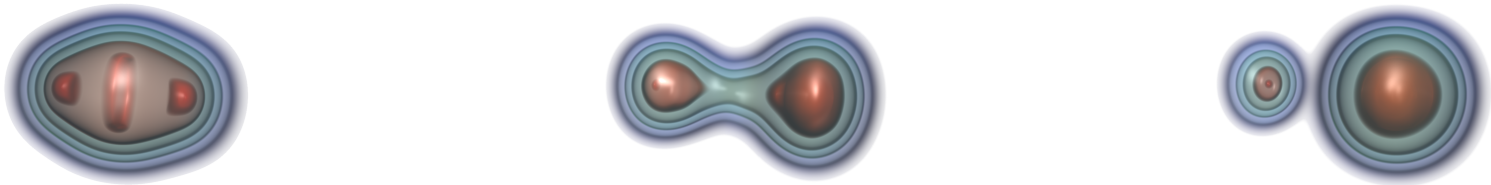
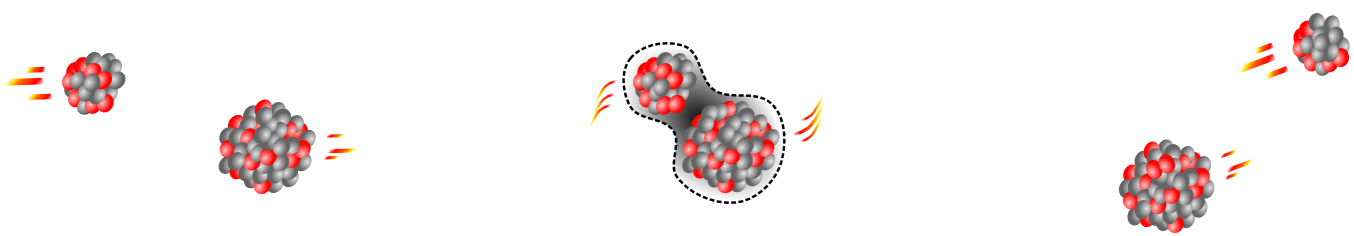


Nuclear dynamics with energy density functional theory

D. Regnier[2,3], T. Czuba[1], H. Dinh[1], N. Dubray[2,3], D. Lacroix[1], R.-D. Lasseri[4], P. Napolitani[1], N. Pillet[2,3], G. Verde[5]

[1]IJCLab, 91405 Orsay, France
[2]Univ. Paris-Saclay, CEA, Laboratoire Matière en Conditions Extrêmes, Bruyères-le-Châtel, France
[3]CEA, DAM, DIF, 91297 Arpajon, France
[4]ENS Paris-Saclay, 91190 Gif-sur-Yvette, France
[5]L2IT, Toulouse, France



The time dependent picture of nuclear processes

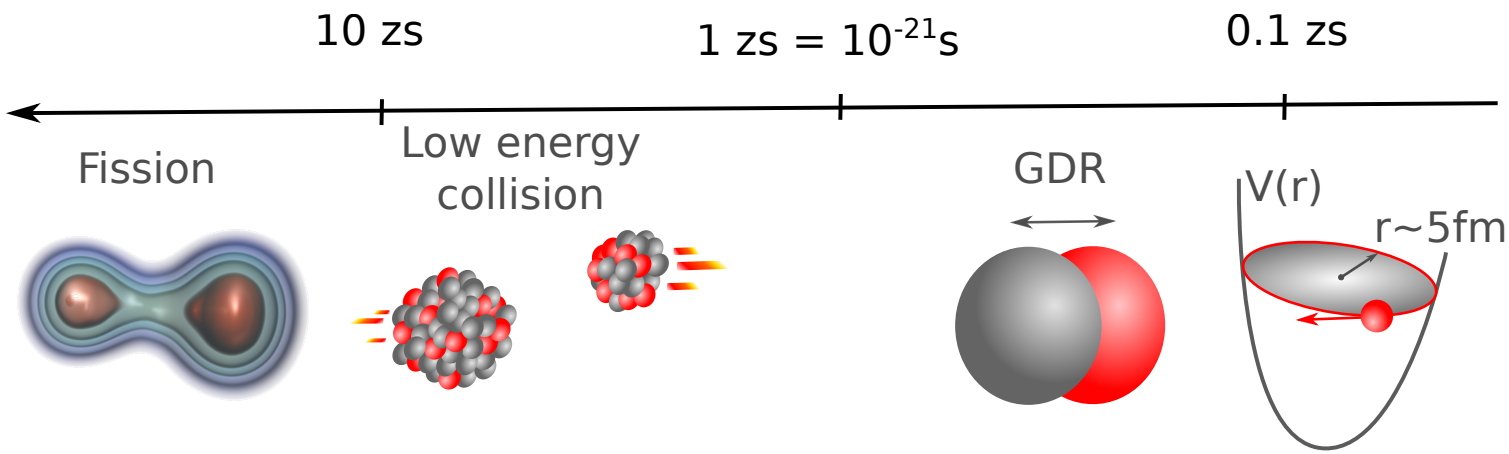
Two ways of studying nuclear systems

$$H\psi_n = E_n\psi_n \qquad i\hbar\partial_t\psi = H\psi$$

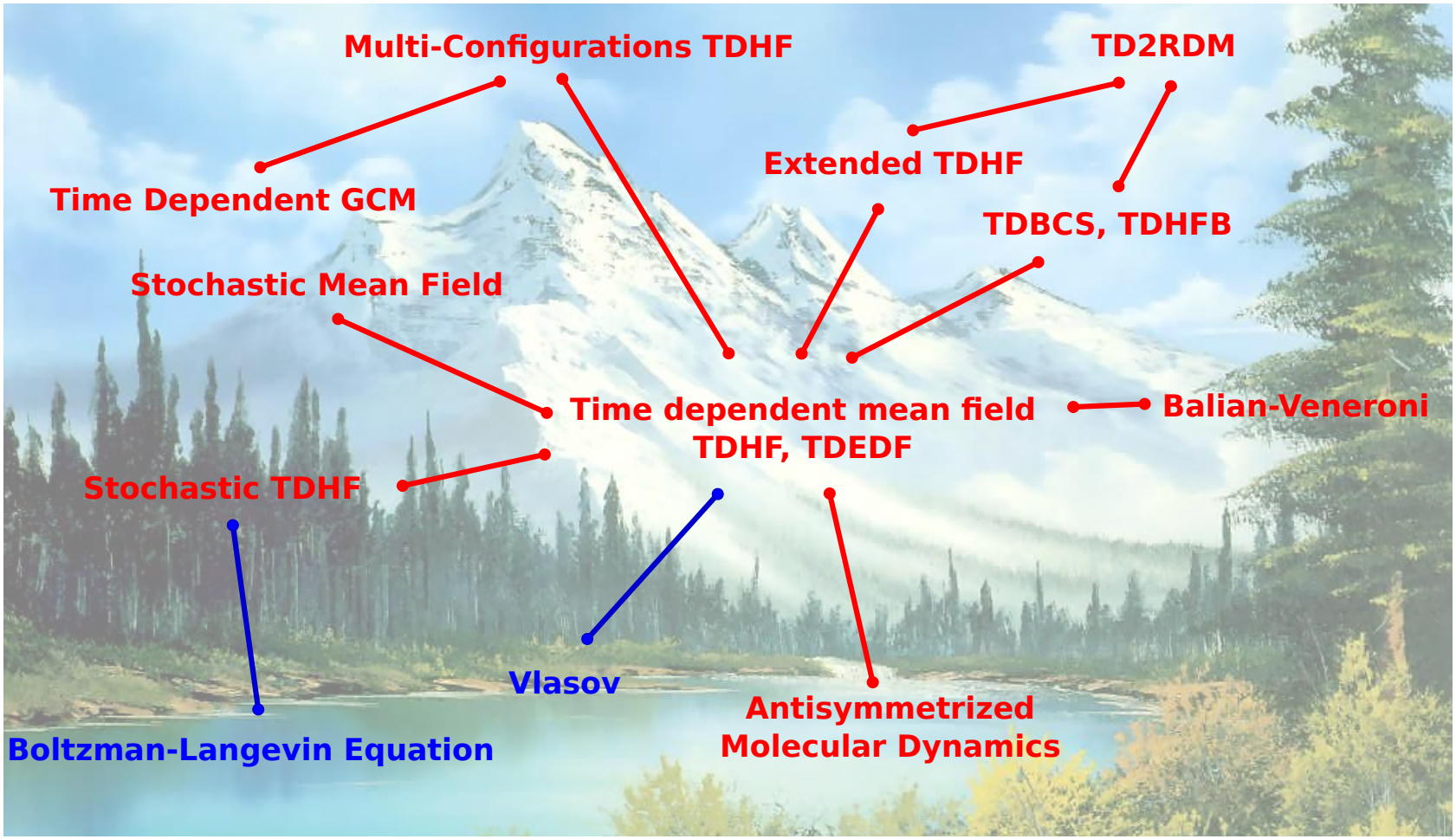
$\Longrightarrow$ Dynamics for any initial condition

$\Longrightarrow$ Dynamics for one initial condition

- **Collective vibrations**:
  Gamma strength function
- **Heavy ion collision**:
  Fusion cross sections, nucleon transfer, nuclear matter properties
- **Induced fission**:
  Mass and charge yields, sharing of the energy and spin

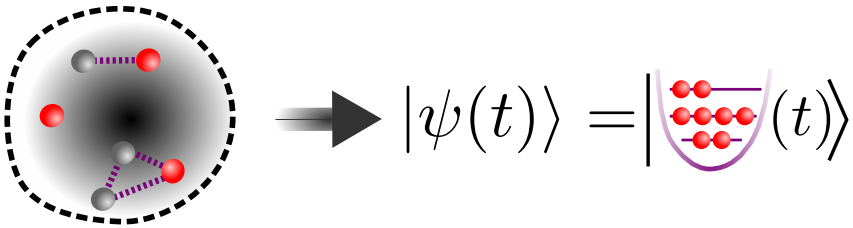


A landscape of time dependent theoretical approaches



- Specialized methods: one application/observable with one method

Fission at the time dependent mean-field level



Recent successes:

2014: ^{258}Fm ^{264}Fm (no pairing)

C. Simenel *et al.*, PRC **89**, 031601(R) (2014)

2015: ^{258}Fm with pairing (TDBCS)

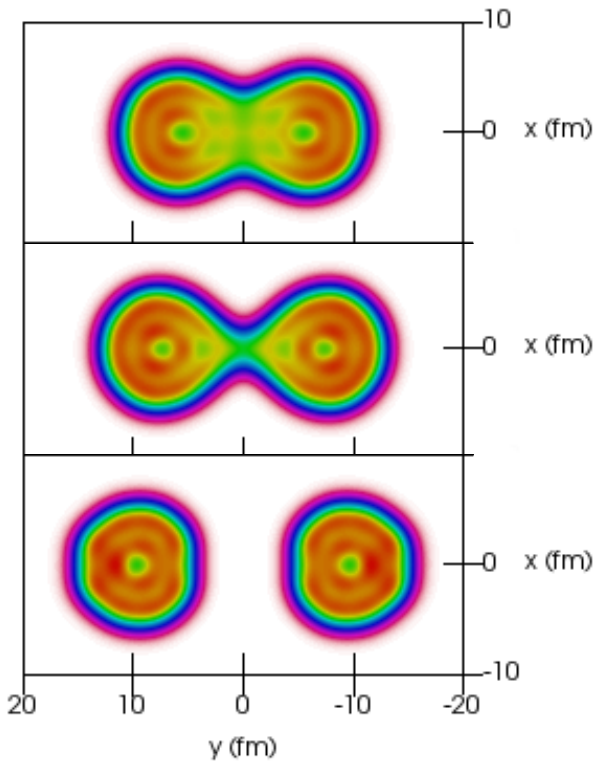
G. Scamps *et al.*, PRC **92**, 011602(R) (2015)

2016: ^{240}Pu with pairing (full TDHFB)

A. Bulgac *et al.*, PRL **116**, 122504 (2016)

2021: Spin of the fragments

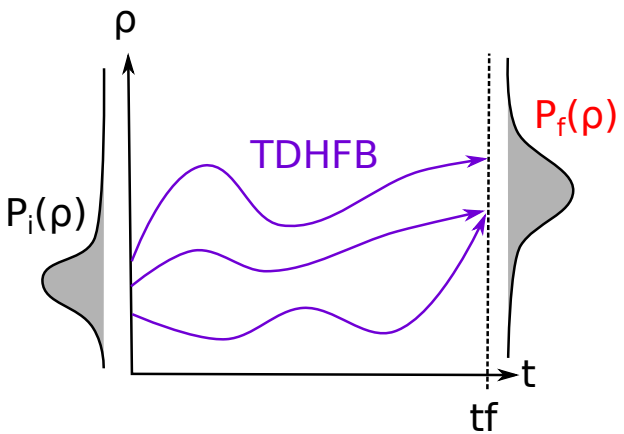
A. Bulgac *et al.*, PRL **126**, (2021)



✓ Dynamics through scission (diabatic aspect)

✗ Fragments mass yields (lack of 1-body fluctuations)

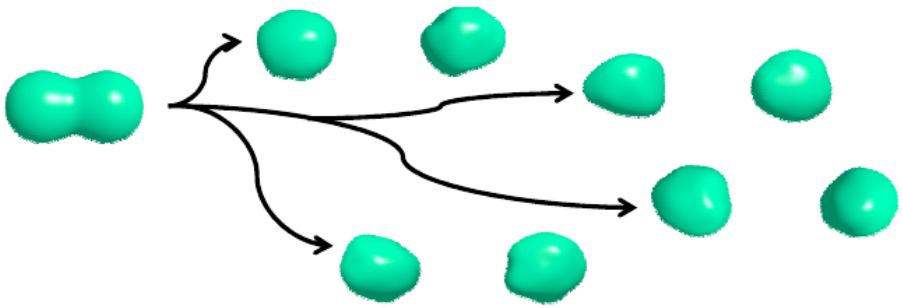
Including fluctuations with a statistical ensemble of trajectories

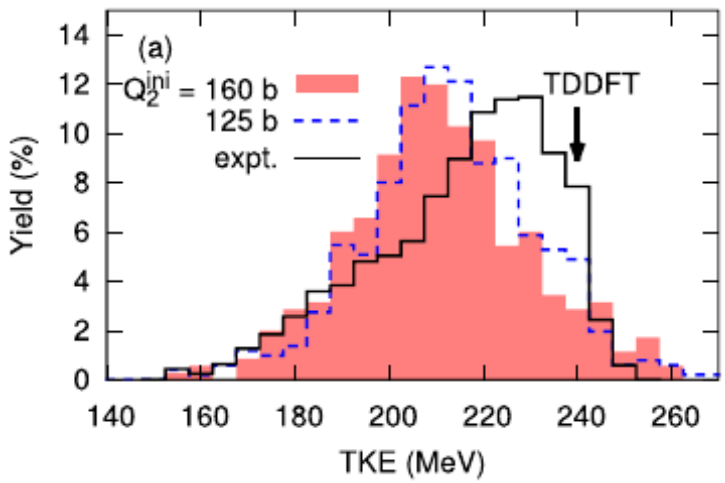


- Statistical distribution of initial states (i.e. Wigner transform)
- Classical averaging of observables

Example: Stochastic Mean Field dynamics of fission

D. Lacroix *et al.*, EPJA 50 (2014)





Y. Tanimura *et al.*, PRL **118** (2017)

✓ Fragment kinetic energy distribution (large fluctuations)

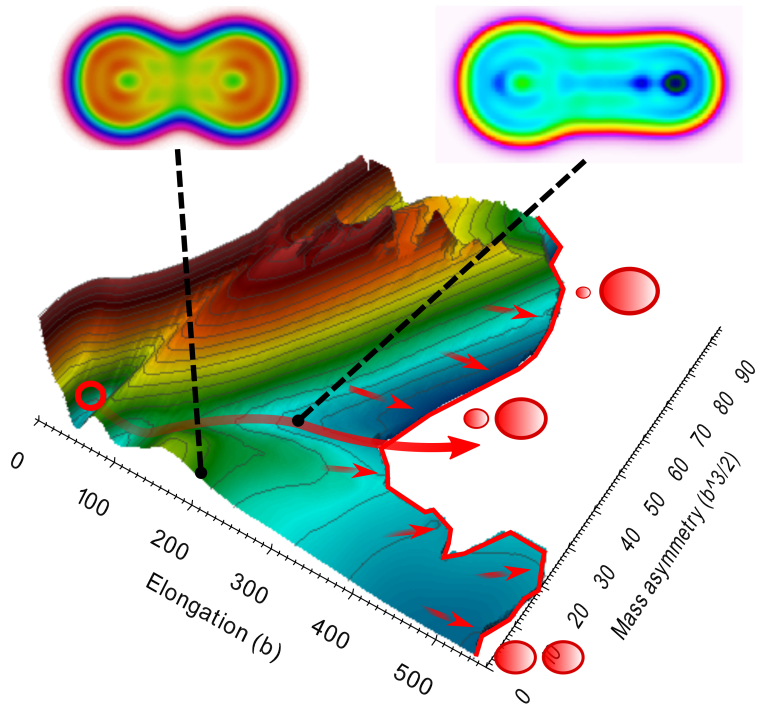
✗ No tunnelling through fission barrier (lack of quantum interferences)

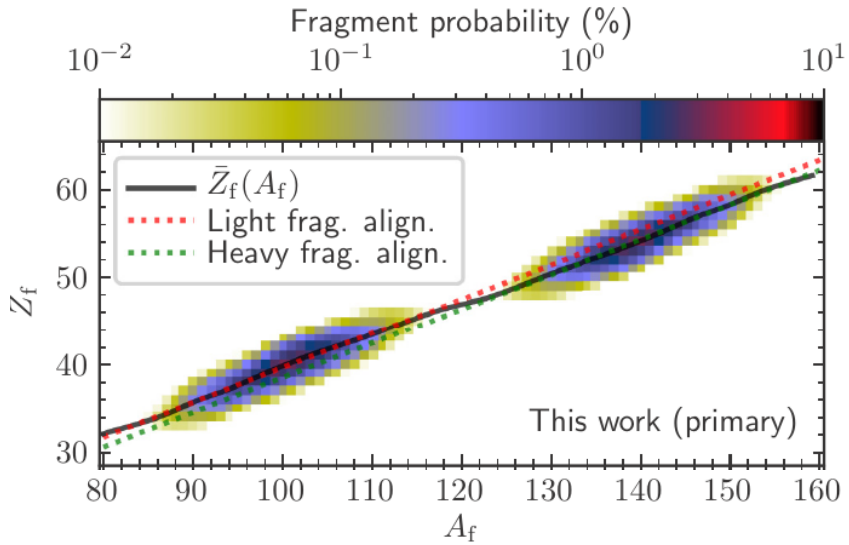
Quantum interferences: Time Dependent Generator Coordinate Method

$$|\psi(t)\rangle = f_1(t)\left|\;\right\rangle + f_2(t)\left|\;\right\rangle + \cdots$$

Constrained HFB solutions with ≠ shapes, time independent

1. Set of parameterized states
2. Dynamics in a collective space





M. Verriere *et al.*, PRC 103 (2021)

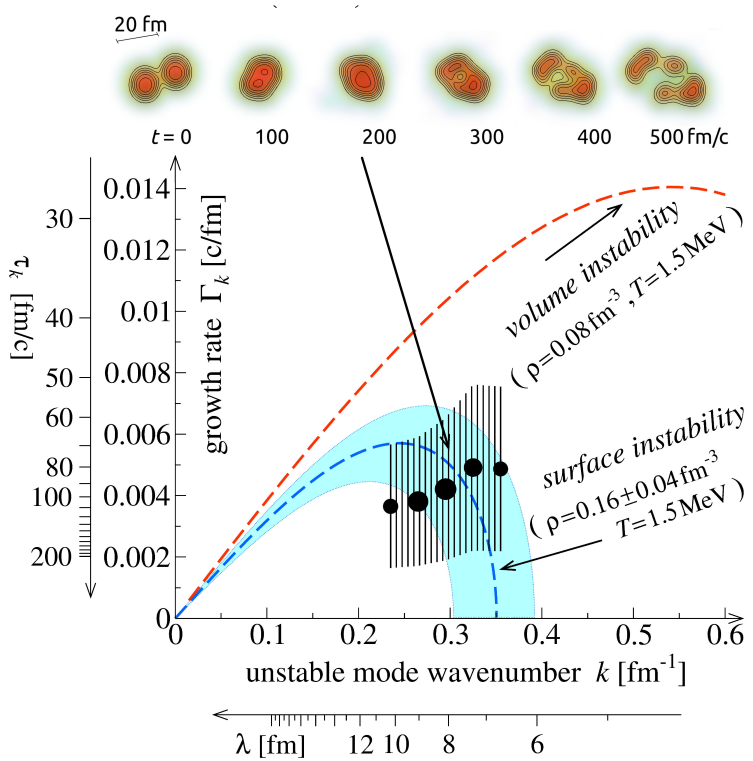
✓ Quantum tunnelling through fission barrier

✗ Dynamics through scission (diabatic aspect)

Clusterization and fragmentation around the Fermi energy

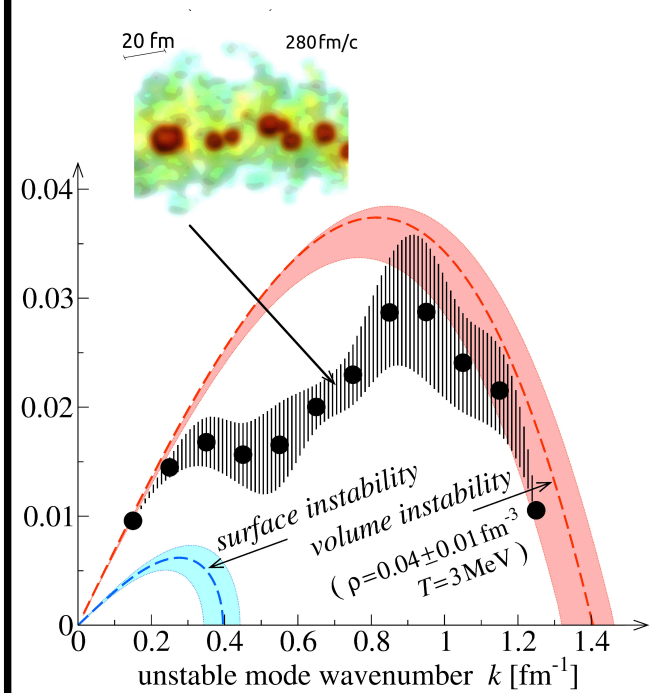
split in four fragments $A \gtrsim 20$ in ^{197}Au+^{197}Au 15AMeV

Boltzmann-Langevin PRC 100 (2019) 054614

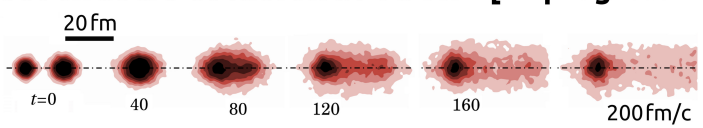


stream of clusters (jet) in ^{36}Ar+^{58}Ni 74AMeV

Boltzmann-Langevin PLB 797 (2019) 134833



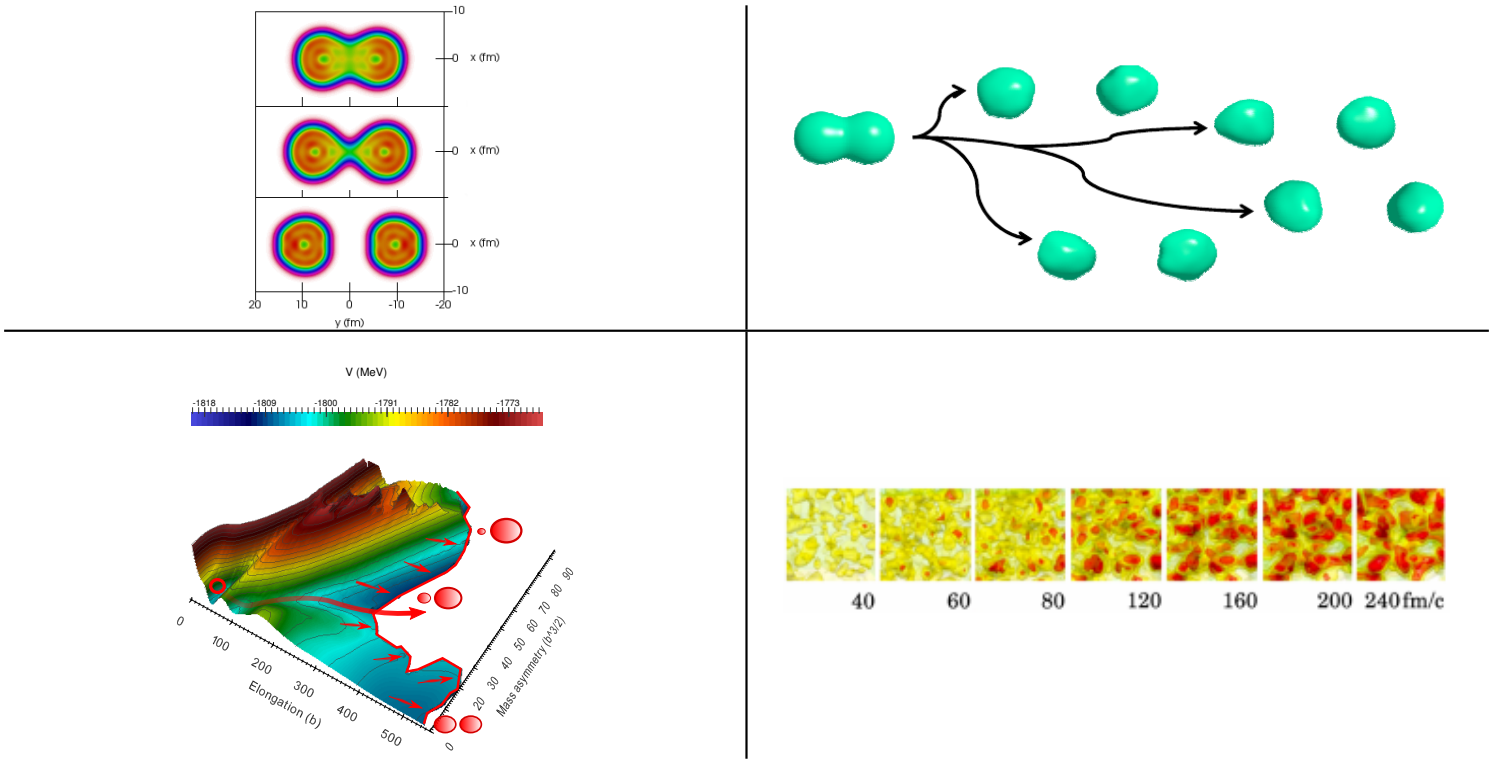
***stochastic collisional* TDHF [in progress...]**



✓ Large fluctuations

✗ Quantum coherence

New methods to rule them all ?



Fluctuation, diabatic motion and quantum coherence

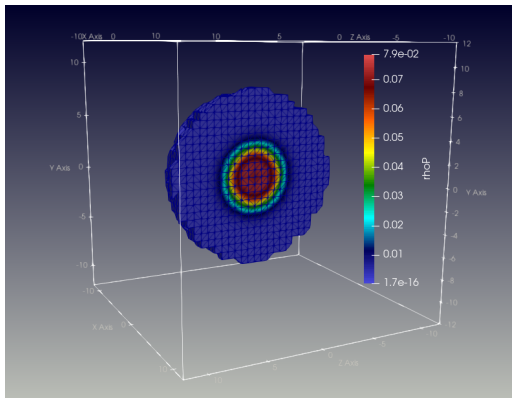
- A theoretical challenge
- A requirement to connect to observation
  - Fusion cross section (production of super-heavy nuclei)
  - Radiative capture cross section (nucleosynthesis)

Prospectives

Modernizing/standardizing our simulation tools

Objectives:

- versatile codes
- sharing with the community
- documented and tested



A new time dependent mean field solver

- Finite element method
- Usable in multi-reference approaches

D. Regnier, D. Lacroix, CEA/IJCLab, started 2021

Fermi energy heavy ion collision: application oriented support

- Support and tutorials for applicative users
- Medical applications: interfacing with GEANT-4, deep learning emulation

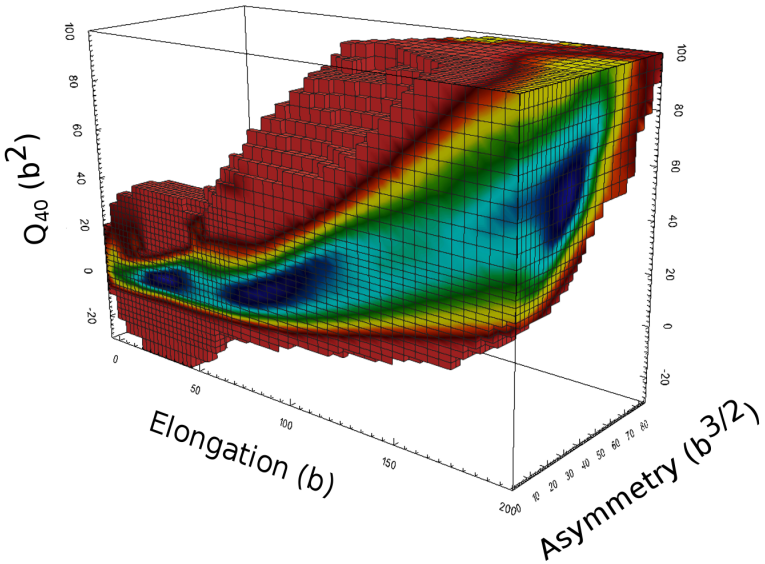
P. Napolitani, G. Verde, et al., IJCLab/L2IT, C. Mancini, INFN Roma ...

Enhancing our description based on collective spaces

Going beyond 2-dimensional spaces

- TDGCM in 3-dimensional spaces

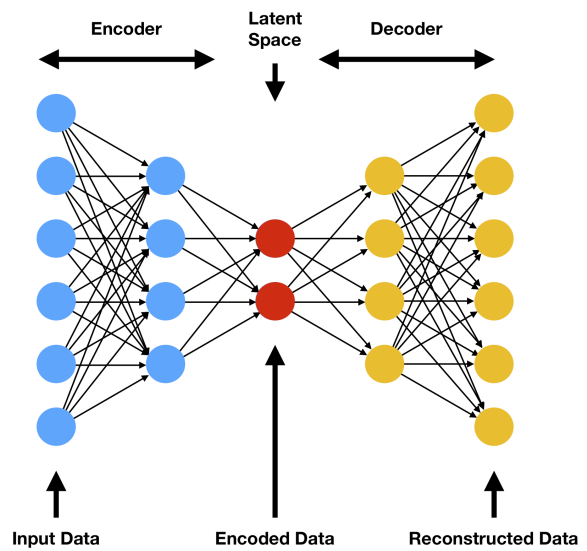
N. Dubray, N. Pillet, D. Regnier
CEA, starting 2021



Building collective spaces with AI

- Unsupervised machine learning learning of collective coordinates

R.-D. Lasseri, D. Regnier
ENS Cachan/CEA, started 2020



Toward diabaticity and collective fluctuations

Exploring phase space approaches to fermions dynamics

- Developpement, implementation and comparisons of theoretical approaches

T. Czuba, D. Lacroix et al. IJCLab

Including intrinsic excitations in TDGCM

- TDGCM expansion including quasi-particles excitations

N. Pillet, R. Bernard, CEA/Autralian Nat. Univ.

Simulating nuclei with Multi-configurations TDHF

- Coupling several time dependent mean field trajectories

D. Regnier, D. Lacroix CEA/IJCLab

Large amplitude dynamics for cluster/fragment production

- Development of TDHF extensions including dissipation and clustering

H. Dinh, P.Napolitani, M.Colonna, started 2019

Thank you for your attention !