Pairing effects in nuclear reactions

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IPN Orsay

Outline:

- Generalities on time-dependent energy density functional theory
- Time-dependent mean-field with pairing
- Collective motion in nuclear
- Reaction mechanisms: transfer reaction and fission

Coll: G. Scamps, Y. Tanimura

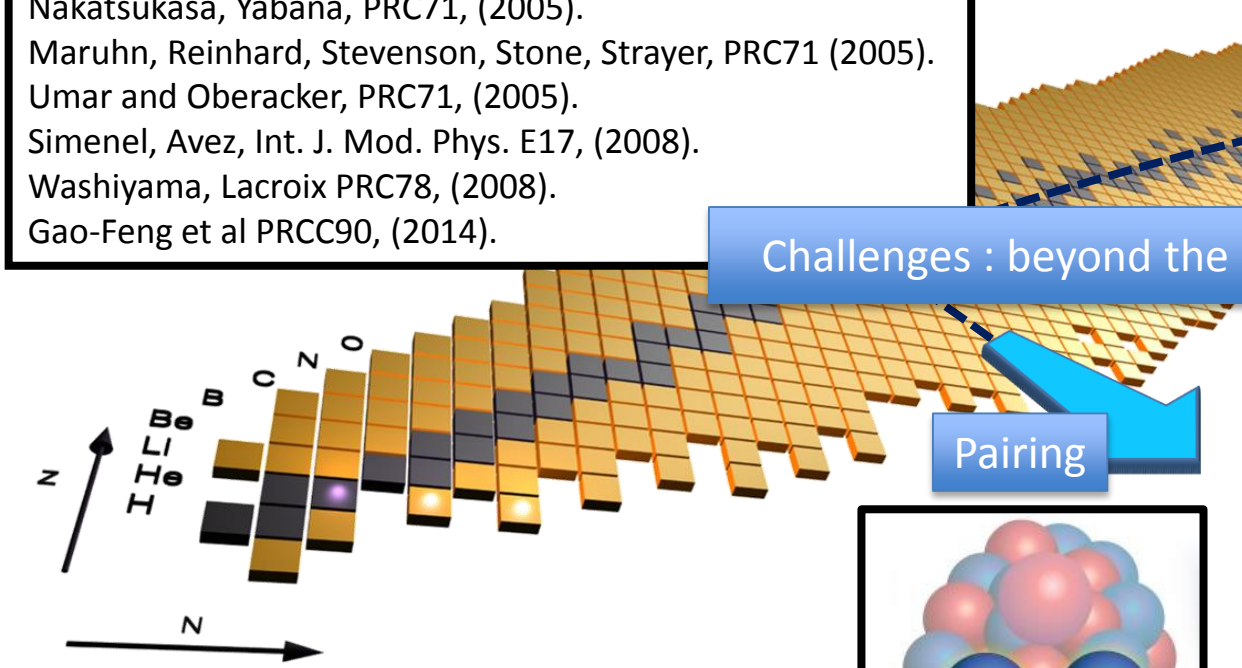
Roadmap: challenges for nuclear reaction/structure models at low energy

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

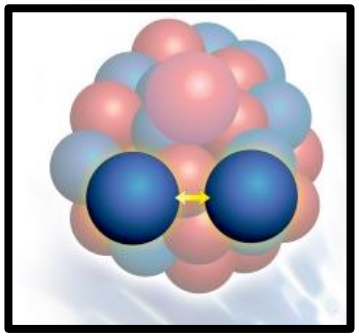
- Symmetry unrestricted simulations
- State of the art functional consistent with nuclear structure

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).

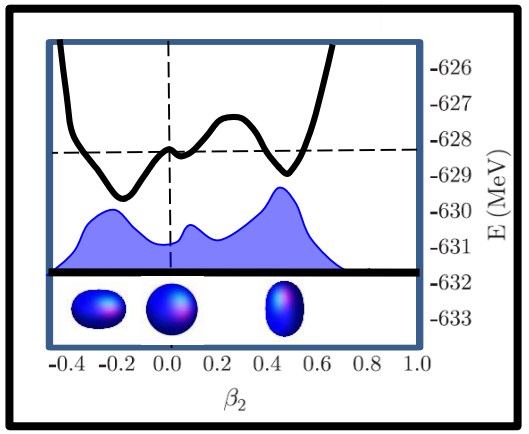


Challenges : beyond the independent particle picture

Pairing

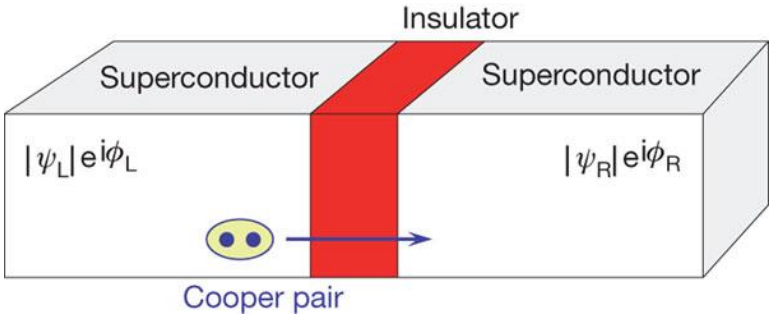


Shape coexistence

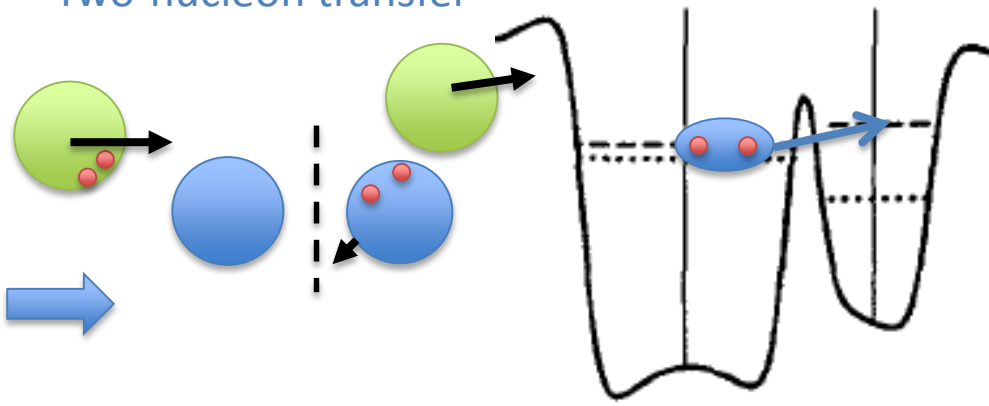


We know that pairing affects dynamic

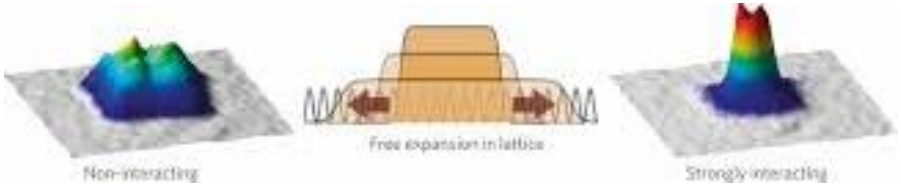
Quantum tunneling

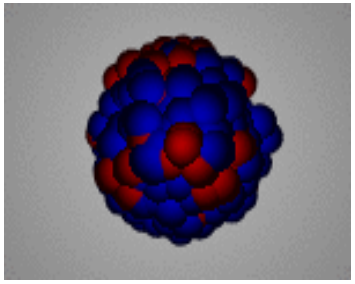


Two-nucleon transfer

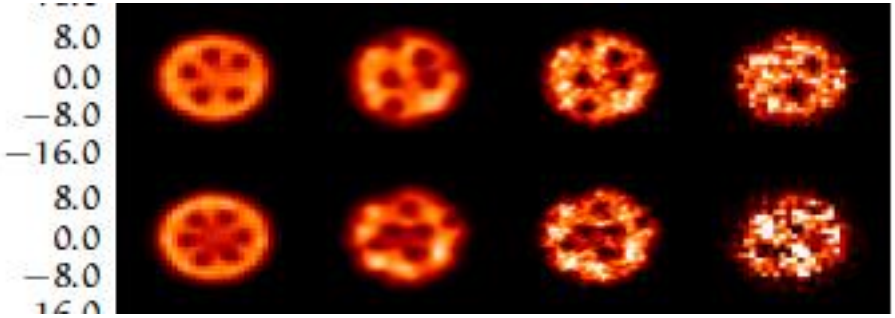


Expansion dynamic





Vortex formation



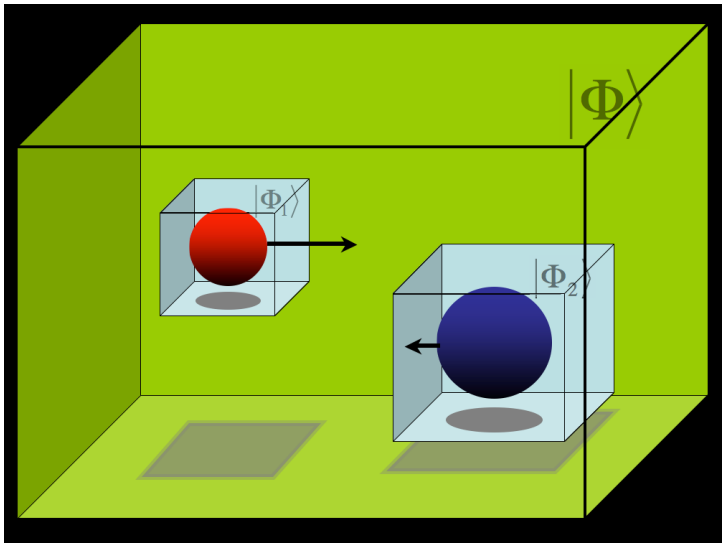
Specific viscosity effect

Difficulty

-interaction

-number of particles (mesoscopic)

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}

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

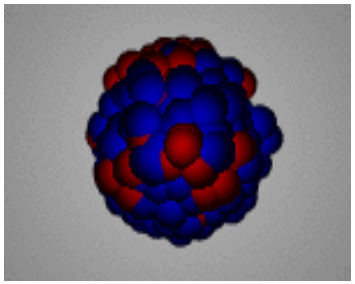
➡ TDHFB is very demanding Stetcu, Bulgac, Magierski, and Roche, PRC 84 (2011)

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

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

Small amplitude motion: mono-nuclear system

Static/quasi-static effects



→ Proper ground state deformations

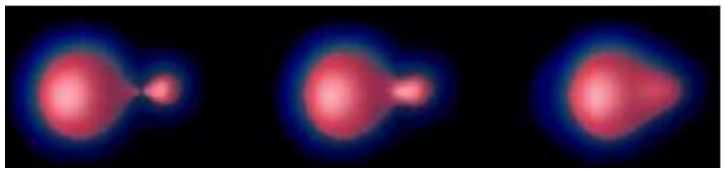
Dynamical effects

→ Onset of new collective modes (Giant Pairing Vib)

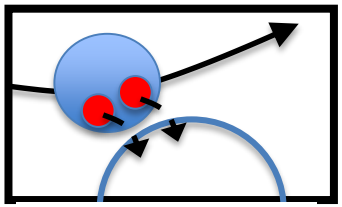
Large amplitude motion: di-nuclear system

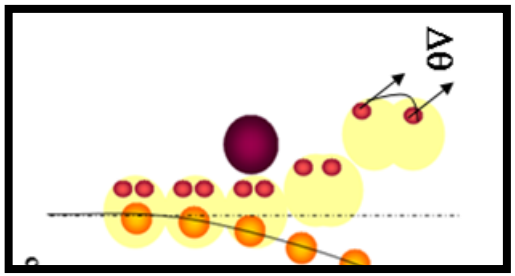
Direct dynamical effects

Fusion/deep-inelastic/direct reactions

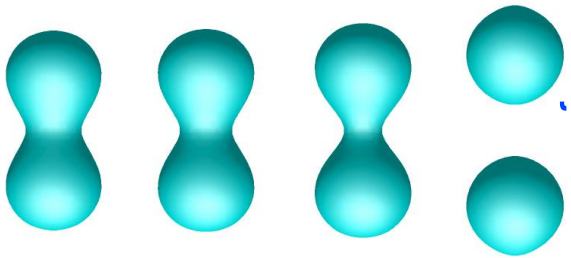


time

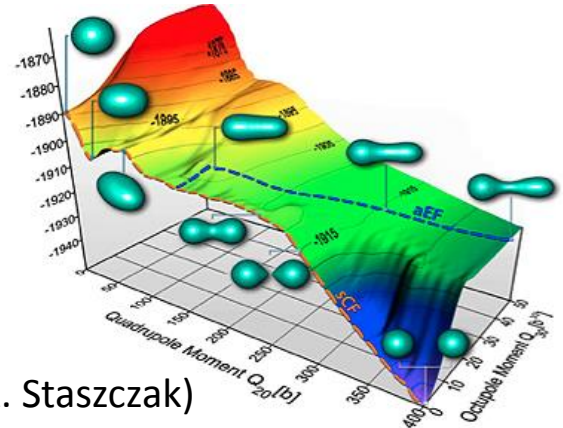




Fission

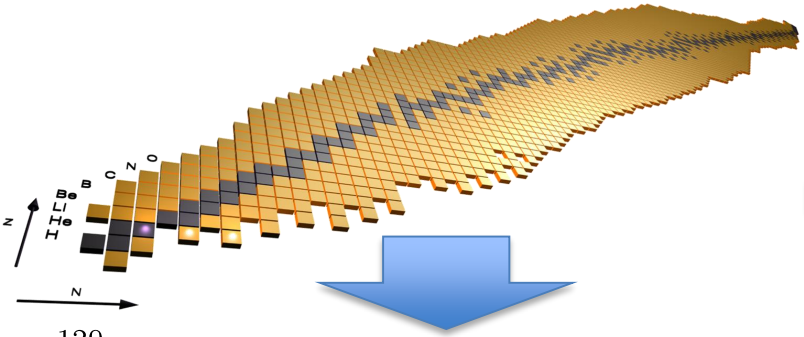


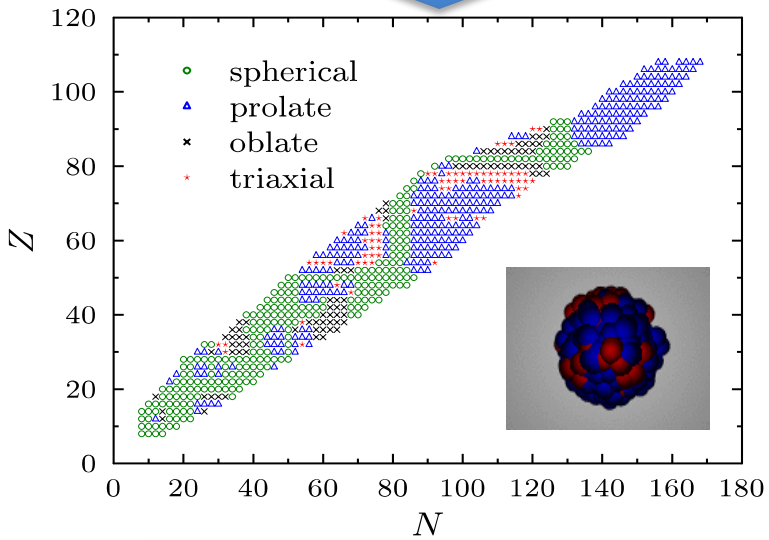
Static vs dynamical effects



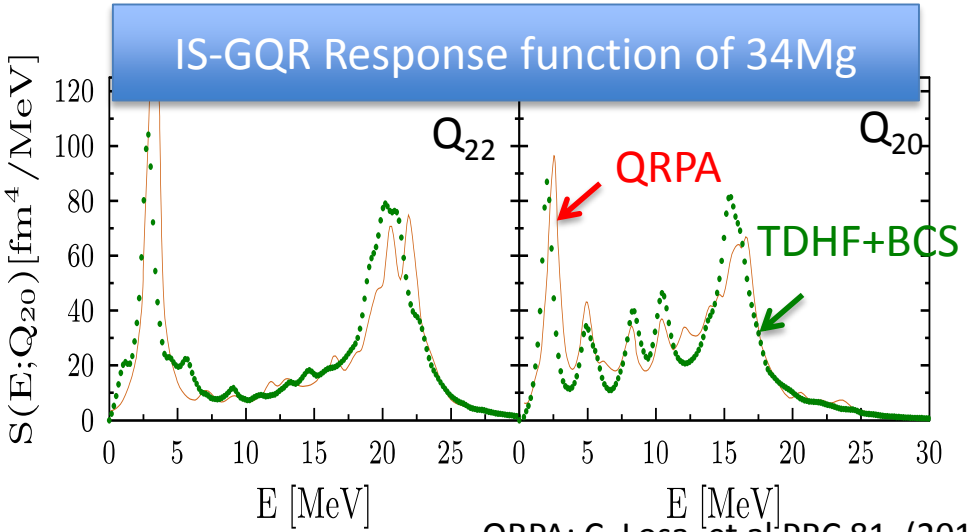
(from A. Staszczak)

Large scale study of giant quadrupole resonances

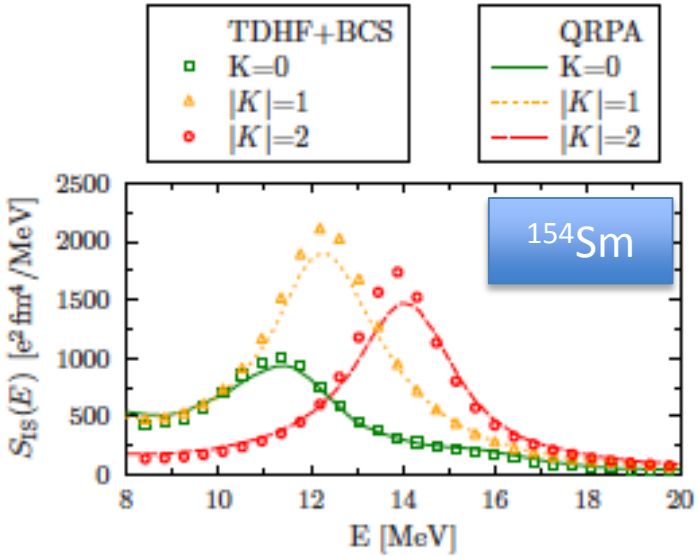




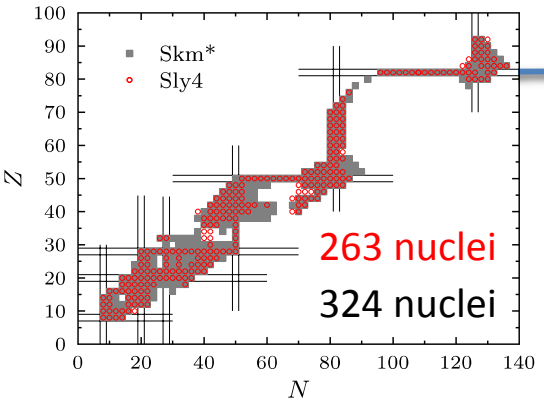
- Systematic study of isoscalar and isovector GQR in
  - (I) Spherical
  - (II) Axially deformed nuclei
  - (III) Triaxial nuclei
- Detailed study of deformation effects
- Benchmark with existing QRPA theory

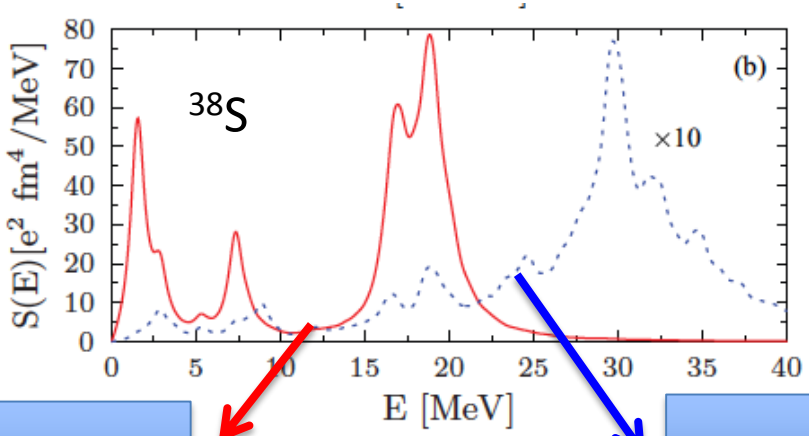


QRPA: C. Losa, et al PRC 81, (2010).



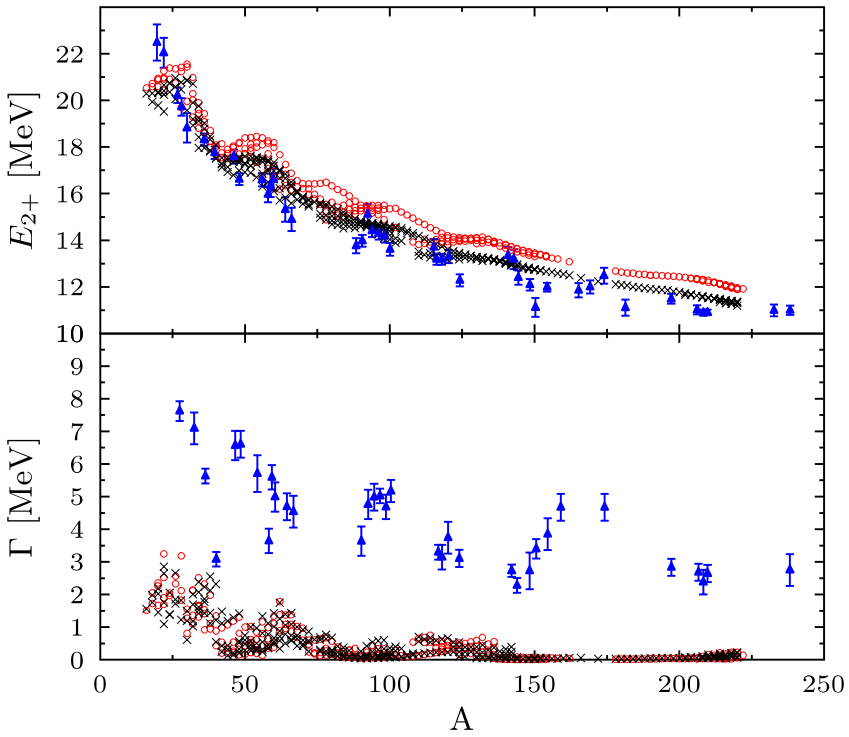
QRPA: Yoshida, Nakatsukasa,PRC88 (2013)

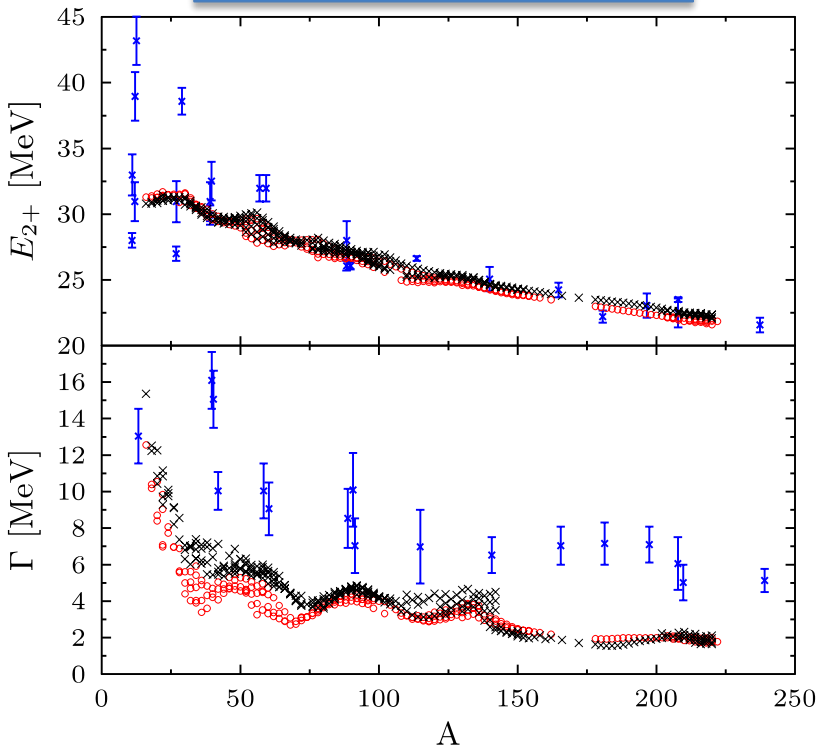




Isoscalar GQR

Isovector GQR



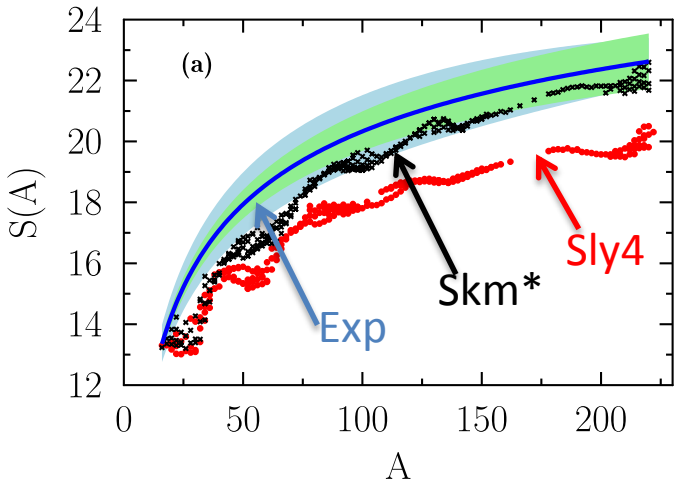


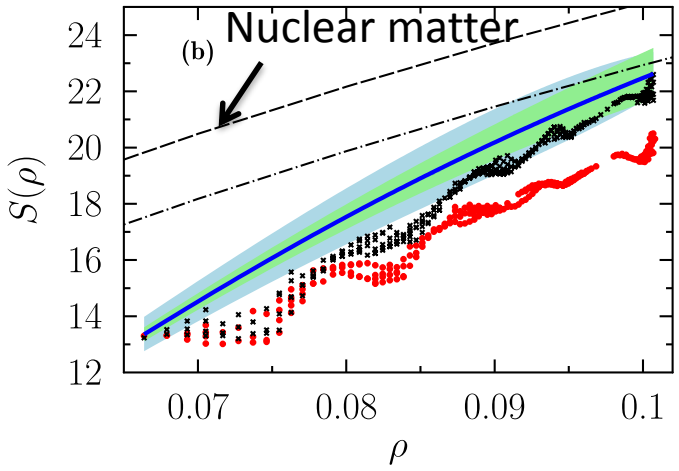
Scamps, Lacroix, PRC88 (2013)

Extraction of the density dependence of the symmetry energy

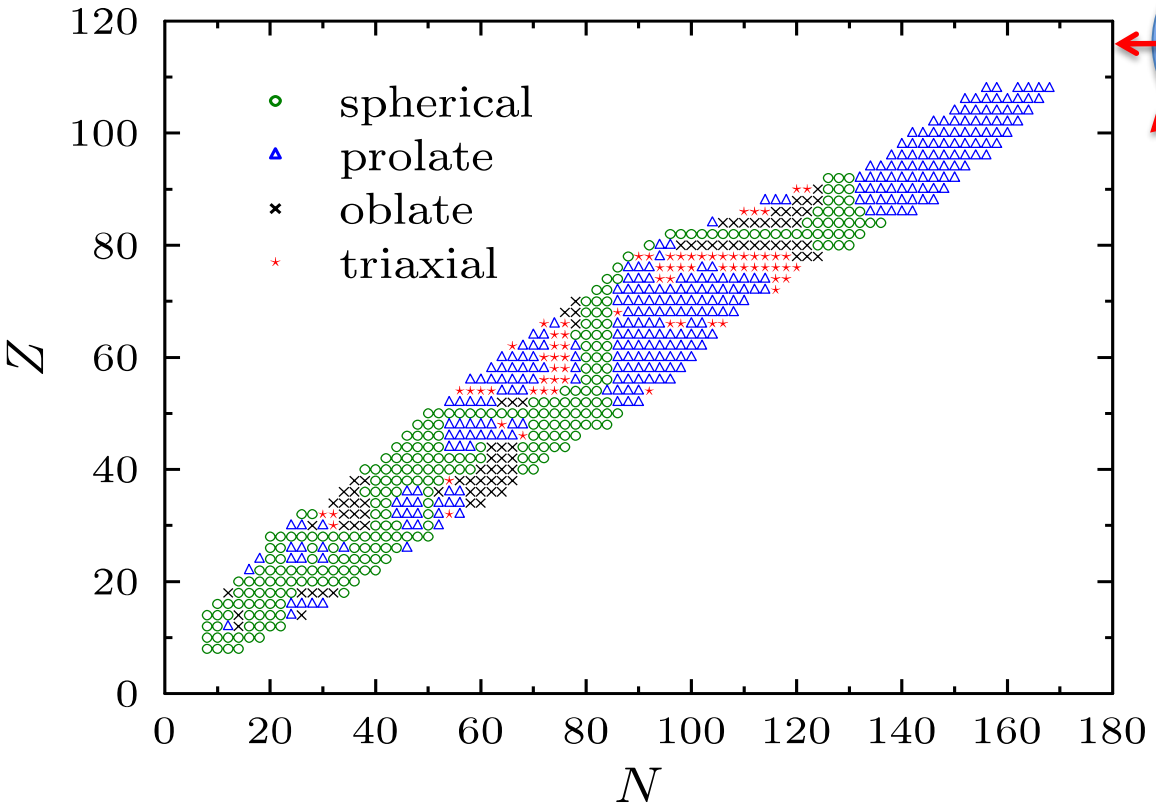
$$S(A) \simeq \frac{\varepsilon_F^\infty}{3}\left\{\frac{A^{2/3}}{8(\varepsilon_F^\infty)^2}\left[\left(E_{2^+}^{IV}\right)^2 - 2\left(E_{2^+}^{IS}\right)^2\right] + 1\right\}$$

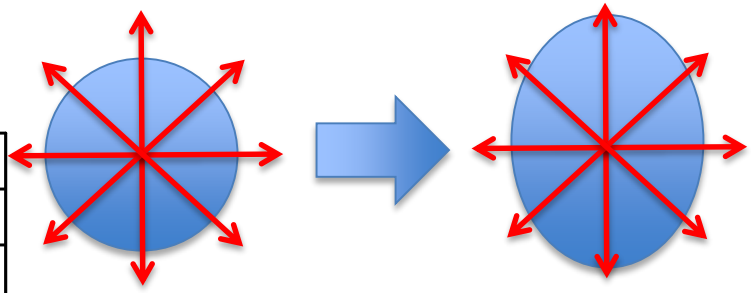
X. Roca-Maza et al, PRC **87** (2013)

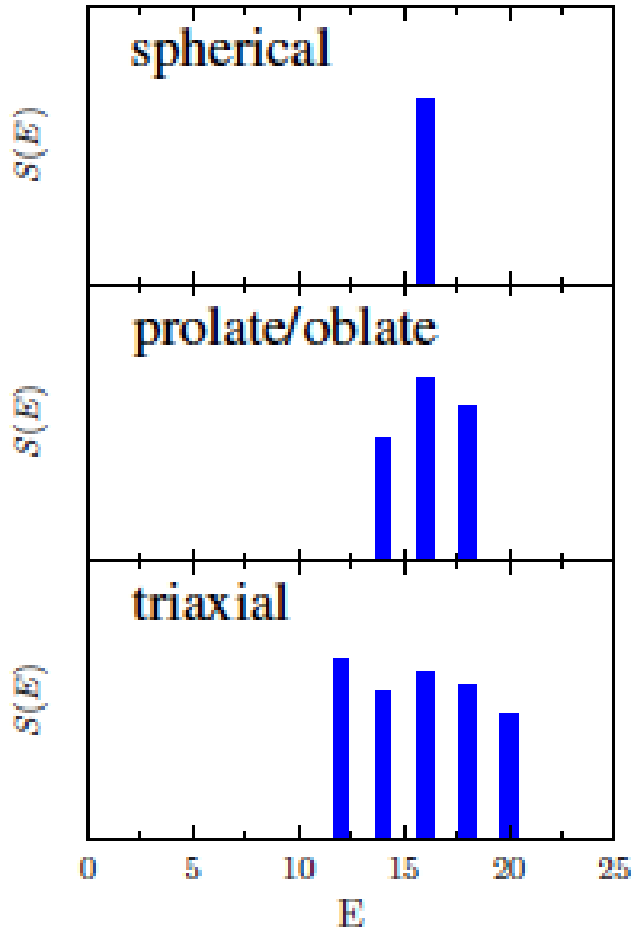




Scamps, Lacroix, PRC88 (2013)





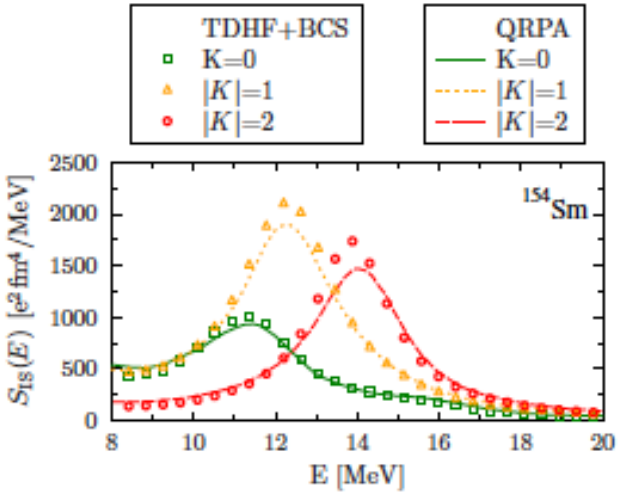


Scamps, Lacroix, PRC89 (2014).

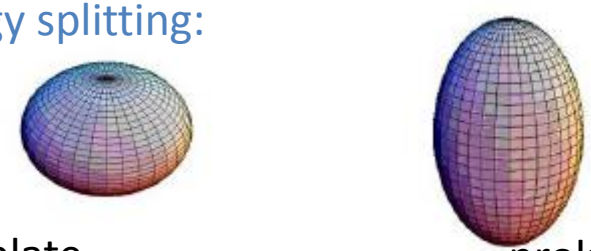
Excitation operators Q_{2K}

$$K = -2, -1, 0, 1, 2$$

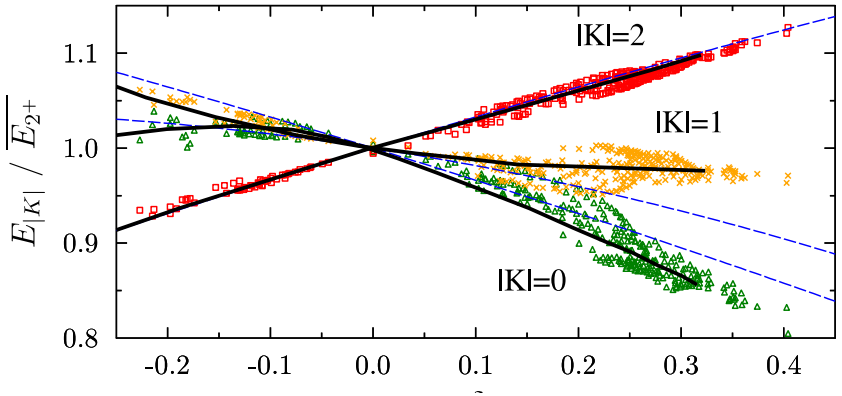
Systematic in deformed nuclei: fragmentation and damping



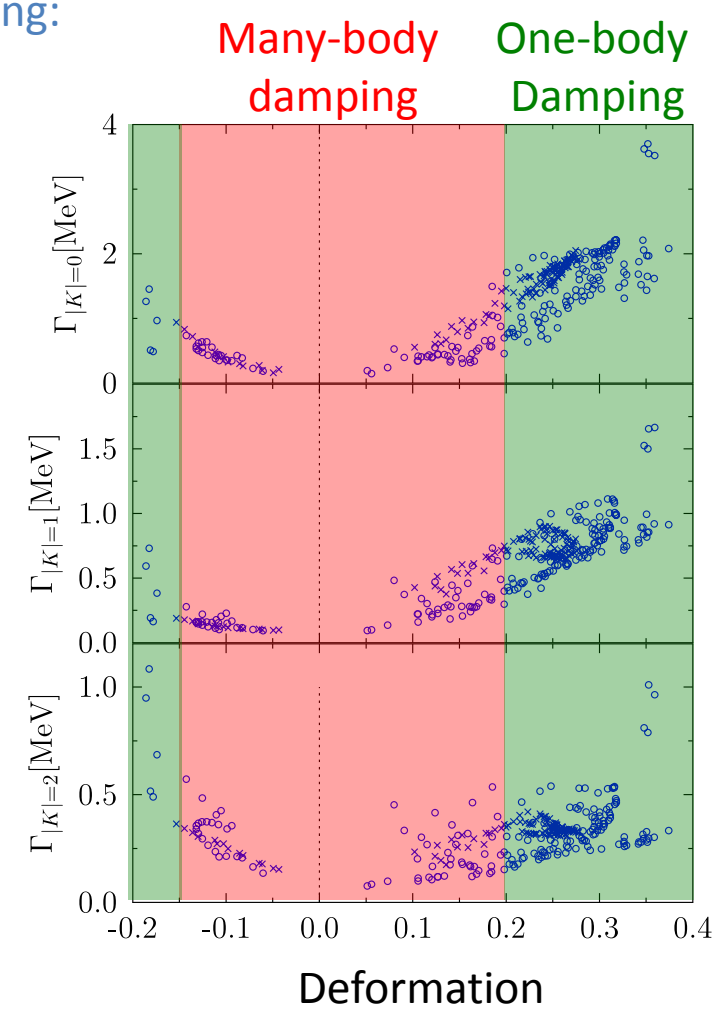
Energy splitting:



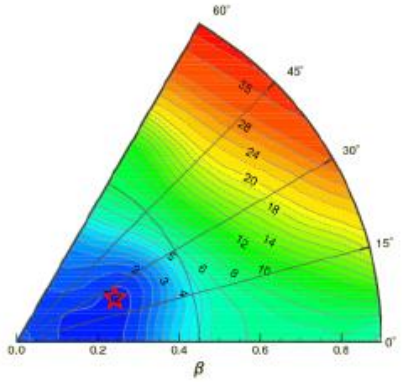
oblate prolate

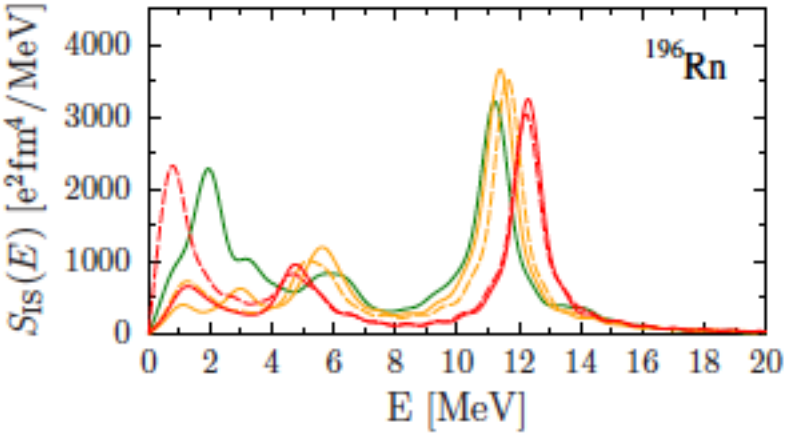


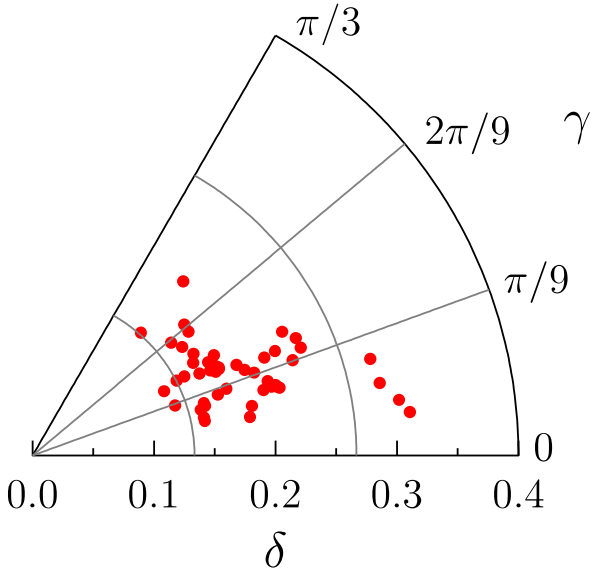
Damping:



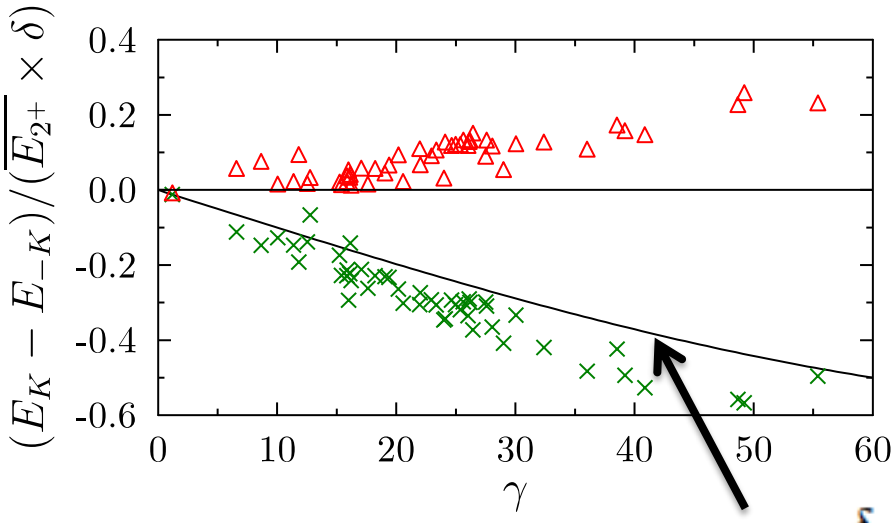
Scamps, Lacroix, PRC89 (2014).







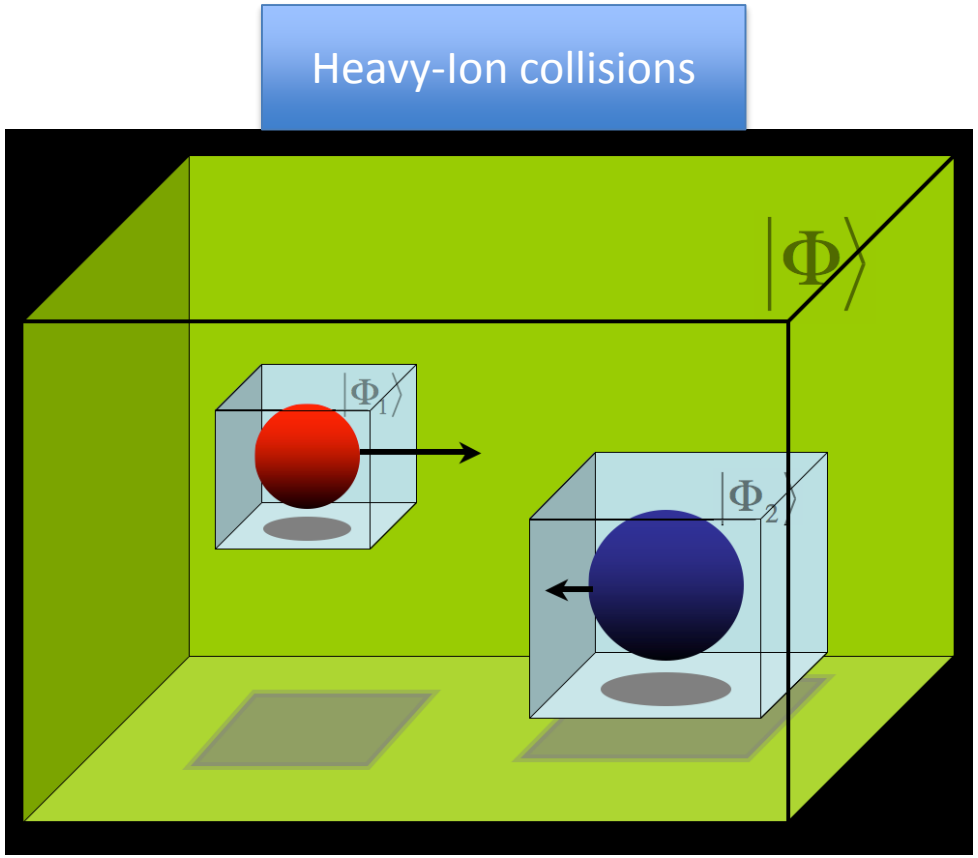
54 triaxial nuclei



$$\Delta E_1 \simeq -E_{\rm sph}\frac{\delta}{\sqrt{3}}\sin\gamma$$

Scamps, Lacroix, arXiv:1401.5211

Nuclear reactions with pairing



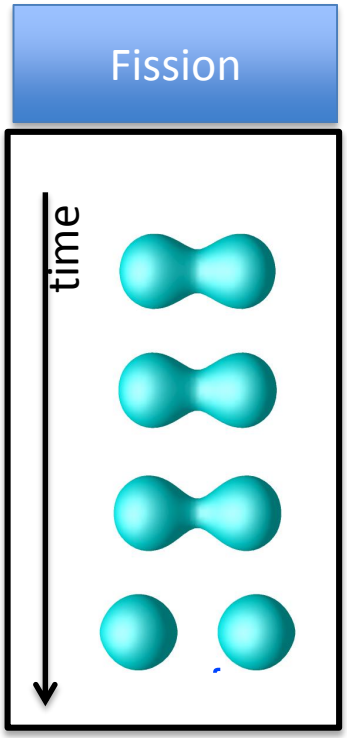
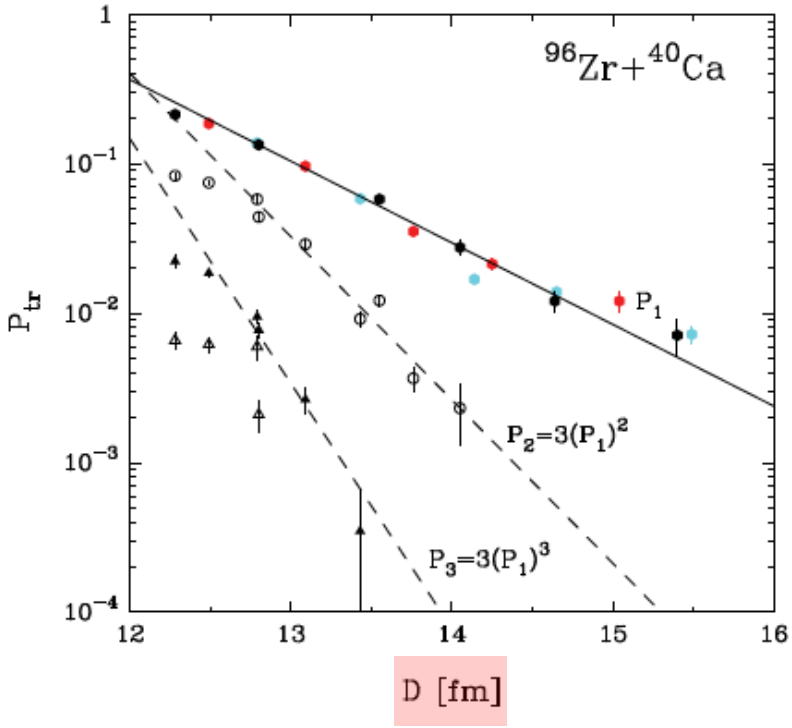


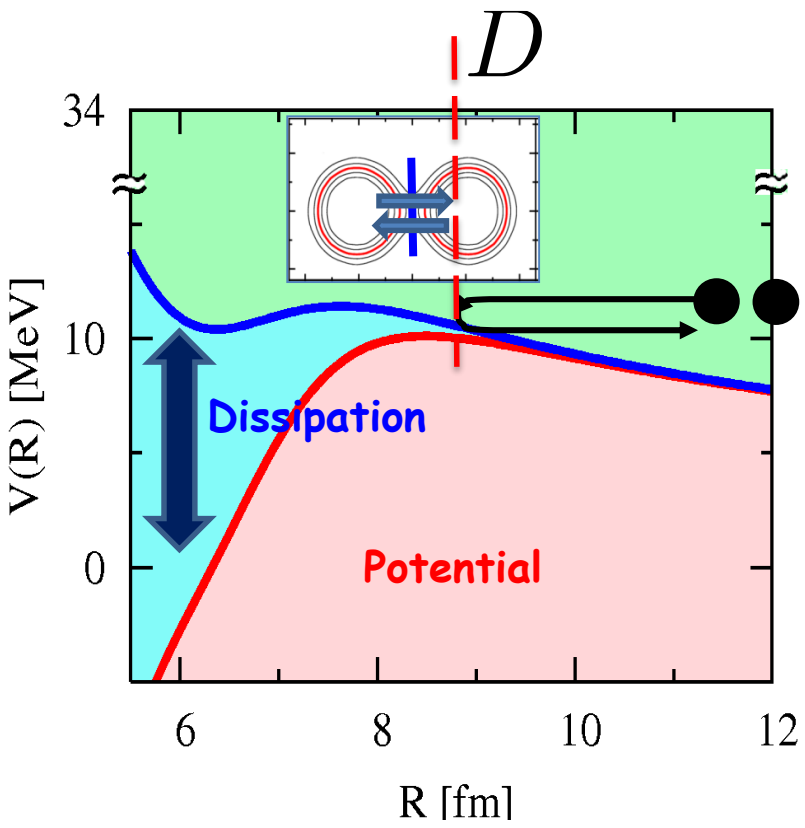
Illustration of useful data (for us)



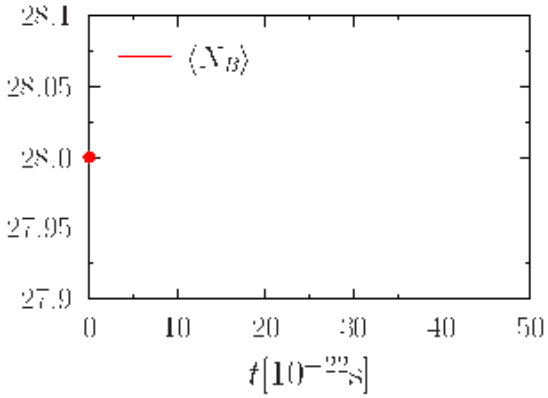
Corradi et al, Phys. Rev. C 84 (2011)

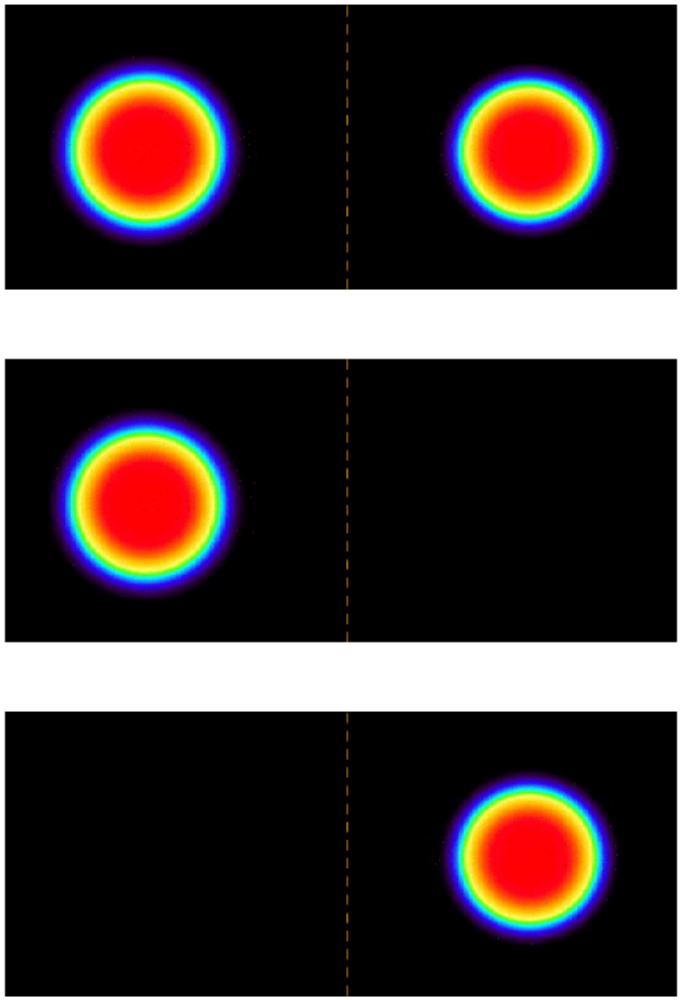
Our goal:

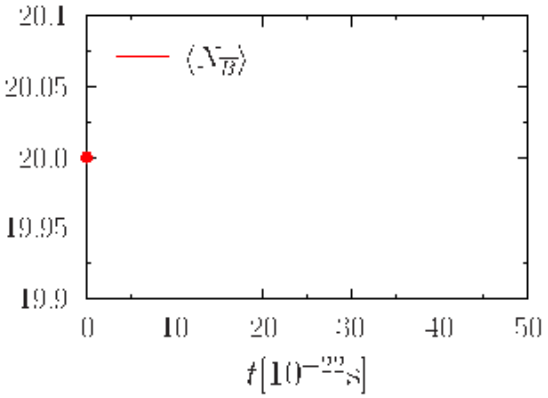
- Consider system with pairing in the GS
- Perform time-dependent simulation
  Close to be compared with experiments



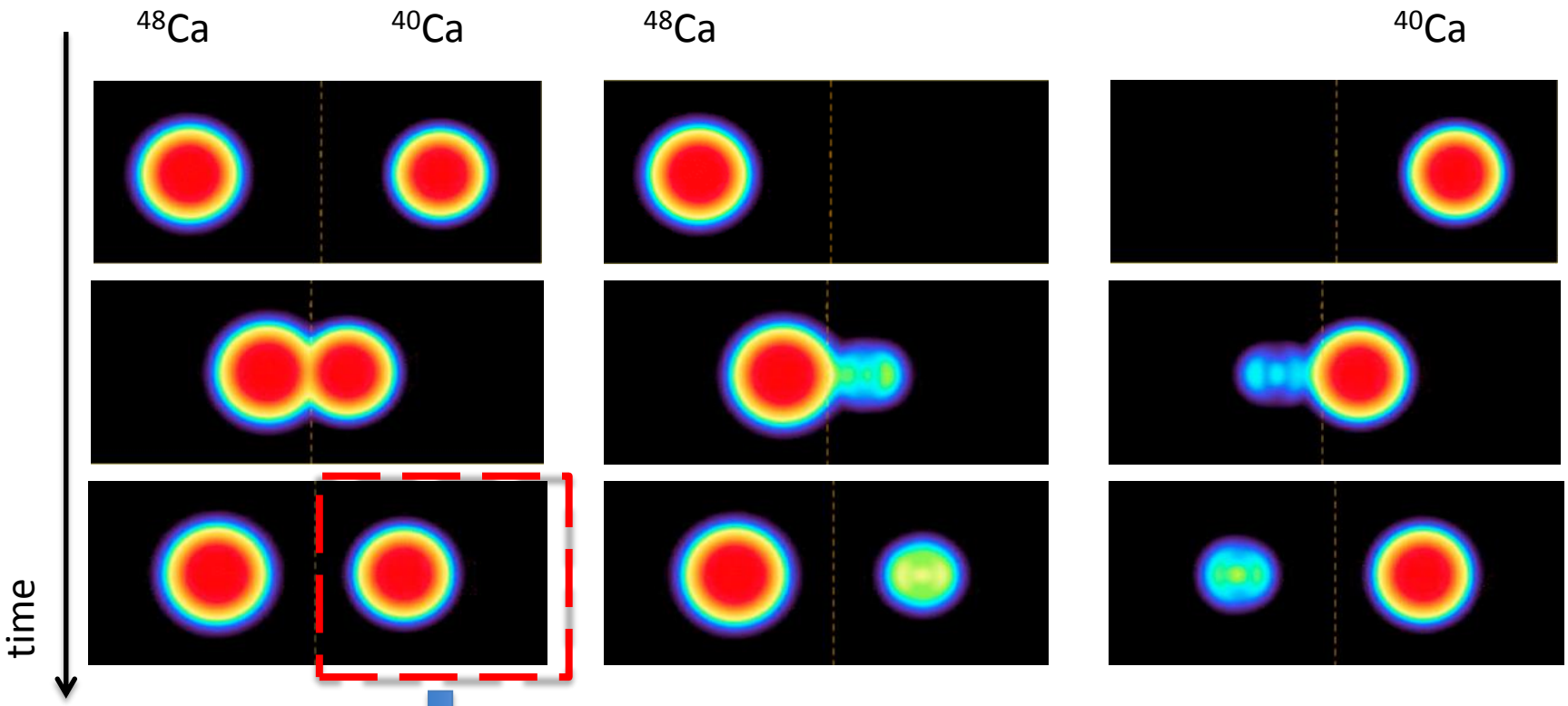
How does it look like from a time-dependent point of view?







(Courtesy G. Scamps)



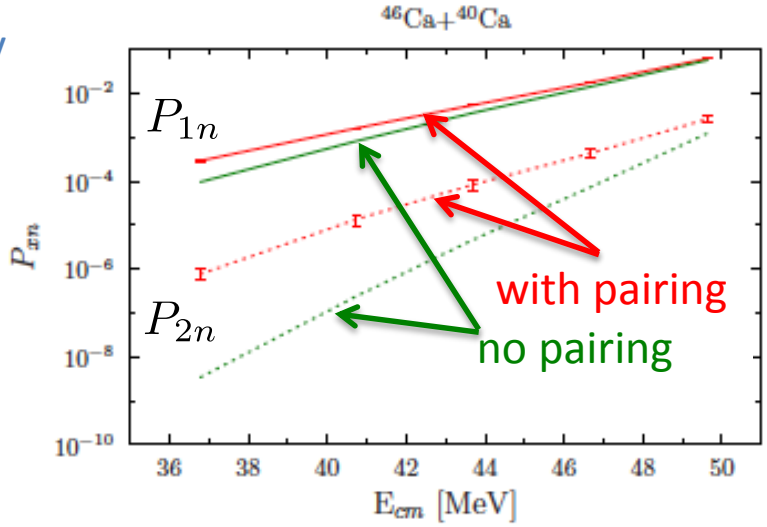
Use projection technique on good particle number

Simenel; PRL105 (2010).
Sekizawa, Yabana PRC 90, 064614 (2014)
Scamps, Lacroix, PRC 87 (2013).

Extract one, two, … nucleons transfer probabilities

$$P_{1n},\ P_{2n}, \ldots$$

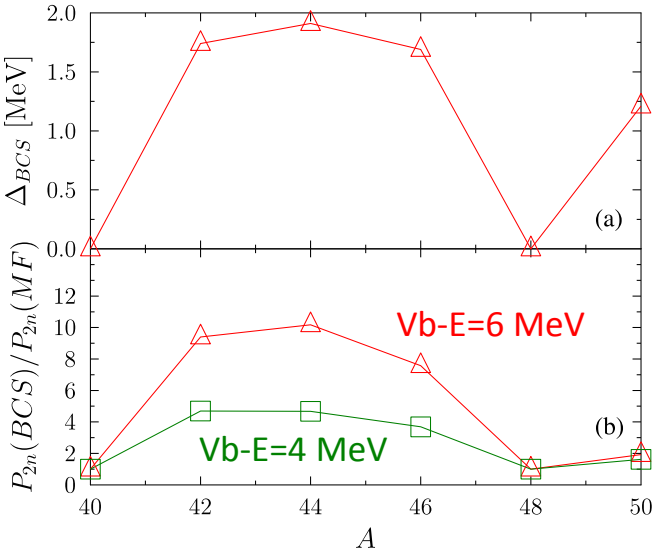
Enhancement of the pair transfer probability



First conclusion

$\nearrow P_{1n},\ P_{2n}, \ldots$

Link between pairing strength and pairing gap:

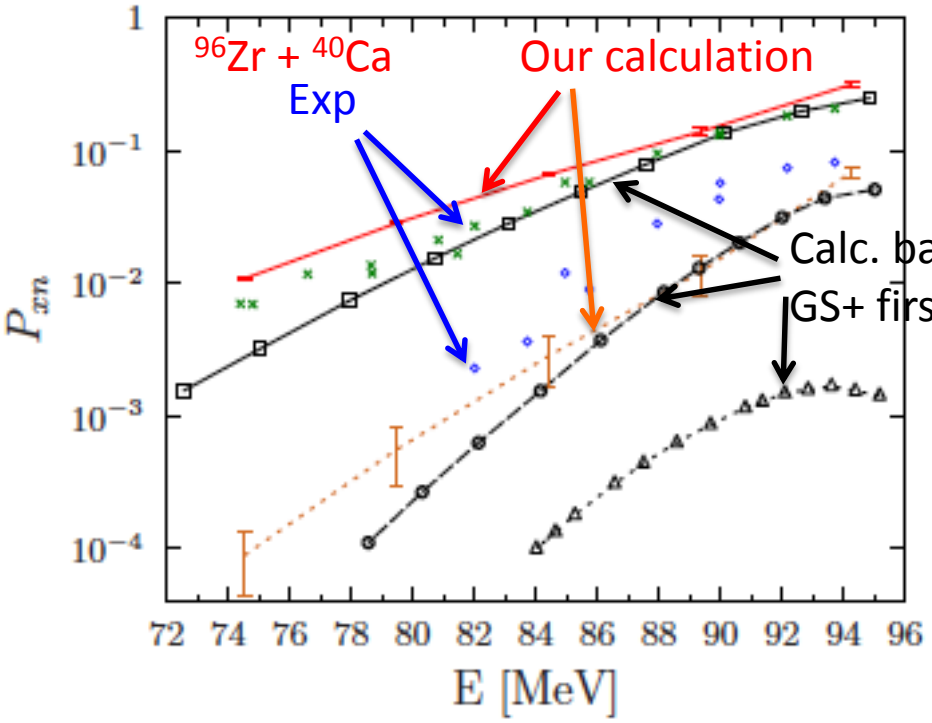


Strong beam energy dependence

Scamps, Lacroix, PRC 87 (2013)

Comparison with experiment

Corradi et al, Phys. Rev. C 84 (2011)



➡ The dynamical approach is competitive Compared to other approaches

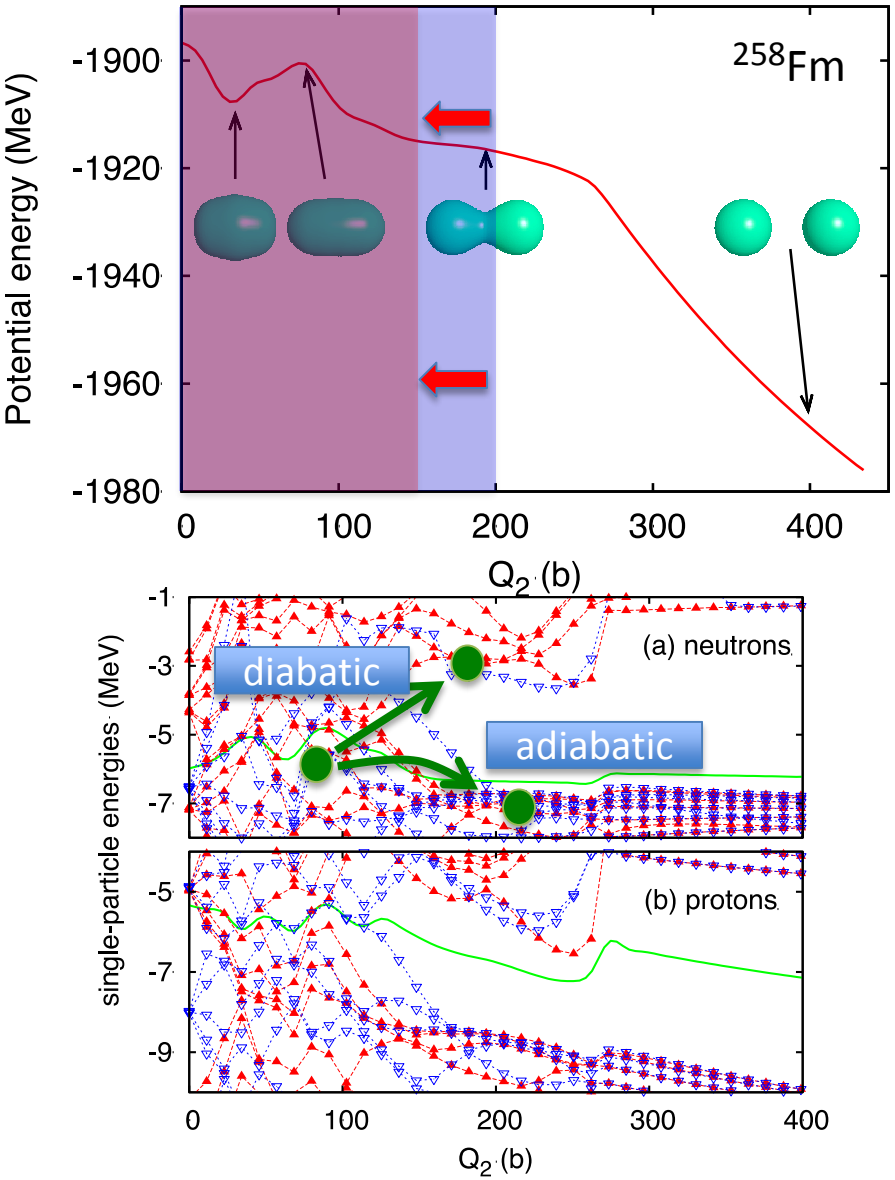
➡ P_{1n} is not so well reproduces:

(Problem with the single-particle field)

➡ P_{2n} is underestimated

(Other effects are important!)

Prospective in the time-dependent description of fission with pairing



Scamps Simenel, Lacroix, arxiv:1501.03592
Tanimura, Lacroix, Scamps, arxiv:1505.05647

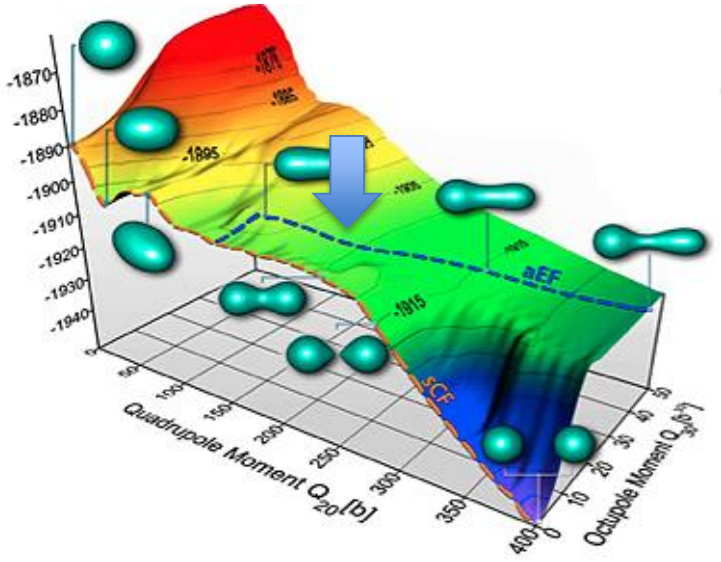
Fission with TD-EDF without pairing

Simenel, Umar, PRC C89 (2014).
Goddard, Stevenson, Rios, arxiv:1504:001909

- 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

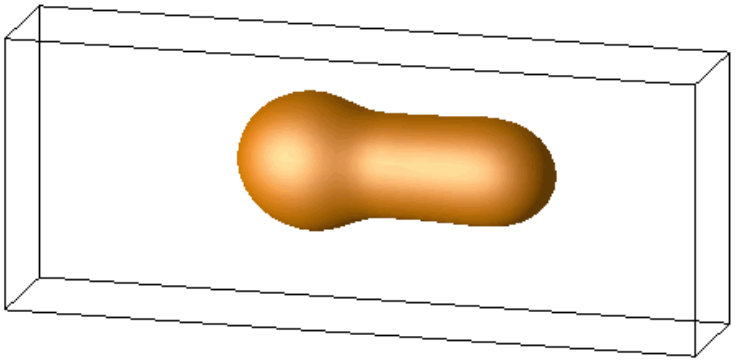
Fission with TD-EDF with pairing

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



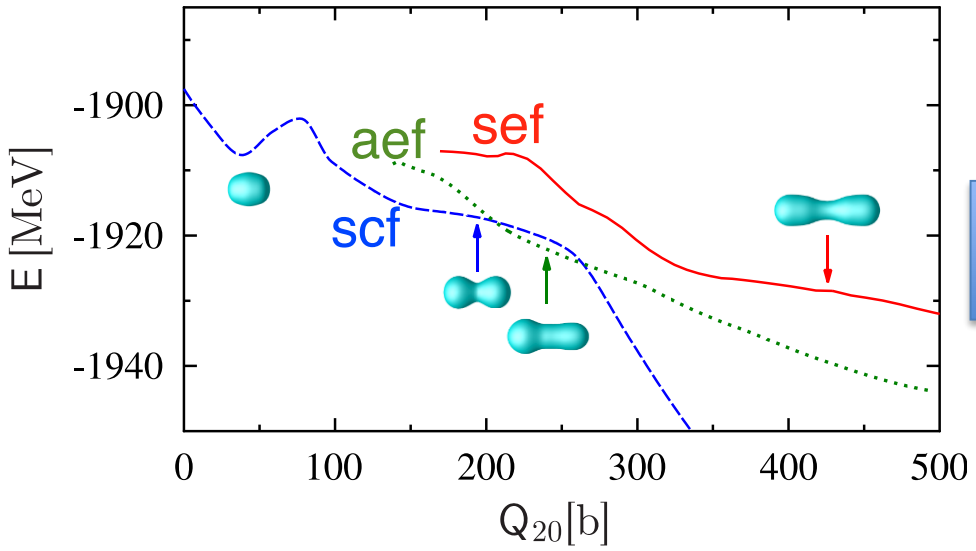
Time-dependent picture of fission

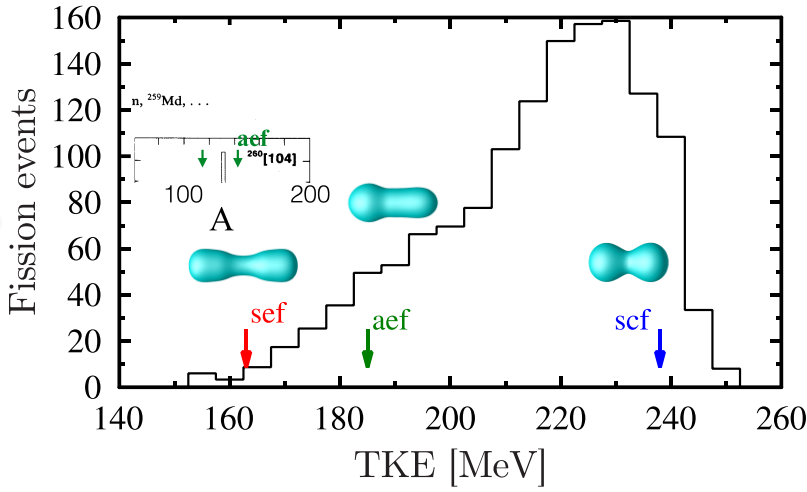
Scamps Simenel, Lacroix, arxiv:1501.03592



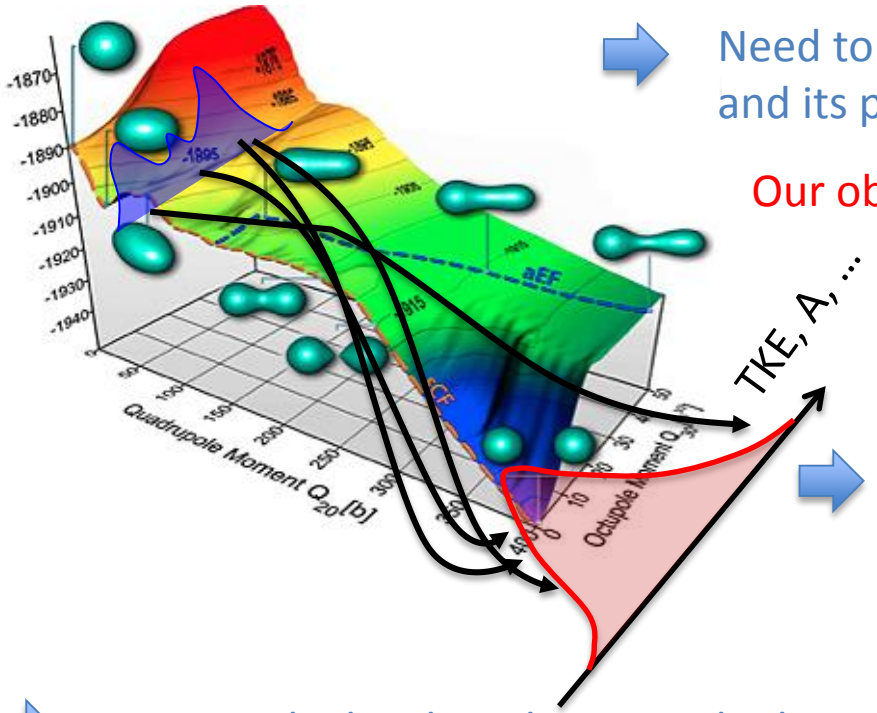
(courtesy G. Scamps)

TKE distribution





(G. Scamps talk)



Need to describe configuration mixing and its propagation

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

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

First step: extract from TD-EDF, Information on selected degrees of freedom

We recently developed a general scheme to deduce collective momenta, collective masses, … from TD-EDF

Tanimura, Lacroix, Scamps, arxiv:1505.05647

Micro

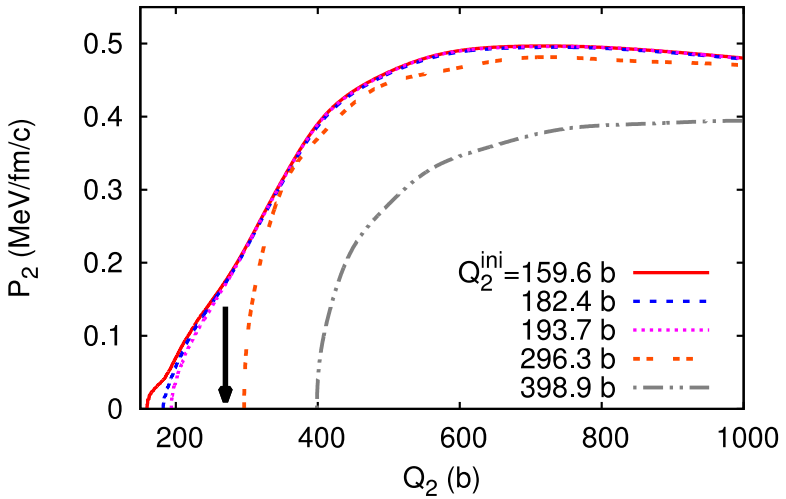
$\rho(t)\ \kappa(t)$

Macro

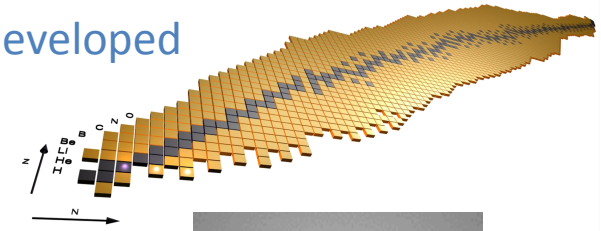
$\{Q_\alpha\}$

$\{P_\alpha\}$

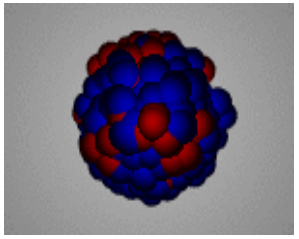
M_α



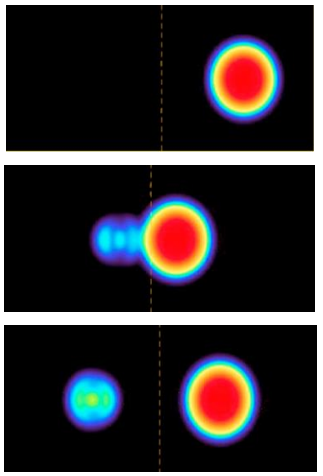
- New versatile TD-EDF codes including pairing are now developed
- This open new applications perspectives



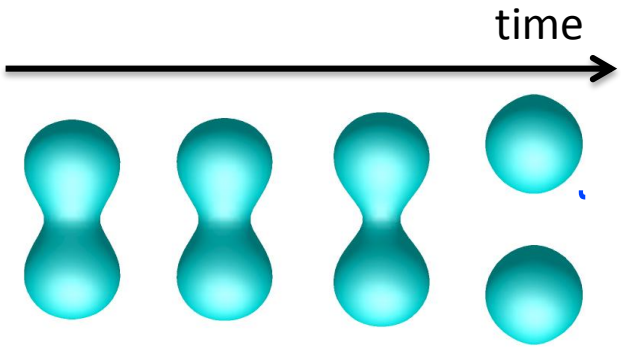
Recent applications



- Systematic of giant resonances in nuclei with various shapes



- Particle transfer below the Coulomb barrier



- Fission of superfluid nuclei

Ongoing effort : include configuration mixing