

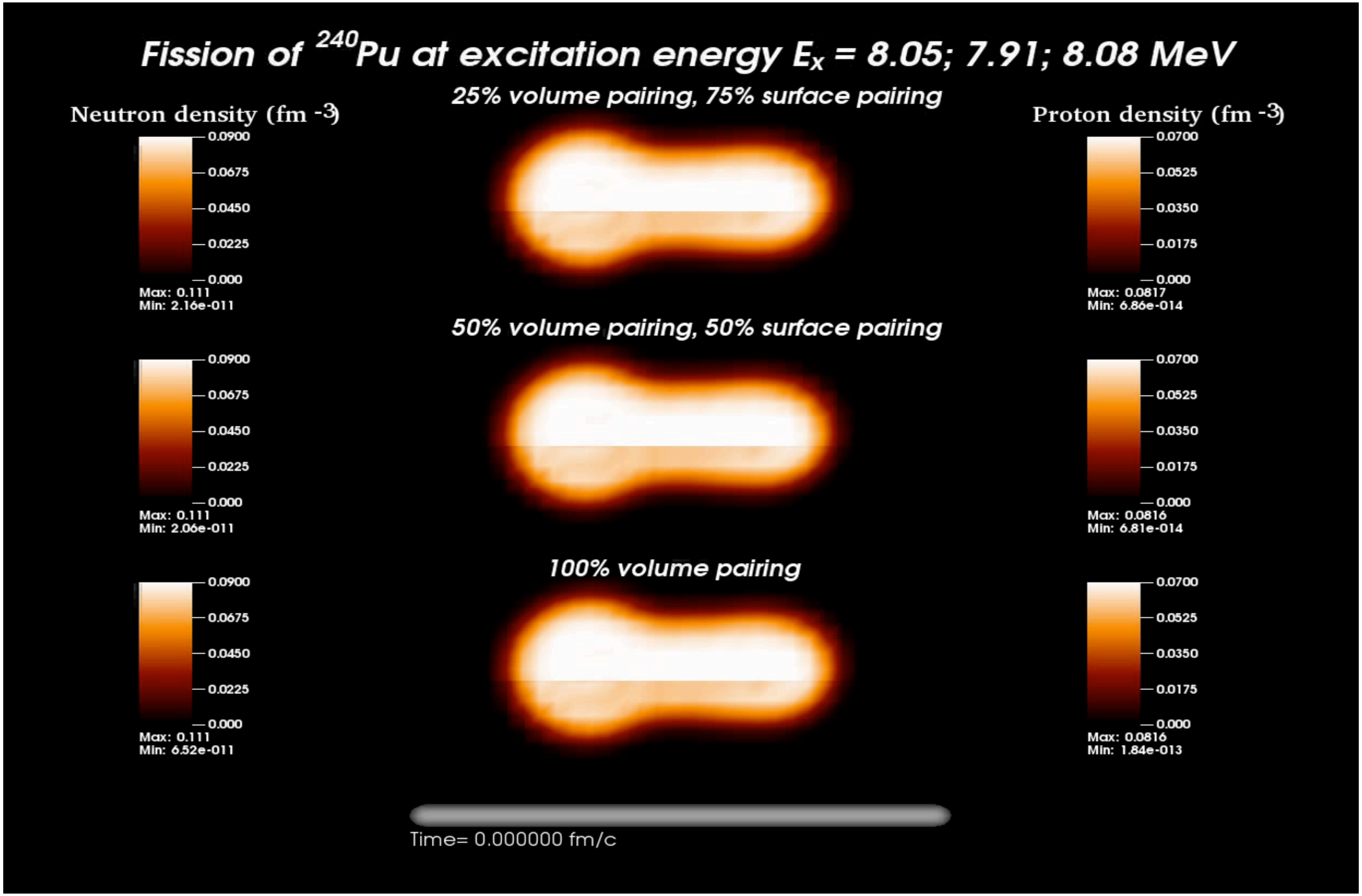


Confirms the finding of:

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

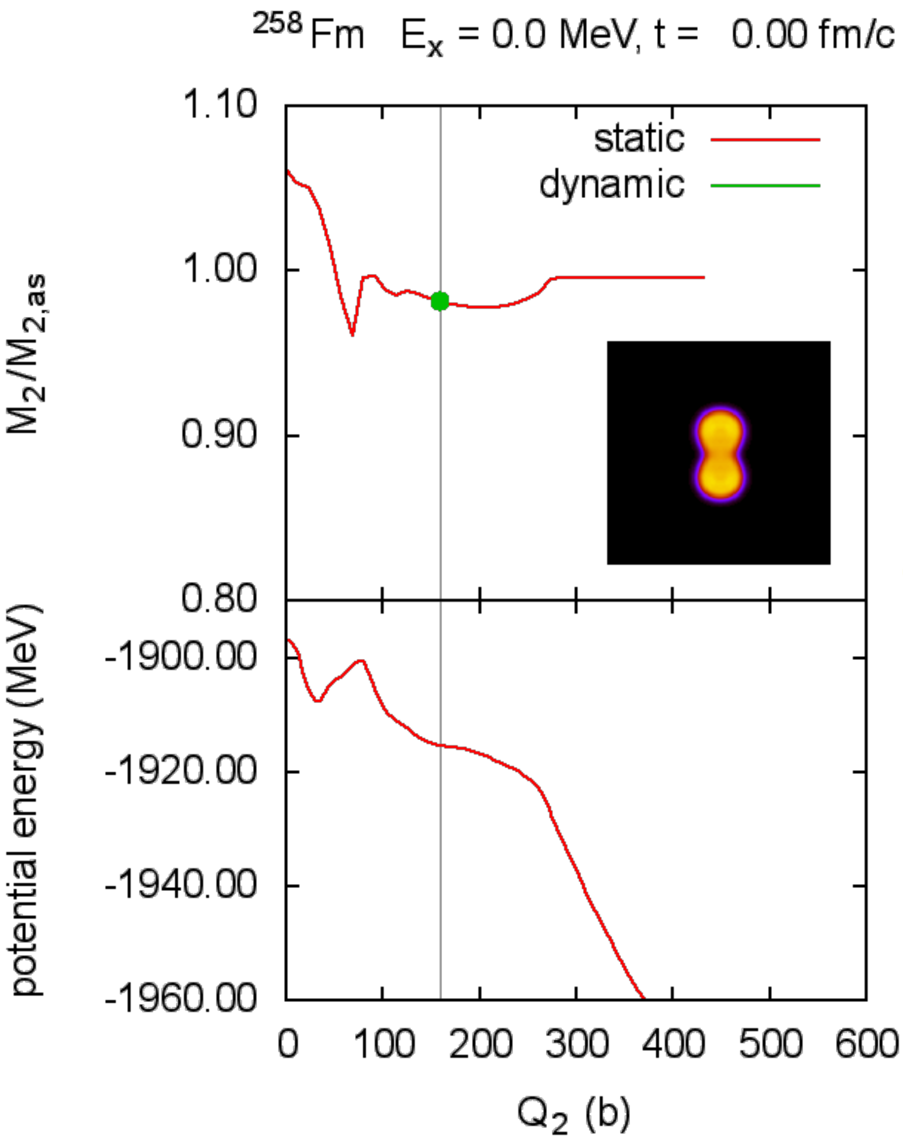
Fission time ?

Still debated



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

Tanimura, DL, Scamps, PRC 92 (2015)



Microscopic dynamic

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

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

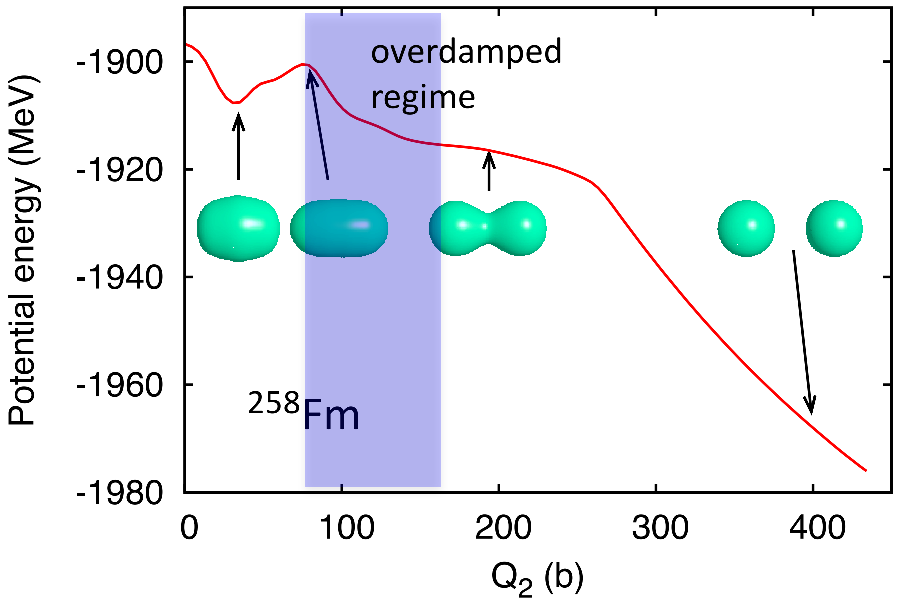
$$\langle[\hat{Q}_\alpha, \hat{P}_\alpha]\rangle = i\hbar, \Rightarrow \frac{1}{M_\alpha(t)} = \frac{1}{m}\mathrm{Tr}[\rho(t)\nabla Q_\alpha \cdot \nabla Q_\alpha],$$

Macroscopic evolution: Dissipation, non-adiabatic effects…

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

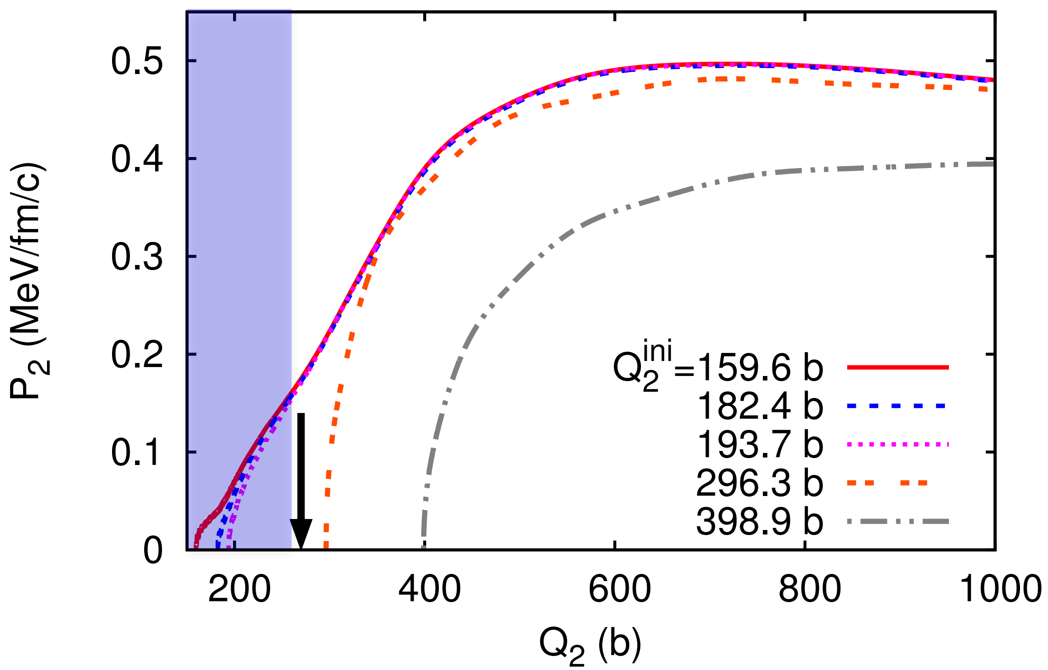
$$E_{\mathrm{diss}} \simeq 20\mathrm{MeV} \quad \mathrm{TKE} \simeq 250\mathrm{MeV}$$

Dissipative regime in TDDFT

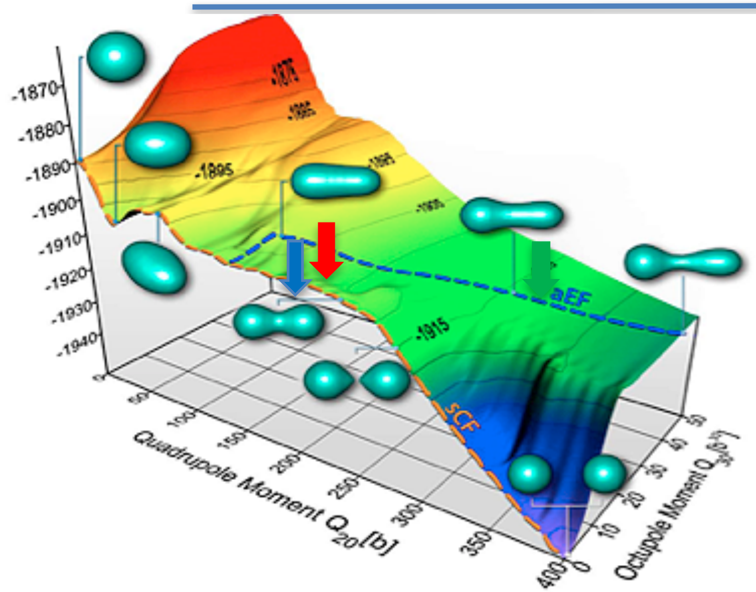


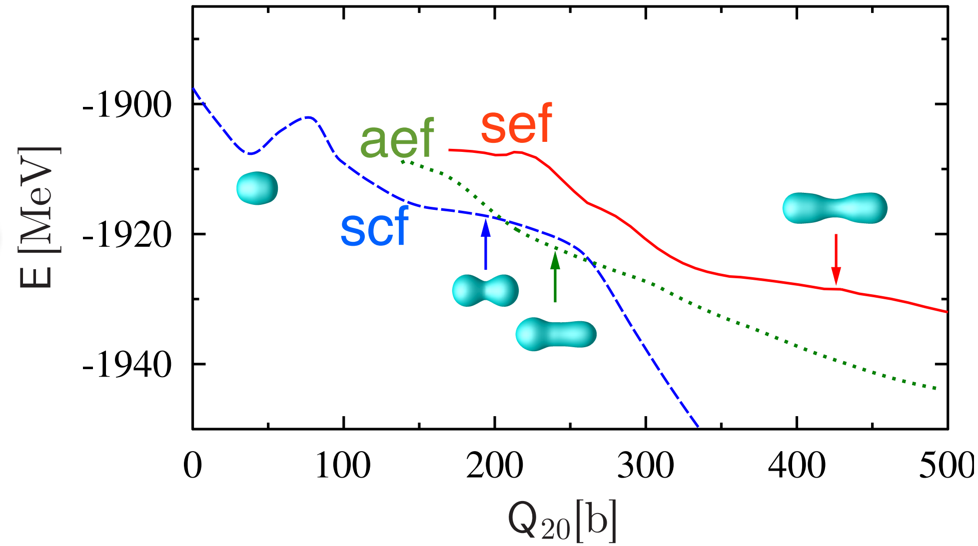
More or less
we confirm the overdamped
regime before scission
(Randrup, Moller model)

Collective momentum evolution



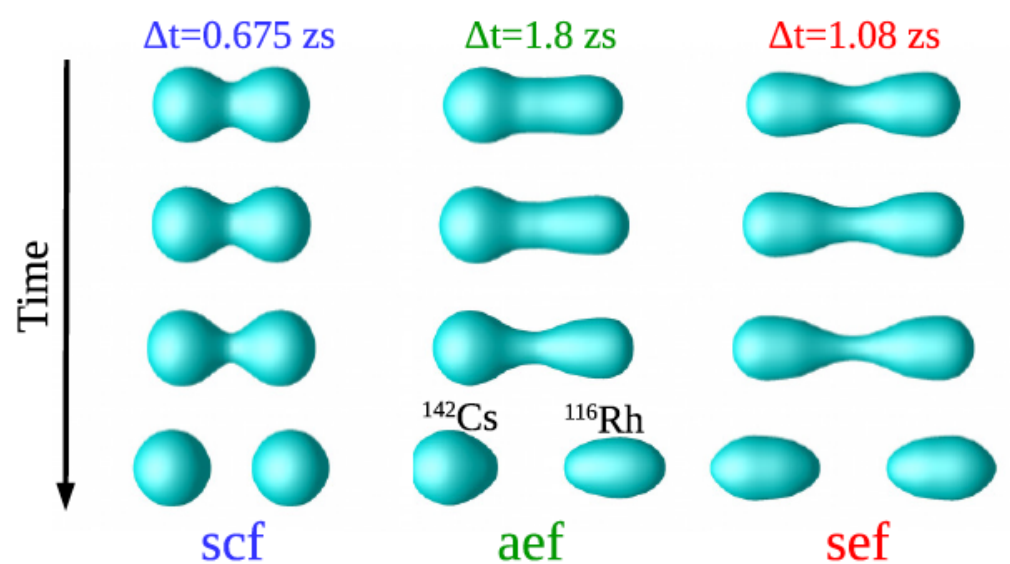
Still open :
Precise values of
dissipative transport
coefficients

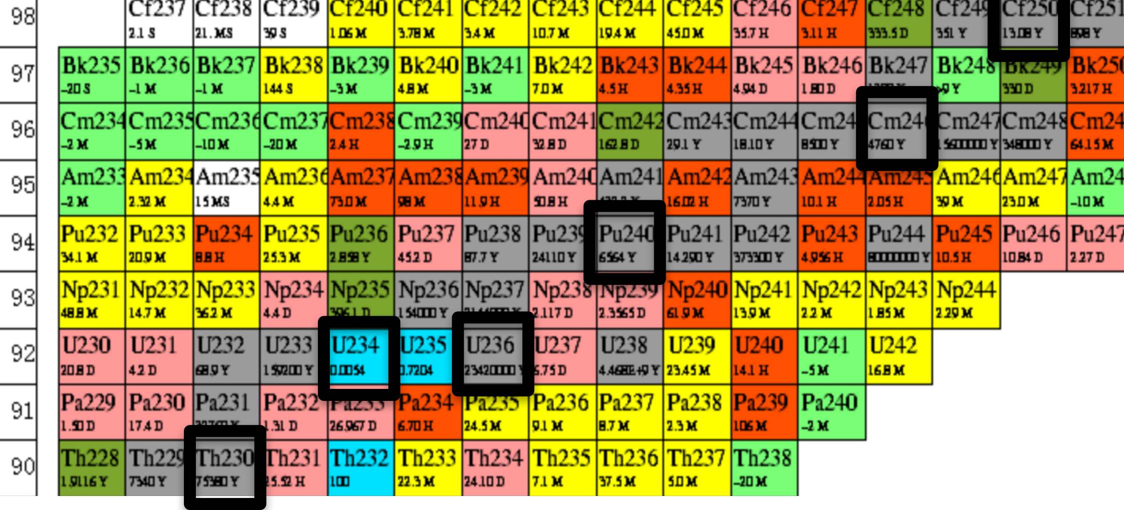




Identification of main fission paths

1 zs = 10^{-21} s

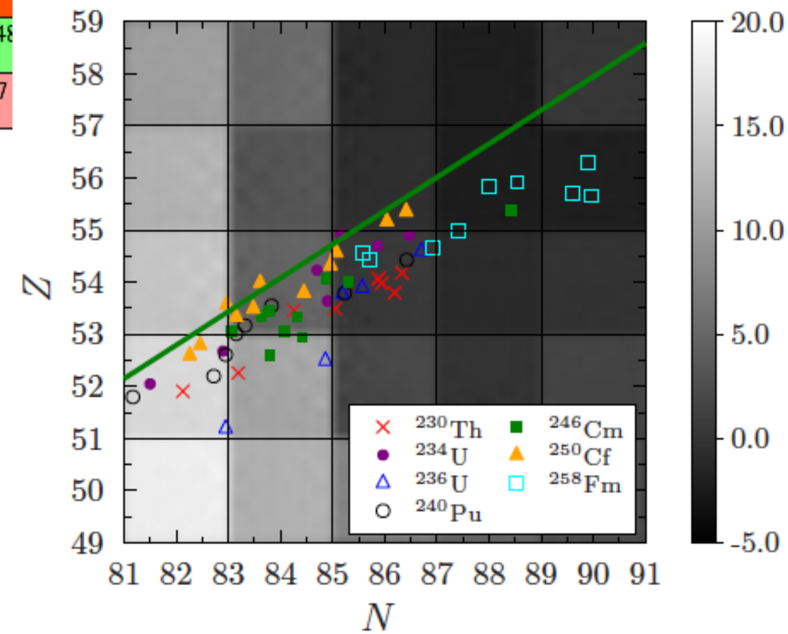




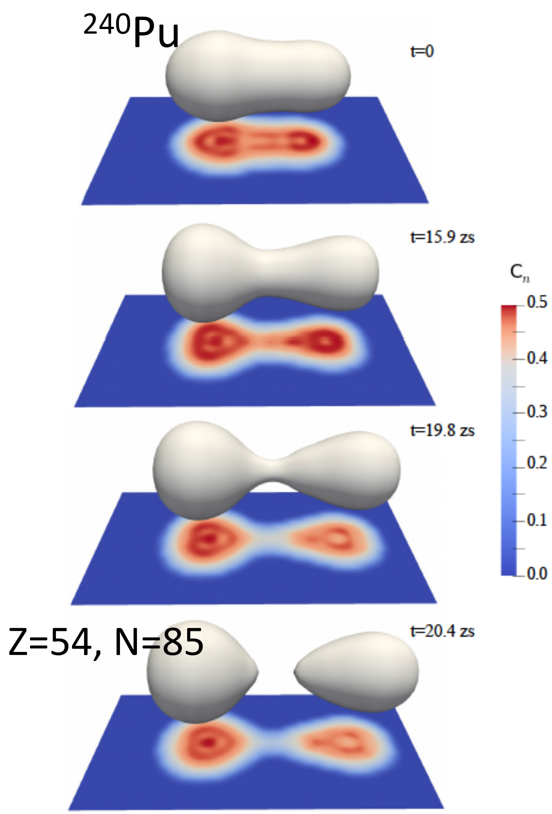
http://www.nuclear.nsdc.cn/nuclear/chart17.asp

Recent systematic analysis: N/Z physics

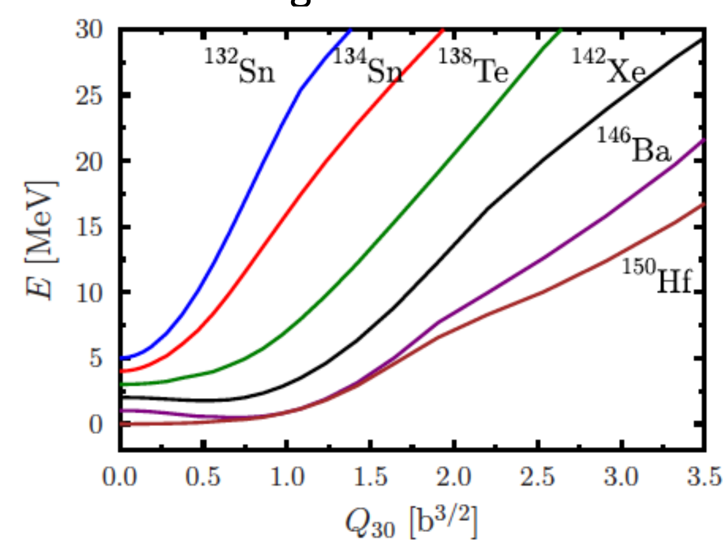
The Z=54 attractor

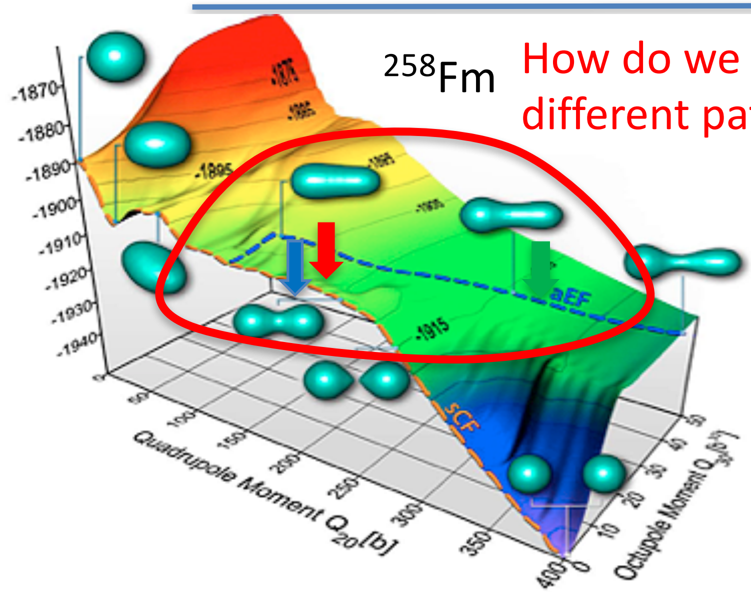


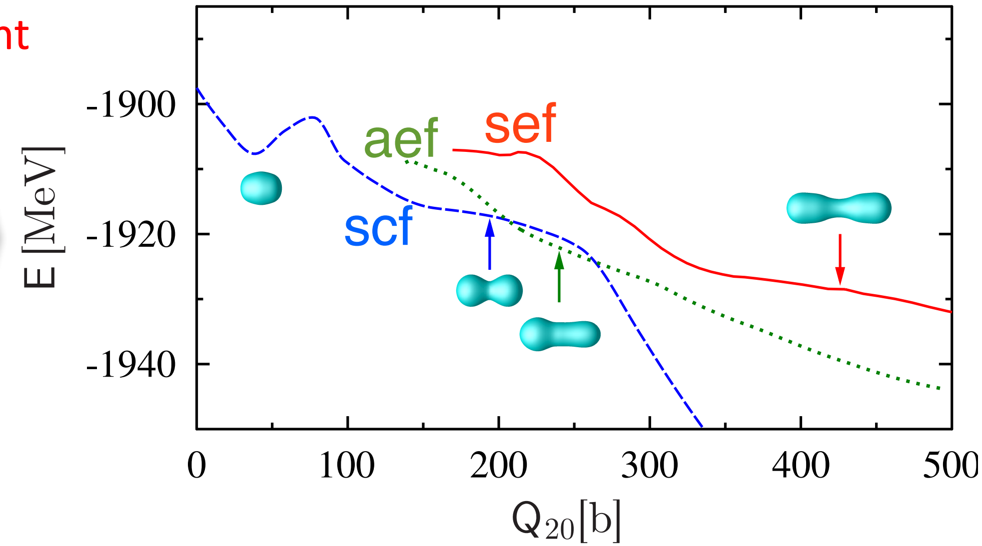
Scamps, Simenel, arxiv (2018)



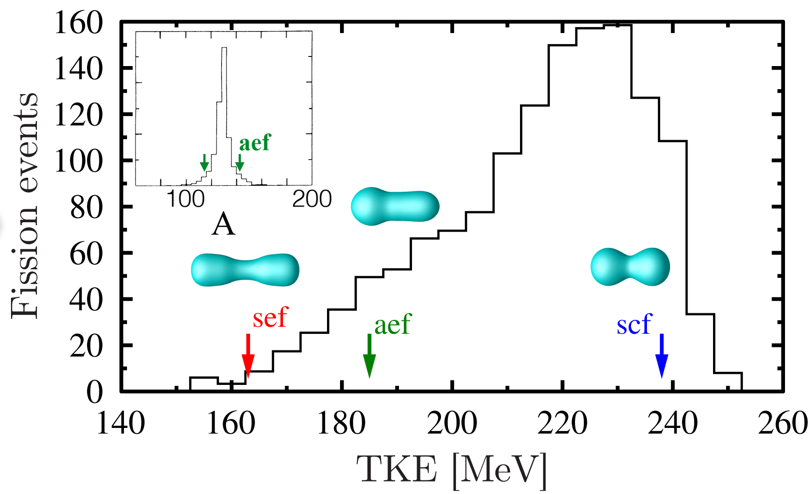
The preferential fission towards fragments with Z=52-56 might stems from the octupole softness around Barium.







Total Kinetic Energy



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

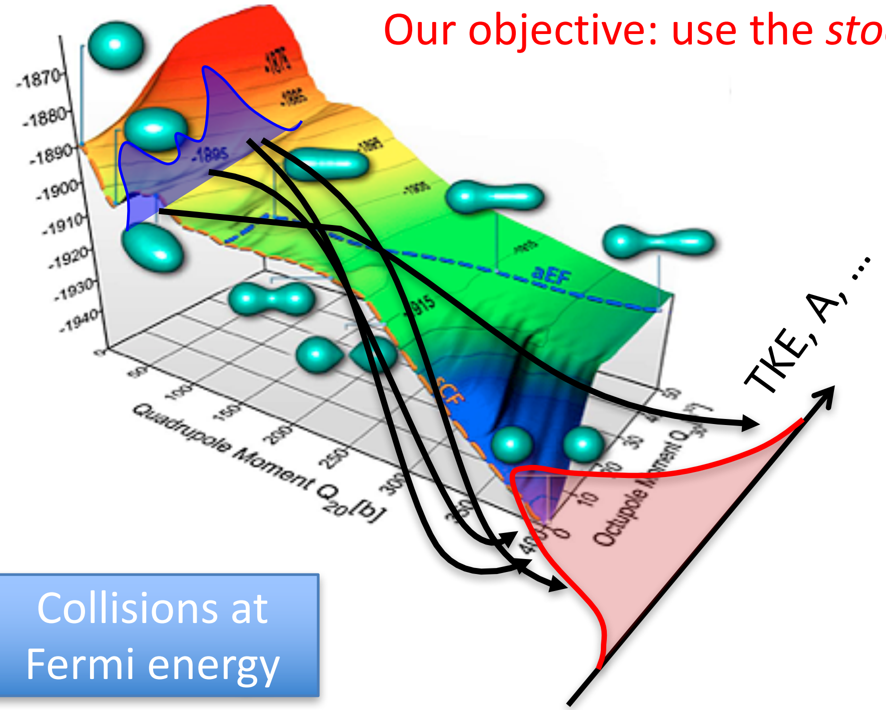
- Fluctuations are underestimated
- Weight of each paths?

Scamps, Simenel, DL, PRC 92 (2015)

Mean-field only will never be able to describe fully fission

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

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

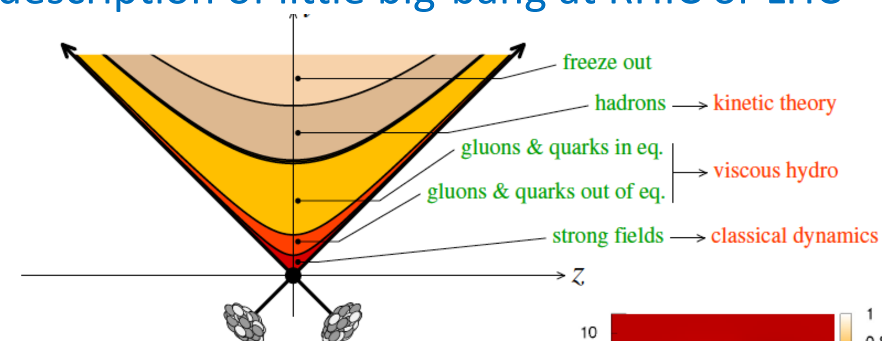


Quantum fluctuations can be treated approximately by sampling initial zero-point motion followed by classical trajectories (here classical=mean-field)

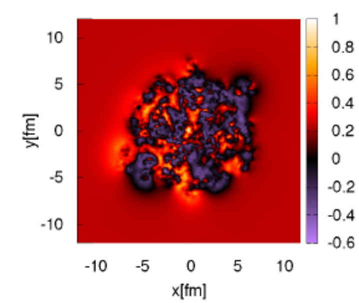
Collisions at Fermi energy

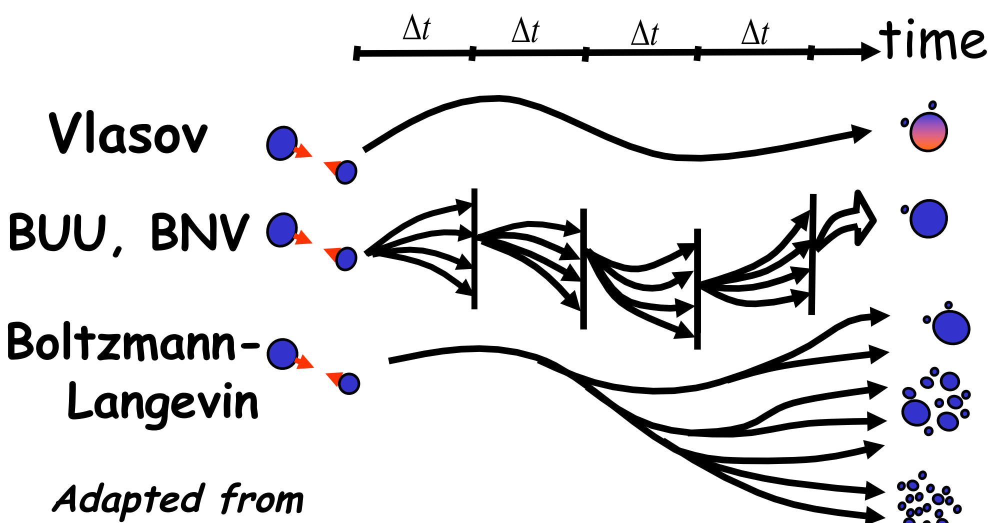
Related approaches:

-description of little big-bang at RHIC or LHC



Gelis, Schenke, arxiv:1604:00335





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

Truncated Wigner theory

For Bose-Einstein condensates

Sinatra, Lobo, and Castin, J. Phys. B 35 (2002)

Mean-Field theory

$$\frac{d\langle A_\alpha \rangle}{dt} = \mathcal{F}\left(\{\langle A_\beta \rangle\}\right)$$ at all time $\sigma_Q^2 = \langle A^2 \rangle - \langle A \rangle^2$

Stochastic Mean-Field

$$\frac{dA_\alpha^{(n)}}{dt} = \mathcal{F}\left(\{A_\beta^{(n)}\}\right)$$

$$\{A_\alpha^{(n)}\}$$

at all time $\Sigma_C^2 = \overline{A^{(n)}A^{(n)}} - \overline{A^{(n)}}^2$

Constraint: $\Sigma_C^2(t=0) = \sigma_Q^2(t=0)$

SMF in density matrix space: simple initial state

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

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

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

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

S. Ayik, PLB 658 (2008)

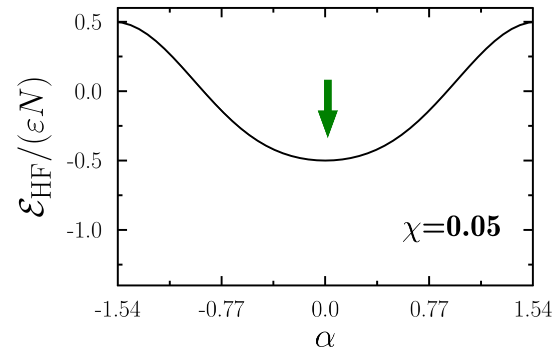
It gives a natural link with the theory of open quantum systems (quantum Langevin approach, non-Markovian, …)

$$m\frac{dv(t)}{dt} = F - \gamma v(t) + \eta(t)$$

The noise comes from the complexity of the bath that is treated through random initial conditions

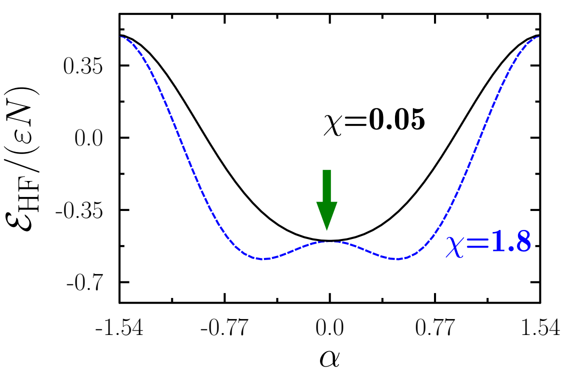
Illustration with the Lipkin model

Harmonic collective space

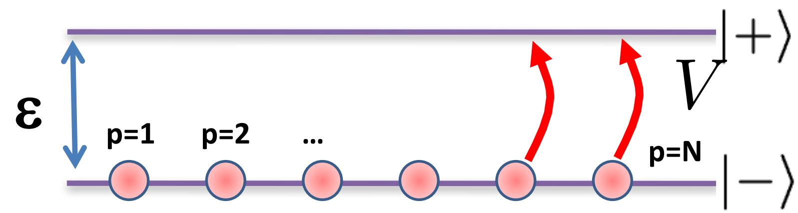


DL, Ayik, Yilmaz, PRC (2012)
DL, Tanimura, Ayik, EPJA (2016)

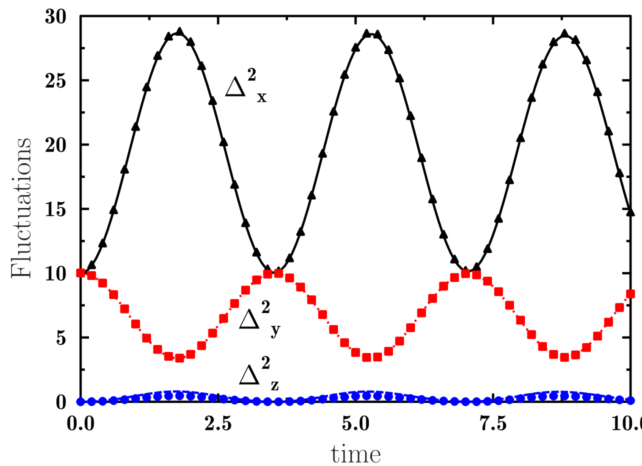
Anharmonic unstable collective space



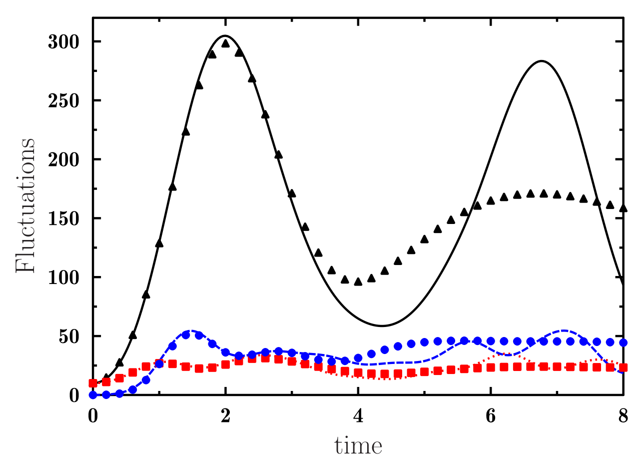
Two-Level Lipkin Model



$$\chi = V/\varepsilon$$

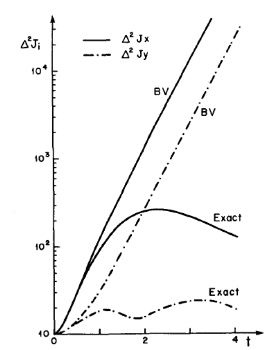


Effect beyond mean-field (RPA like) almost exactly treated!



Short time is properly treated.
Decay time also…

BV result



$$\chi = 1.5$$

Bonche, Flocard, NPA437 (1985)

Progress

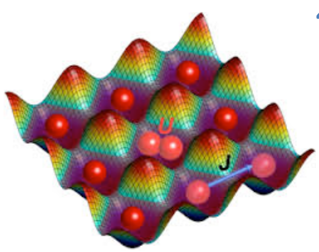
➡ Extension to superfluid systems: TDHFB with fluctuations

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)

DL, Ayik, Yilmaz, PRC (2012)
DL, Ayik, EPJA [Review] (2016)

SMF in density matrix space

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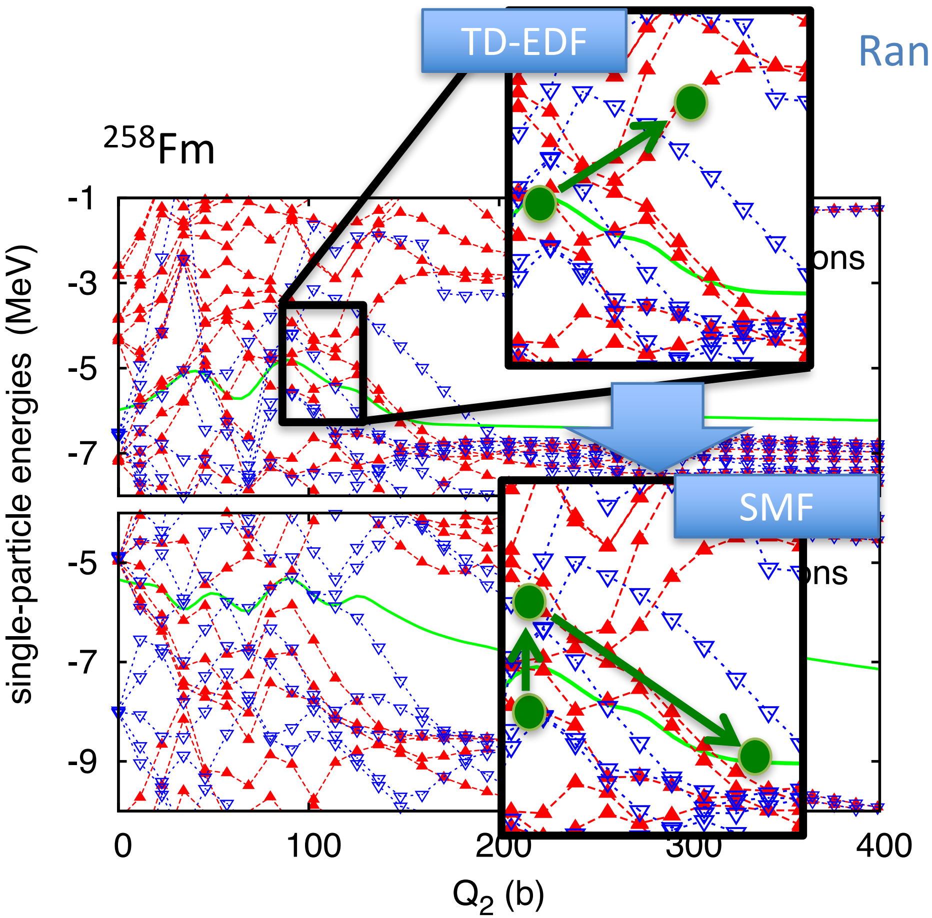
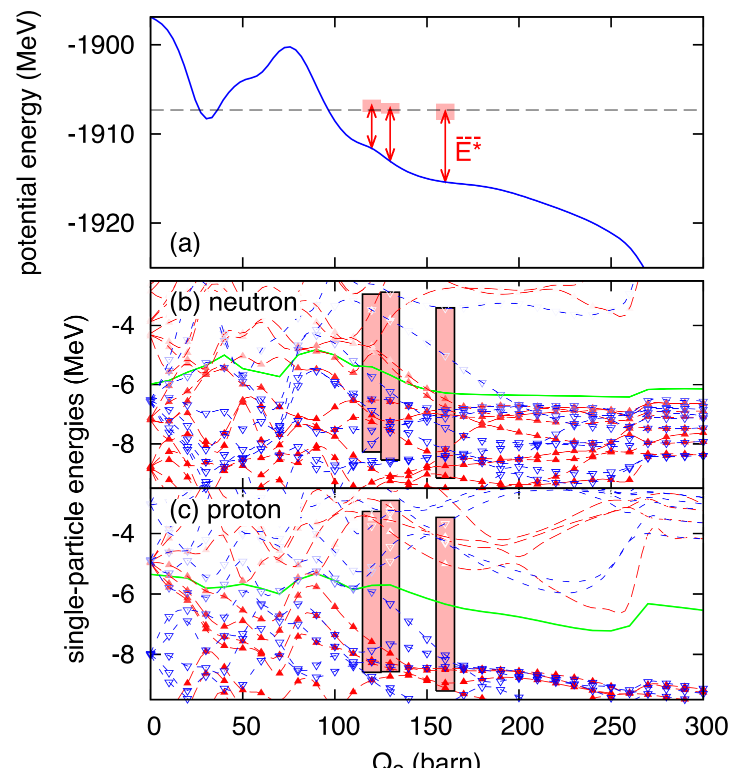
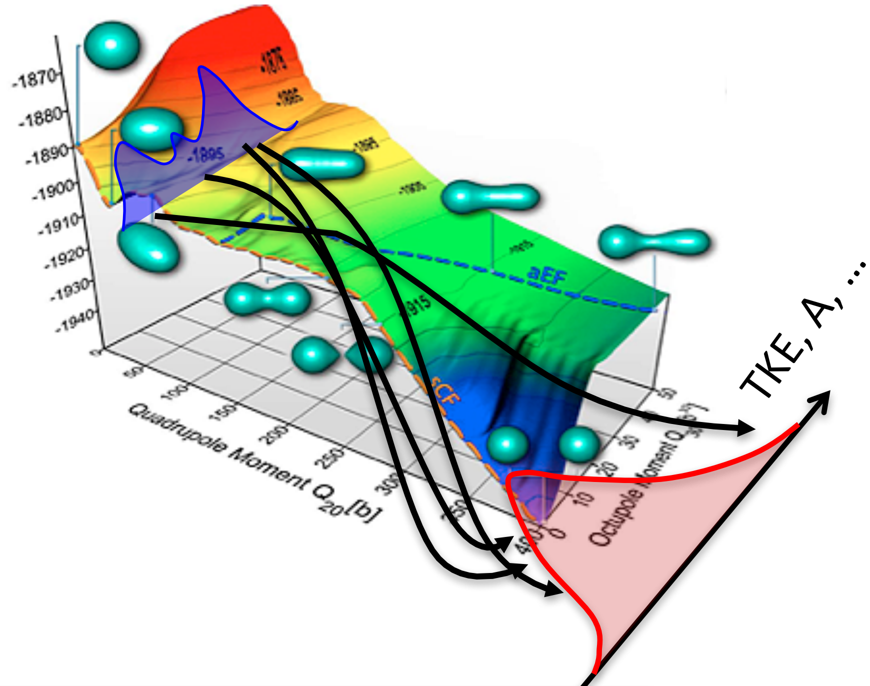
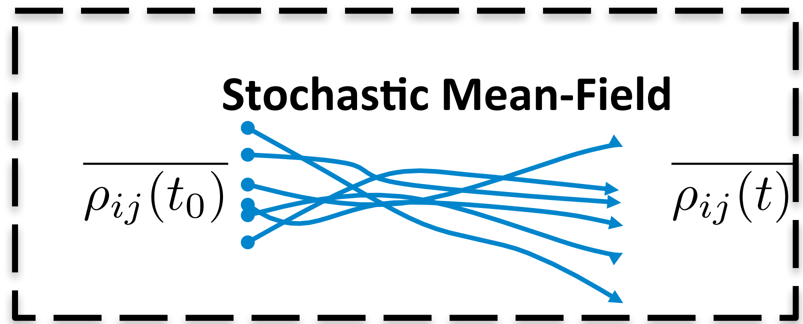


Range of fluctuation fixed by energy conservation



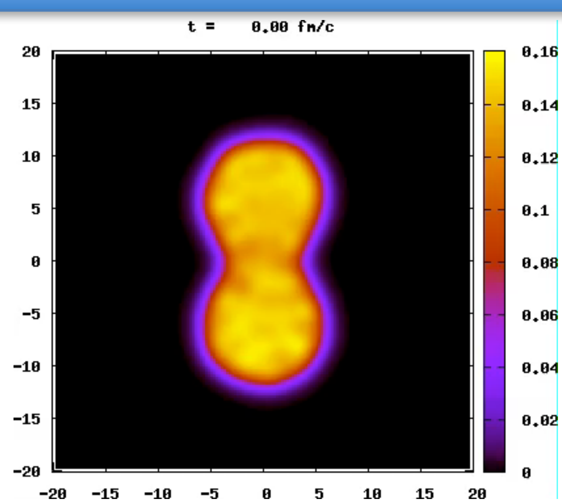
How to conceal microscopic deterministic approach and randomness ?

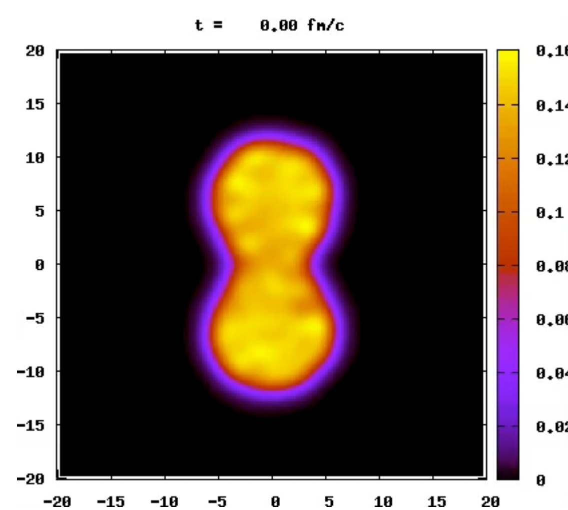




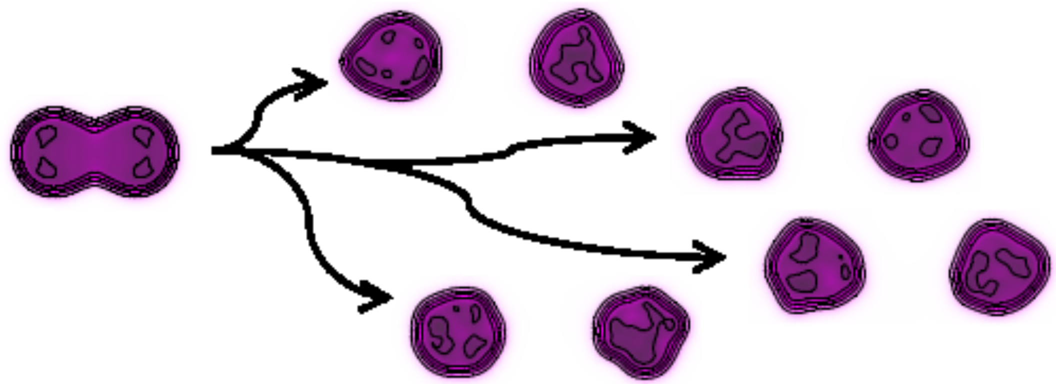
Numerical effort:
-Generates a sample of microscopic trajectories (typically 300 to 1000)
-Each trajectory is 8-10 days CPU time

Some trajectories illustration



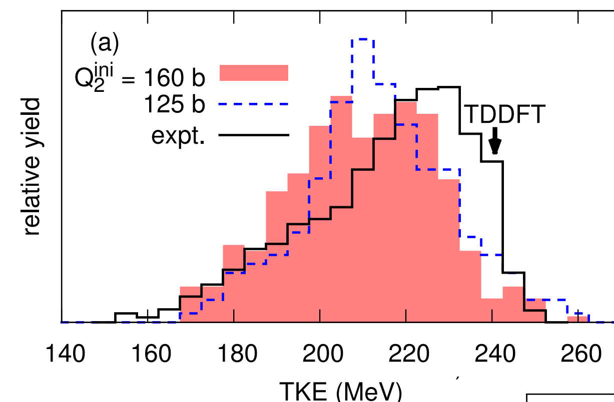


Phase-space average method: experiment versus theory



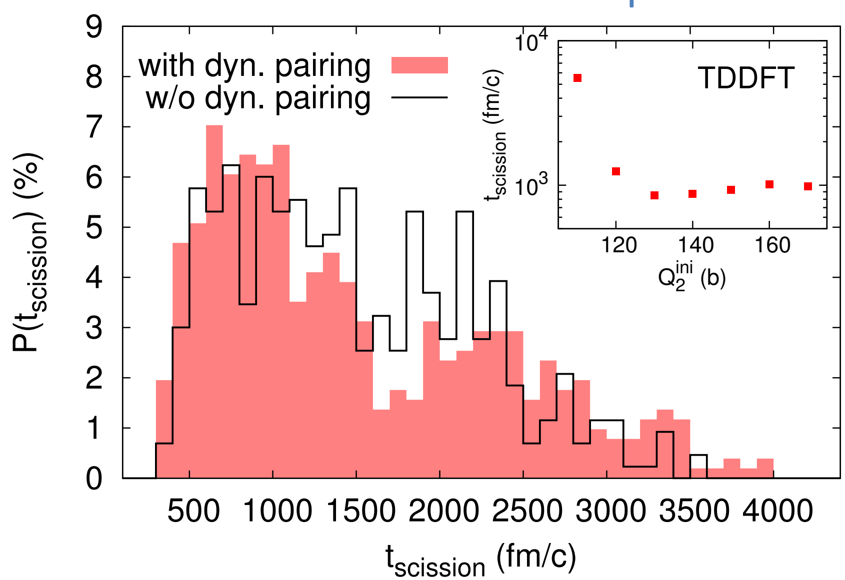
Tanimura, Lacroix, Ayik, PRL (2017)

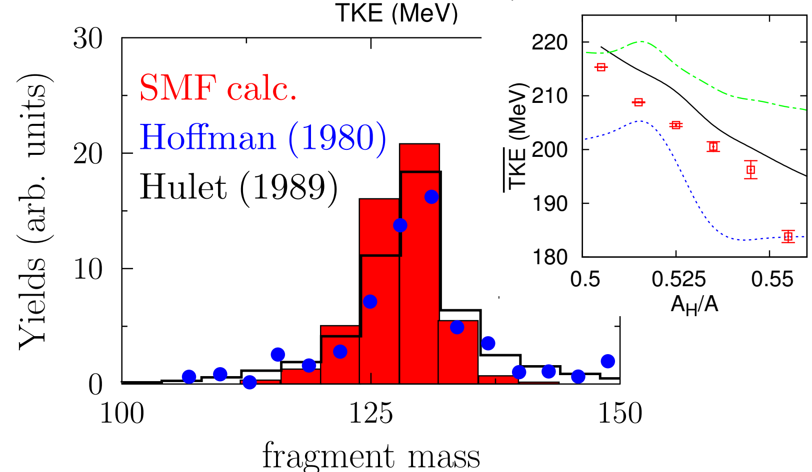
Theory vs experiment

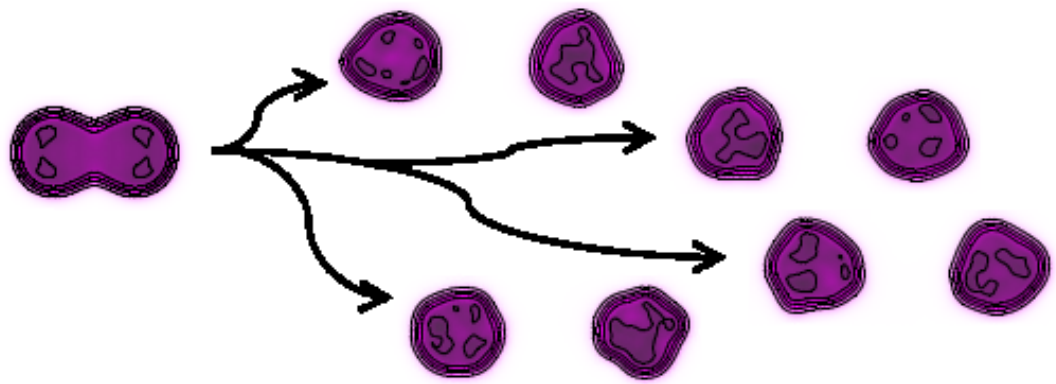


From deterministic to statistical approach

Time to reach scission point

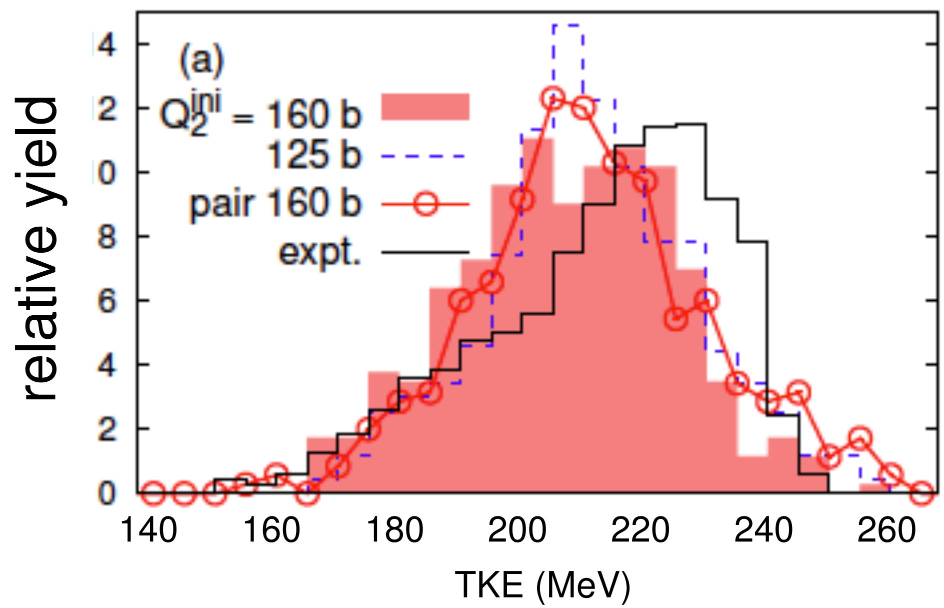




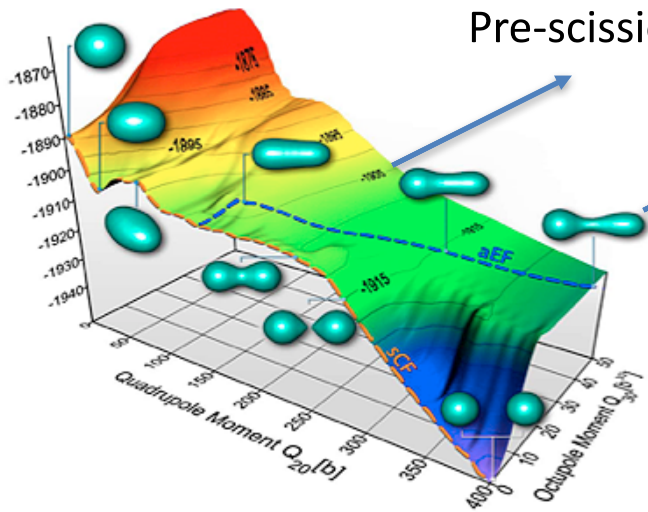


Tanimura, Lacroix, Ayik, PRL (2017)

Quantum fluctuation versus dynamical pairing



How to conceal microscopic deterministic approach and randomness ?

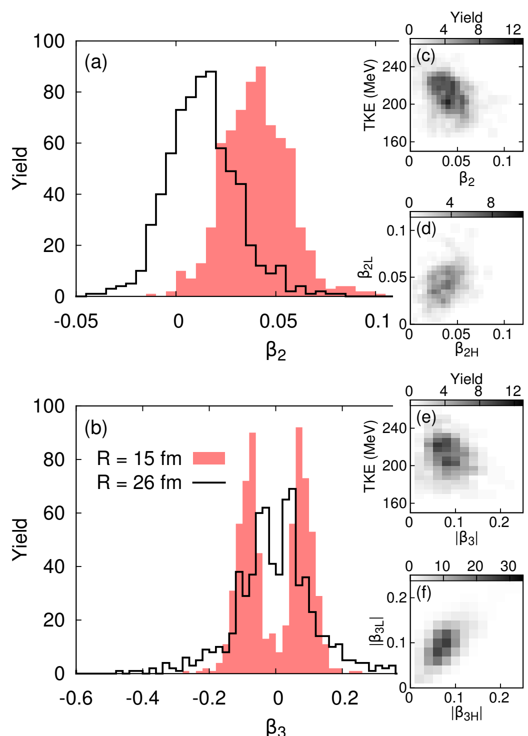


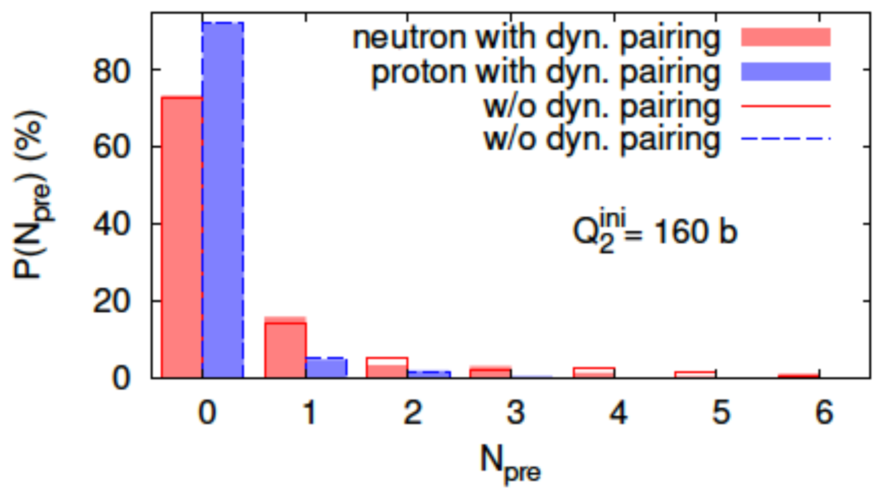
Pre-scission neutron?

Post-scission neutron ?

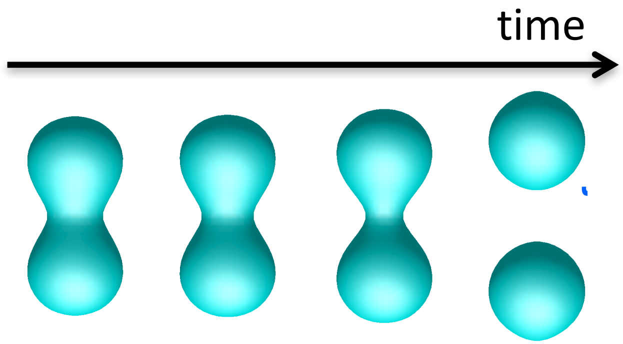
Precission neutron emission

Internal deformation of fission fragments





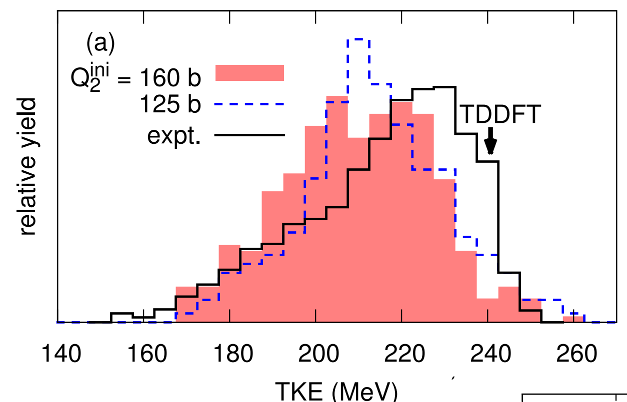
- TDDFT codes including pairing are now developed
- This open new applications perspectives



Applications to fission

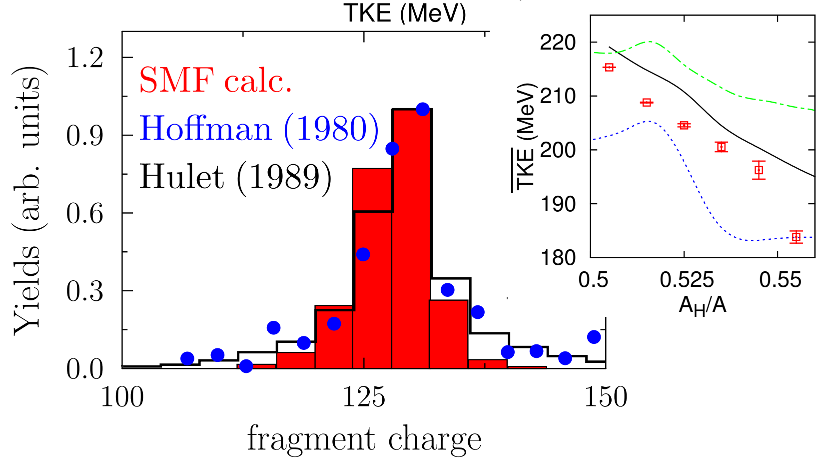
- Fission of superfluid nuclei
- Collective mass and dissipation
- Dynamical time-scale to scission

Theory vs experiment

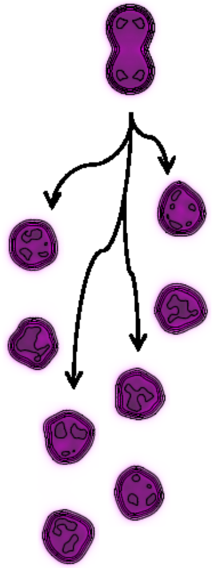


Beyond mean-field with quantum fluctuations

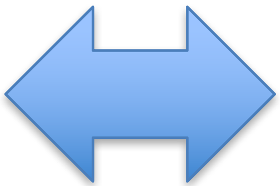
- First application with sampling of initial phase-space in TD-EDF
- TKE and mass distribution of 258Fm
- Towards a systematic study of spontaneous and induced fission

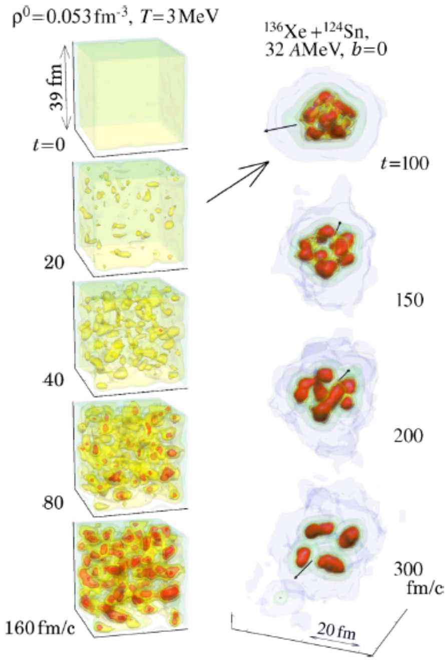


Unifying low and Fermi energy theories



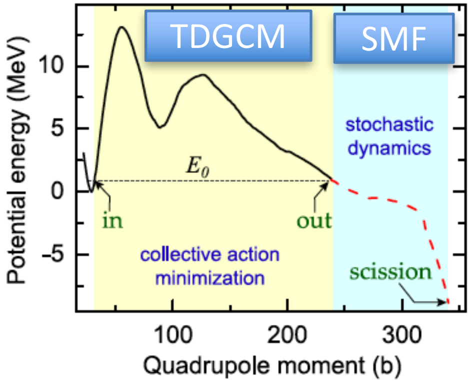
Tanimura et al, PRL118, (2017)



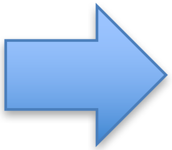


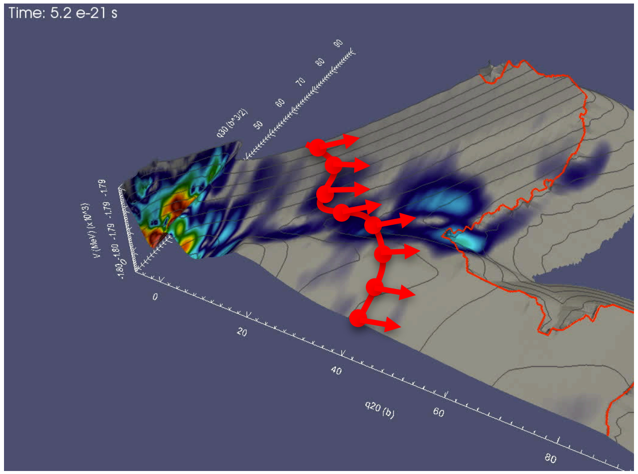
Napolitani, Colonna, PRC 96, (2017)

Nuclear Fission from the early stage



Sadhukhan, Nazarewicz, Schunck, PRC 93, (2016)





Regnier, Schunck, DL (2018)