INSTITUT DE PHYSIQUE NUCLÉAIRE
ORSAY

Recent ideas and developments on reactions theory

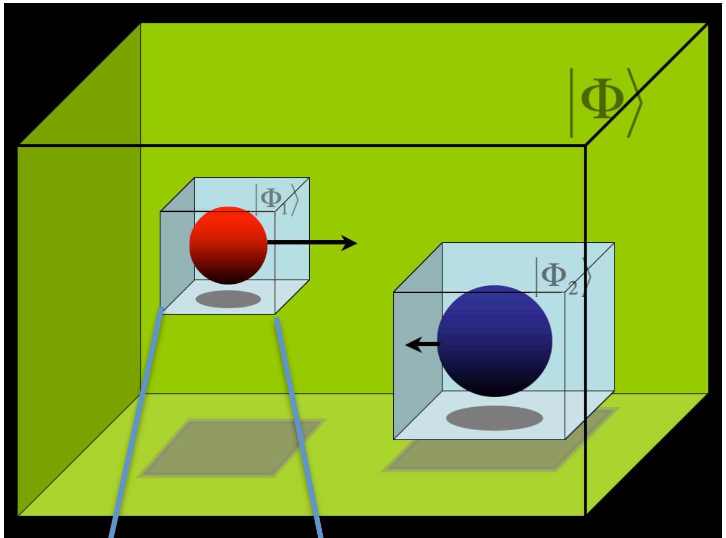
Denis Lacroix

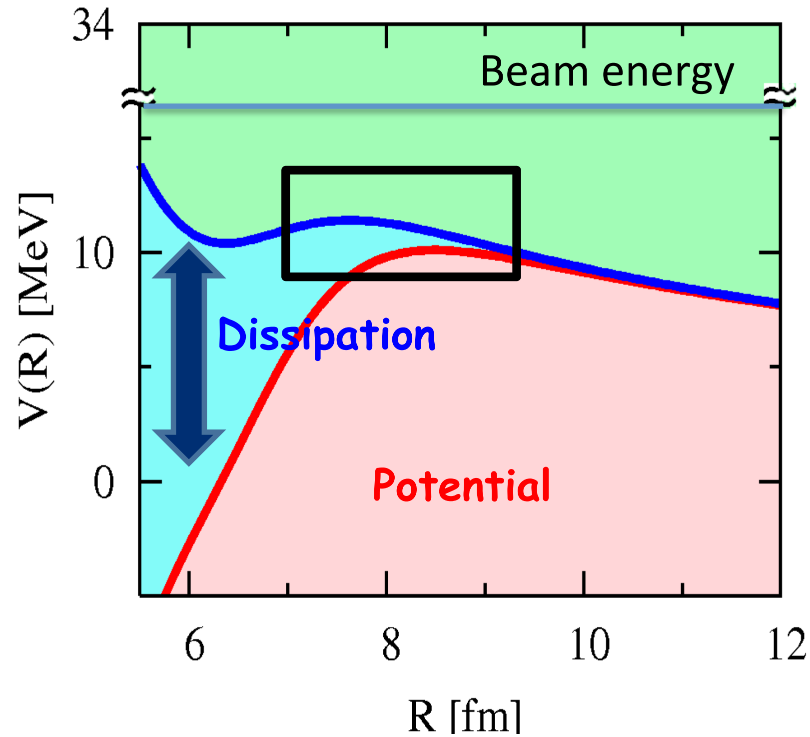
IPN Orsay

Outline:

- Pairing effects on dynamics
- Collective motion and Transfer reaction
- Effect of quantum fluctuations on large amplitude collective motion

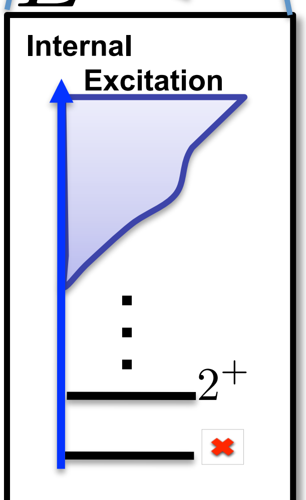
Coll: S. Ayik, G. Scamps and
Y. Tanimura, D. Gambacurta,
B. Yilmaz





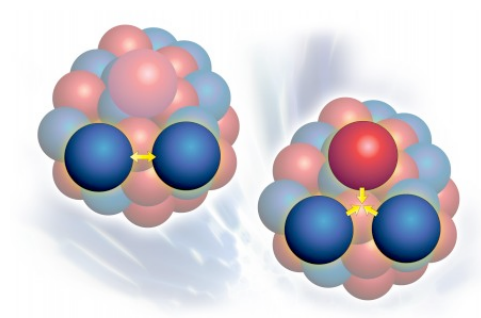
Beam energy tunes the energy scale

$E^* \searrow$

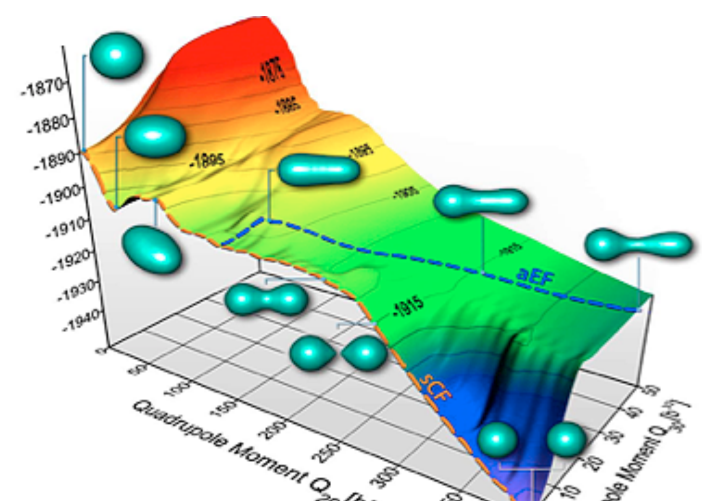


Enhanced collective effects

$$E^* \simeq E_{\rm cor}$$

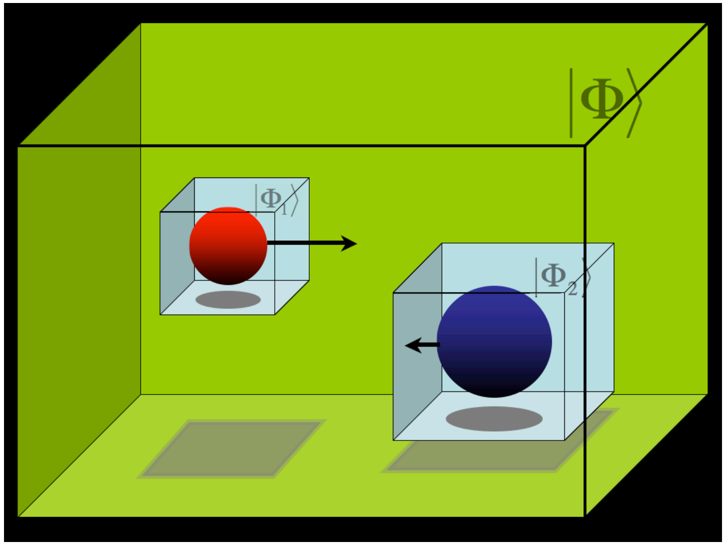


Enhanced correlation effects



(from A. Staszczak)

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)

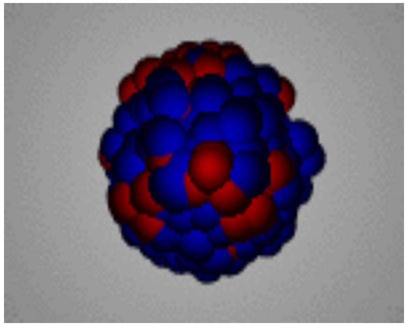
Neglect Δ_{ij}

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

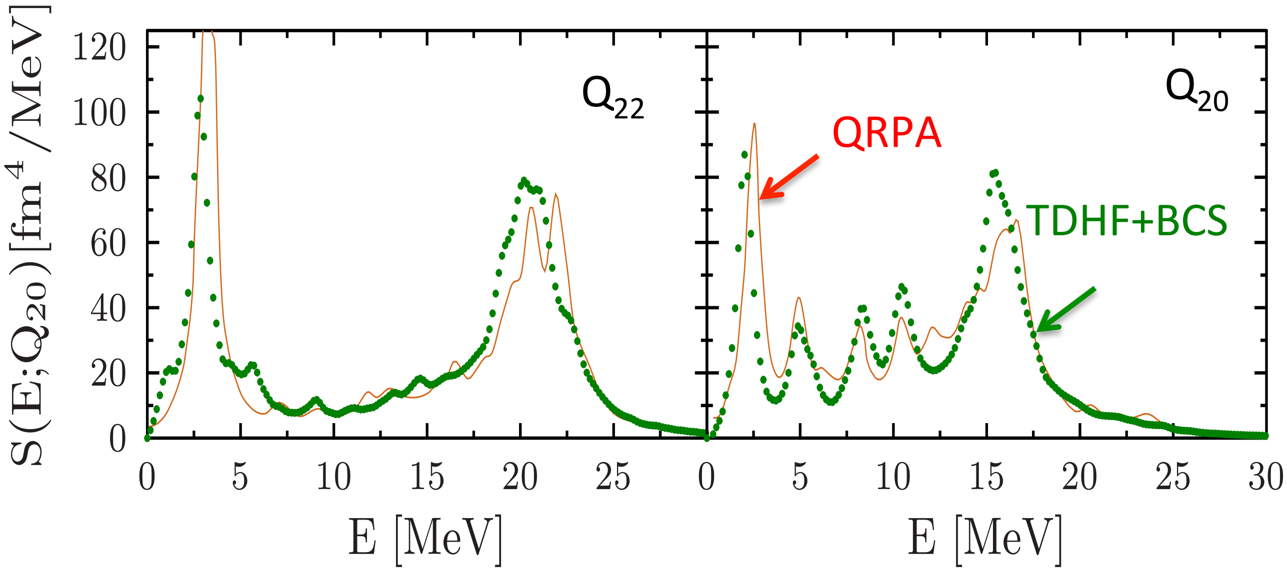
- TDHFB is very demanding — Stetcu, Bulgac, Magierski, and Roche, PRC 84 (2011)
- Reasonable results for collective motion — Ebata, Nakatsukasa et al, PRC82 (2010)
- Sometimes more predictive than TDHFB — Scamps, Lacroix, Bertsch, Washiyama, PRC85 (2012)

Comparison TDHF+BCS / QRPA

Illustration with the GQR



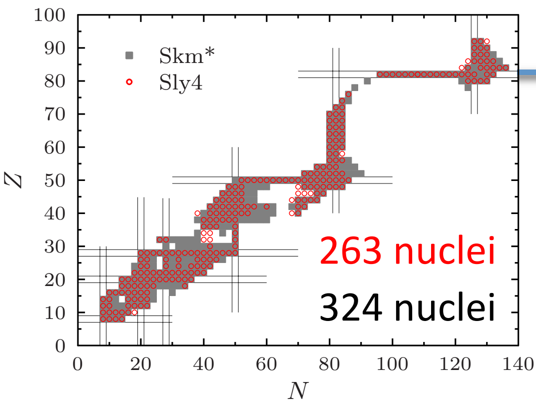
Strength distribution in deformed ^{34}Mg

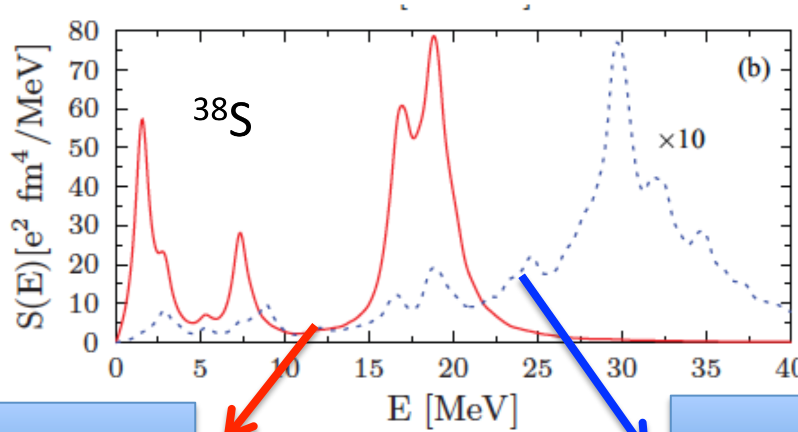


QRPA: C. Losa, et al PRC 81, (2010).

- Almost no difference between TDHF+BCS and TDHFB (QRPA)
- Main effect of pairing is to set the right deformation

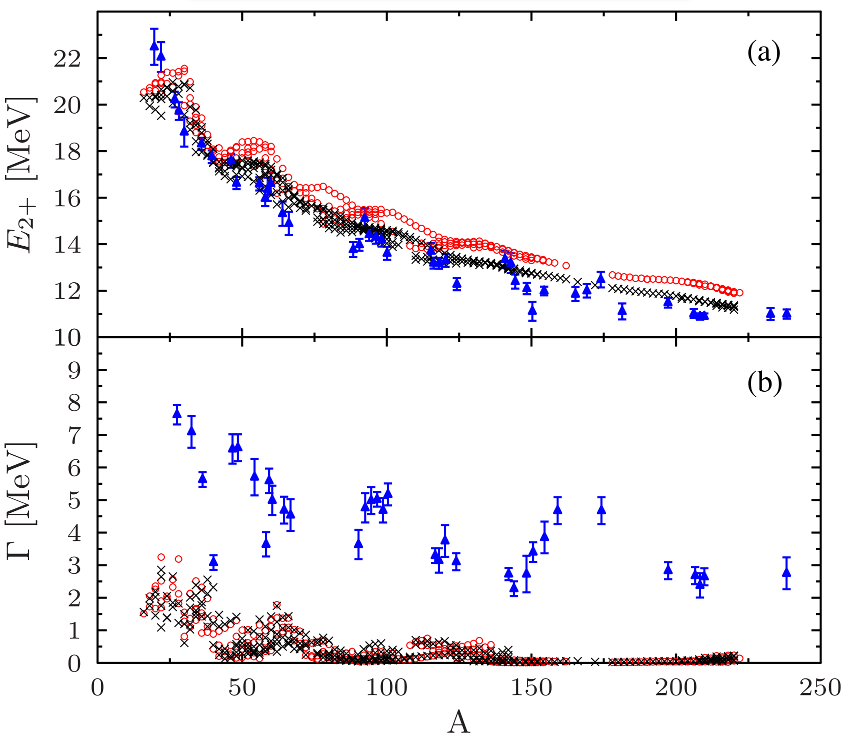
Systematic in Spherical nuclei

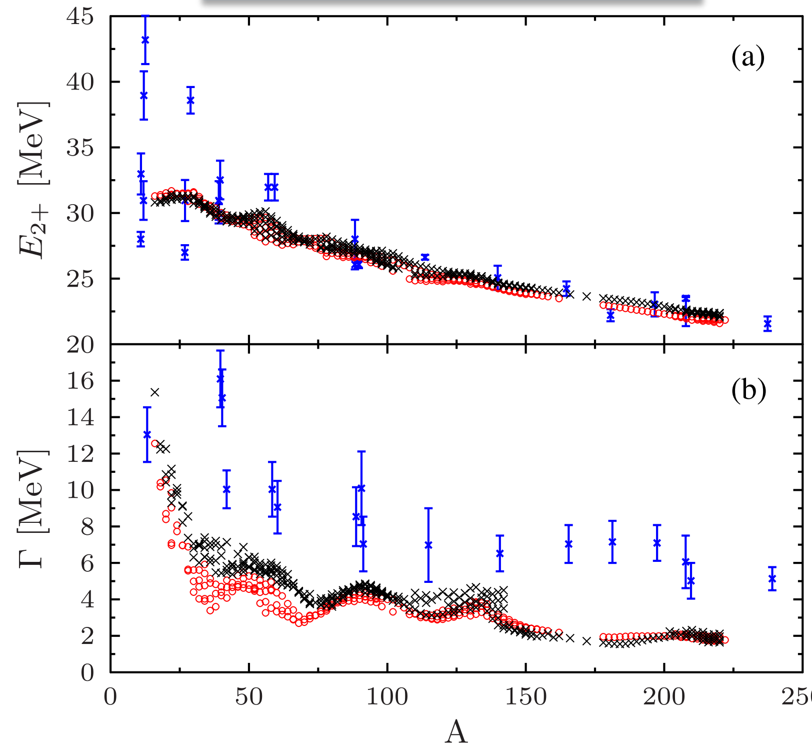




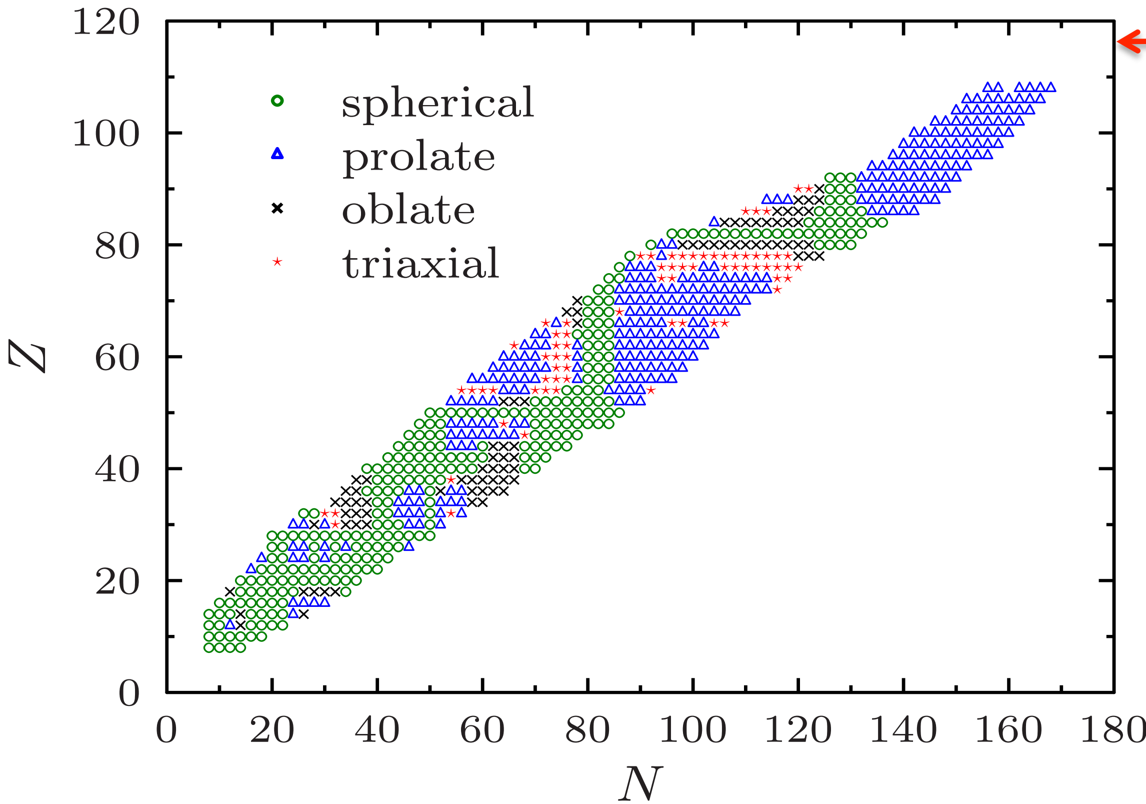
Isoscalar GQR

Isovector GQR

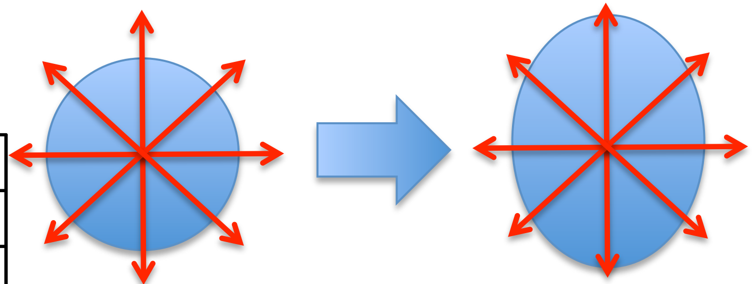


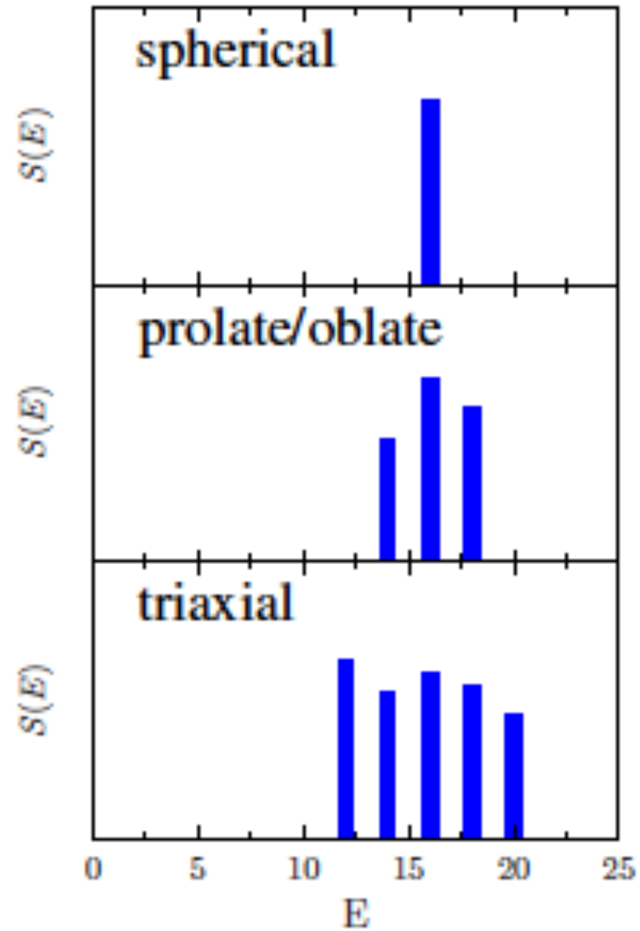


Scamps, Lacroix, PRC88 (2013)



Scamps, Lacroix, PRC89 (2014).

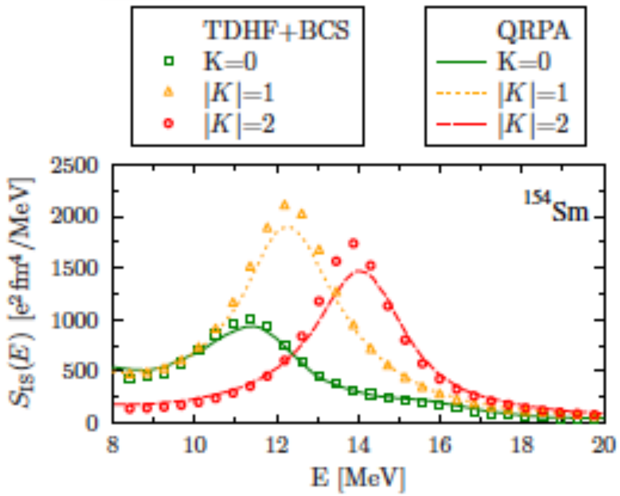




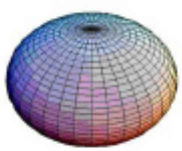
Excitation operators

$$Q_{2K}$$

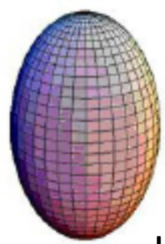
$$K = -2, -1, 0, 1, 2$$



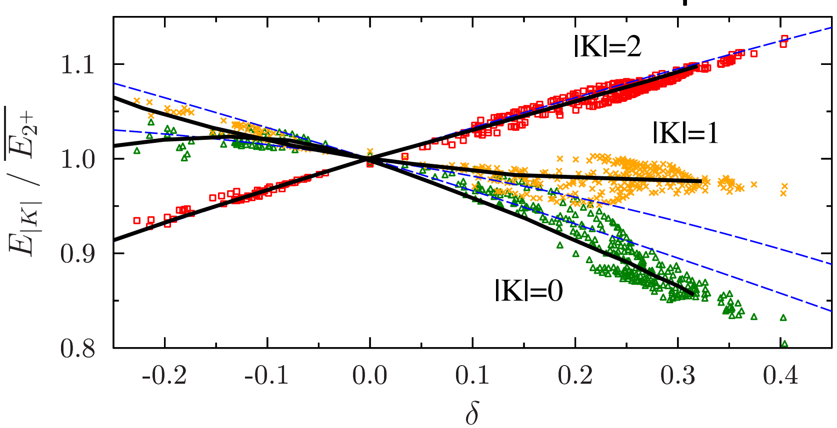
Energy splitting:



oblate

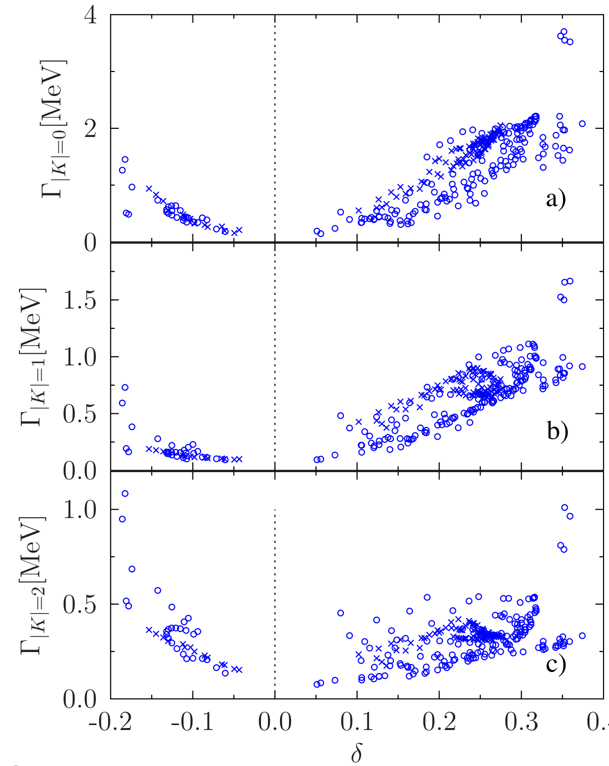


prolate

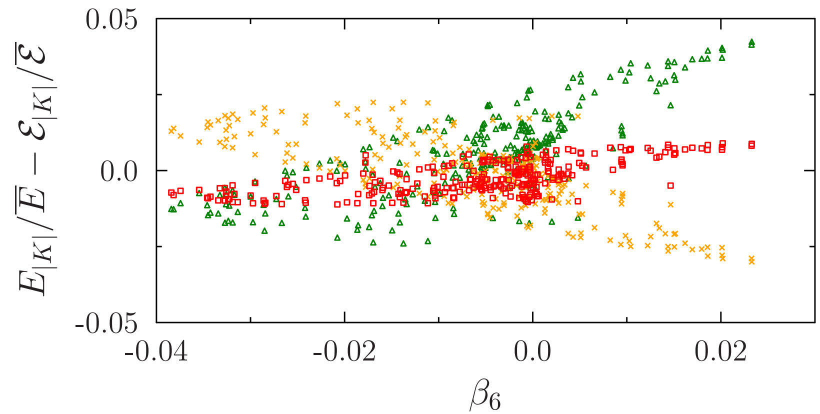


Scamps, Lacroix, PRC89 (2014).

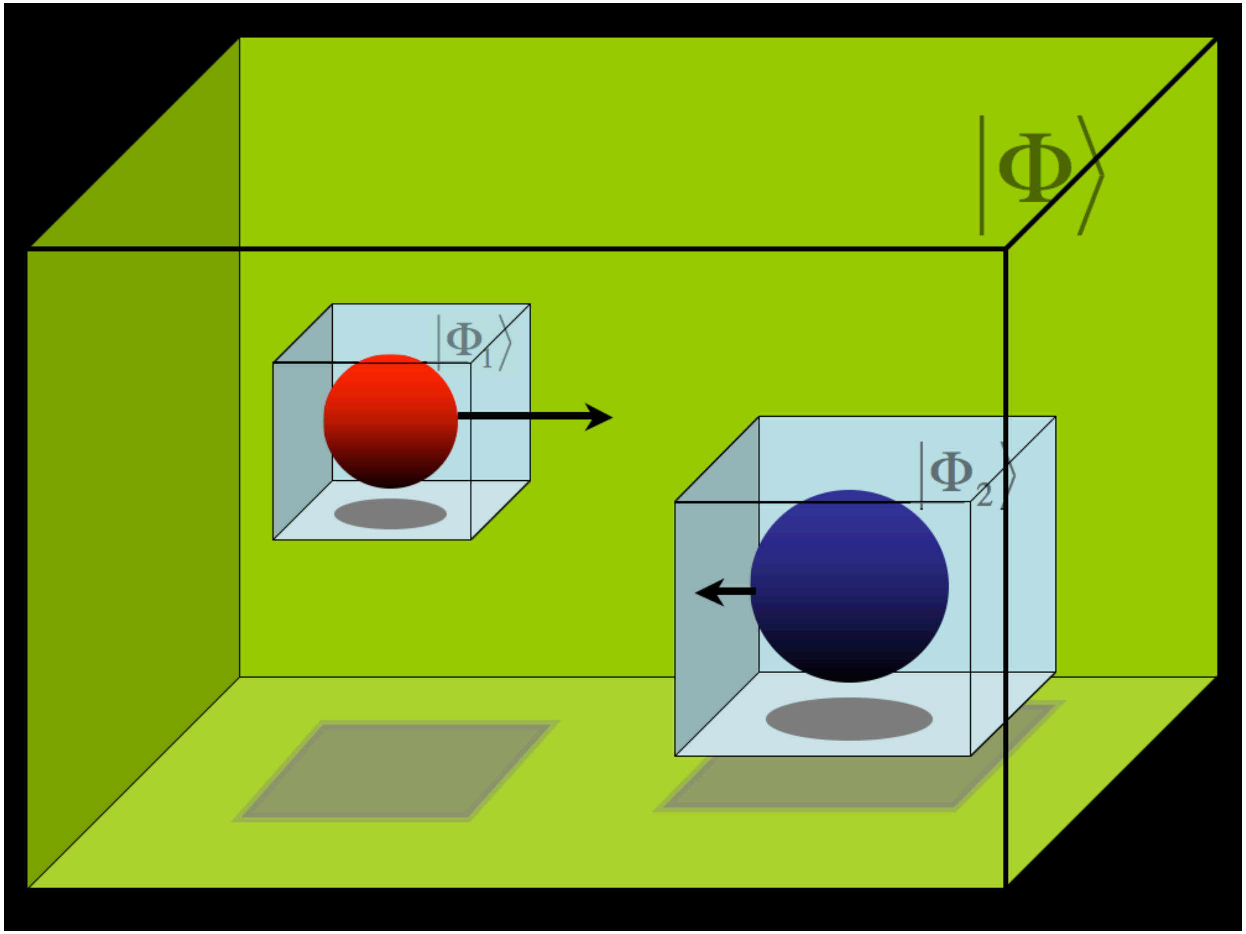
Damping is more complex:



High order deformation is important



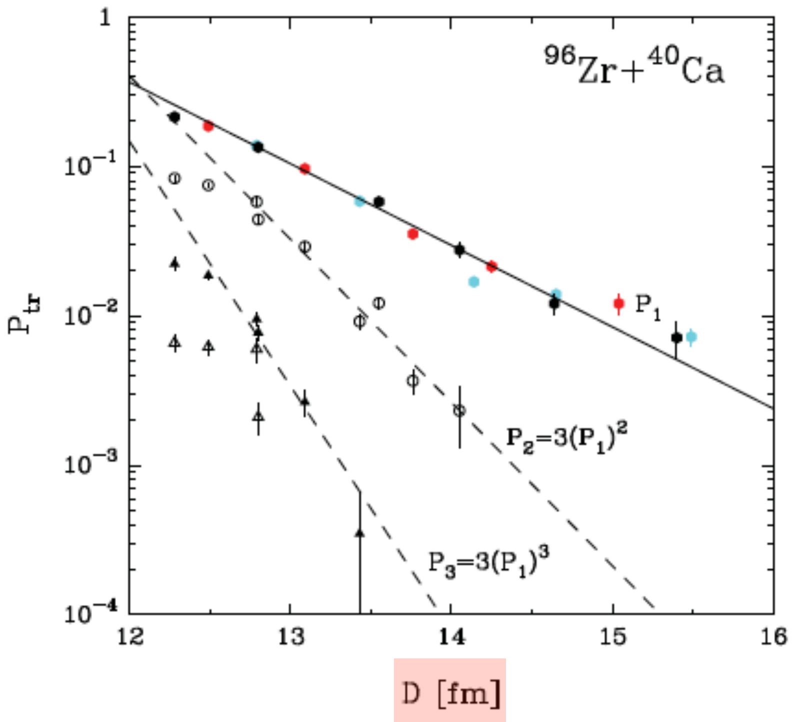
From one to two nuclei



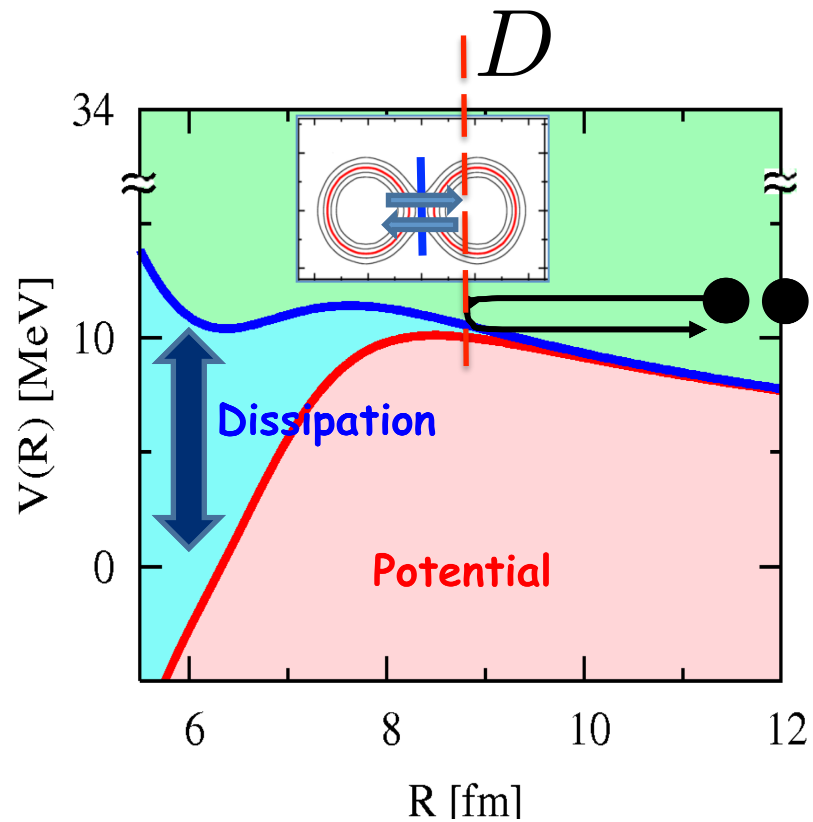
Our goal:

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

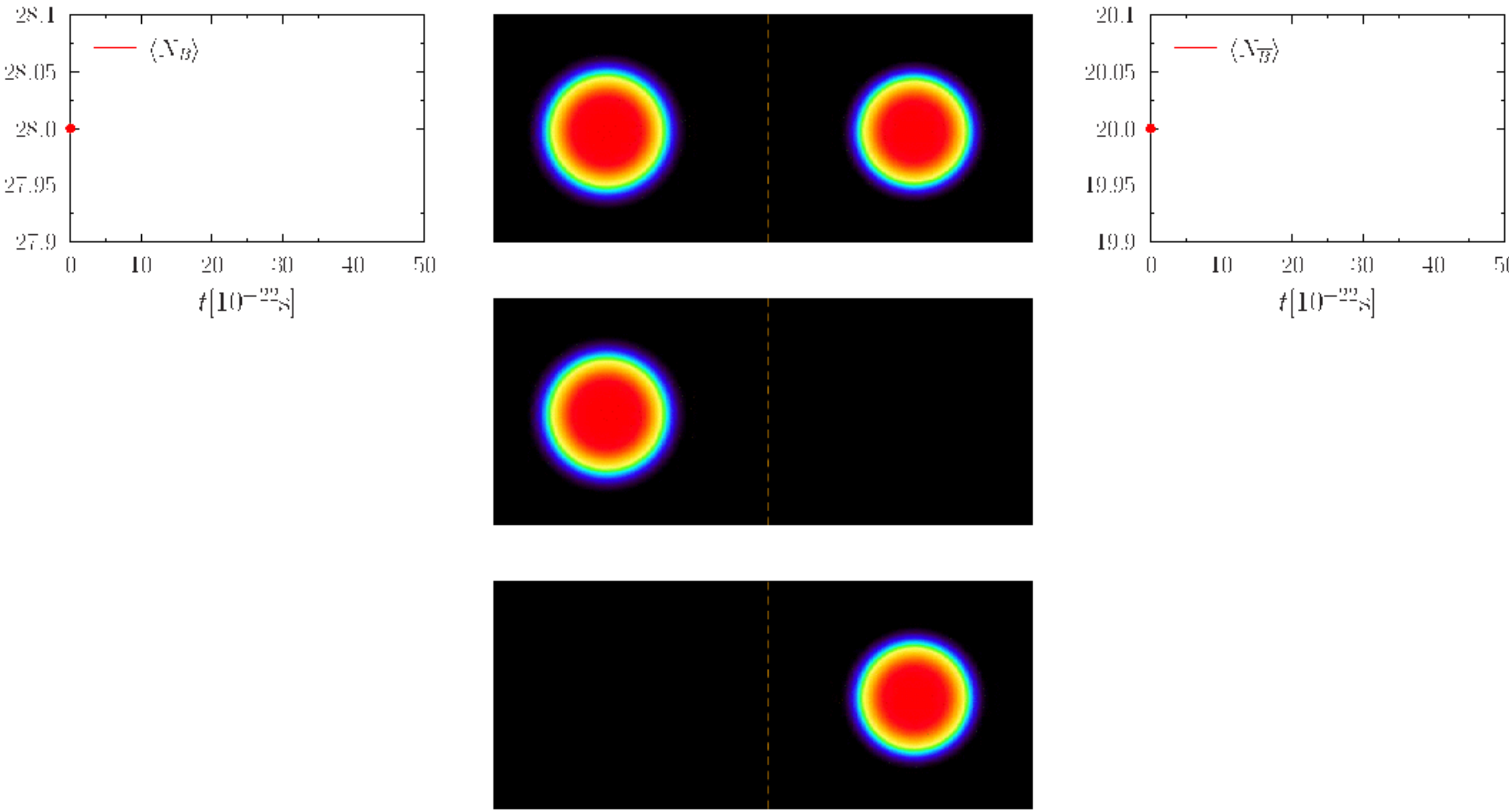
Illustration of useful data (for us)



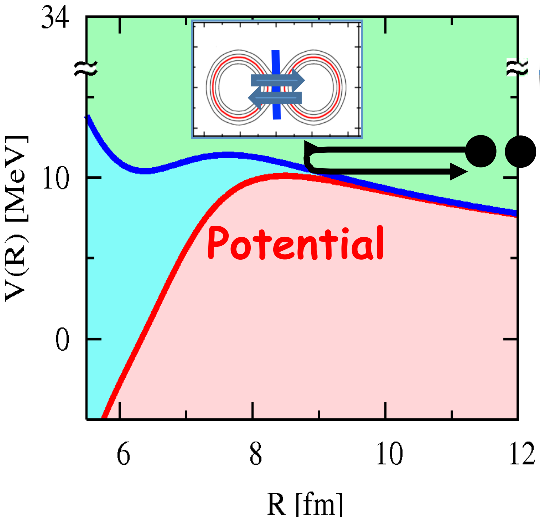
Corradi et al, Phys. Rev. C 84 (2011)



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

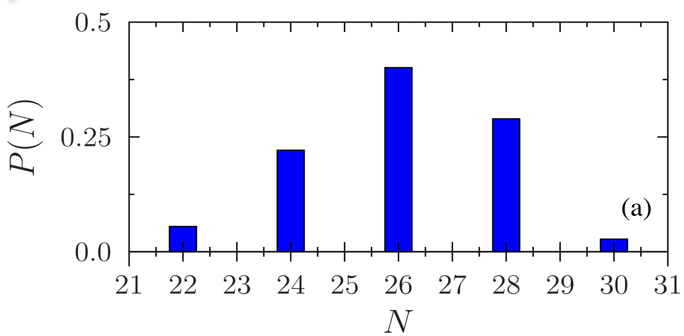


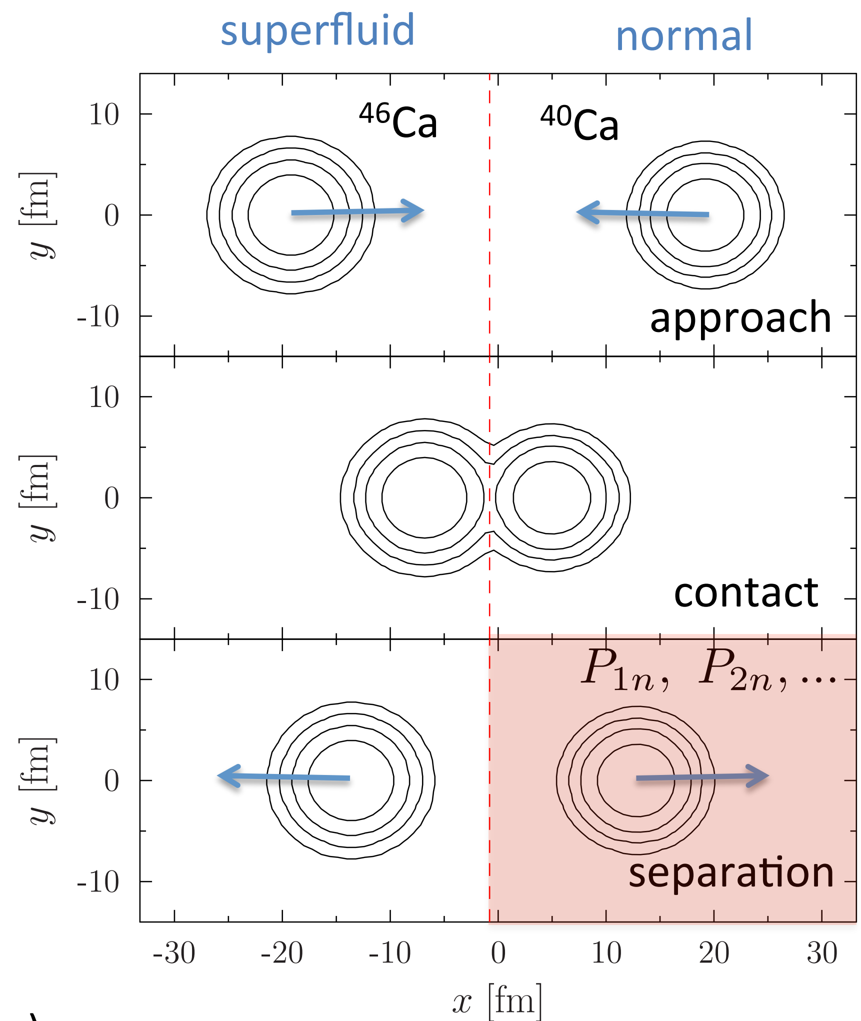
(Courtesy G. Scamps)



Besides the numerical difficulty, interpreting results is not so easy…

- ^{46}Ca or not ^{46}Ca ?





- Requires 2 projection (total and left side)

Scamps, Lacroix, PRC 87 (2013)

The no pairing limit ?

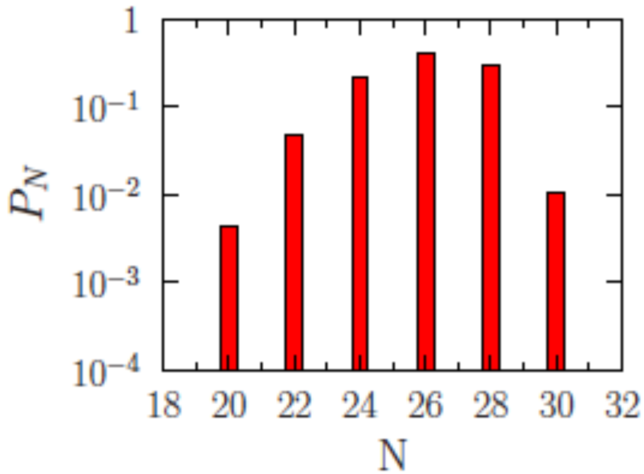
- HFB : spherical HF: deformed

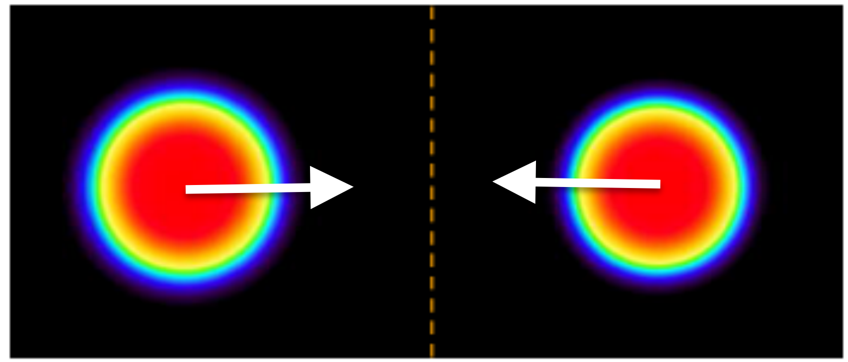
We used a generalization of TDHF to statistical Density matrix (filling approximation)

Initial time

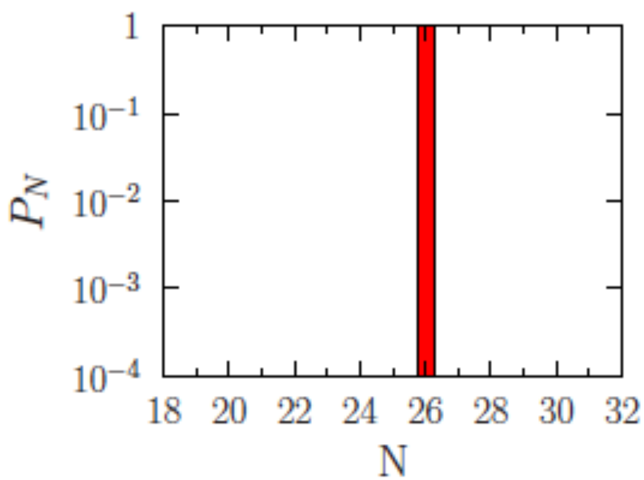
Single projection scheme (only on the left side)

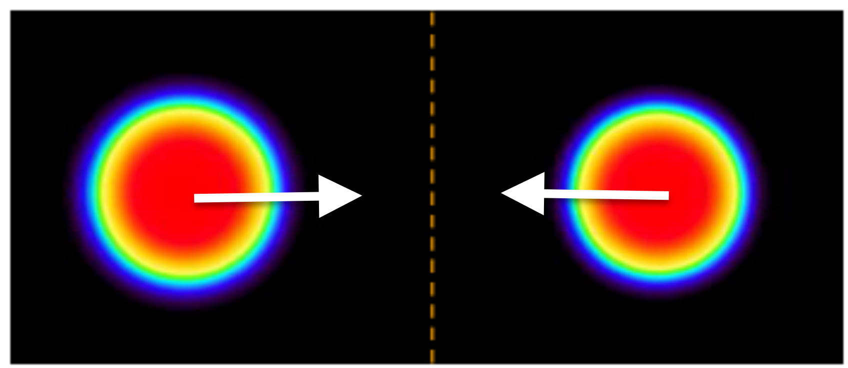
^{46}Ca + ^{40}Ca





Double projection scheme (total and left side)



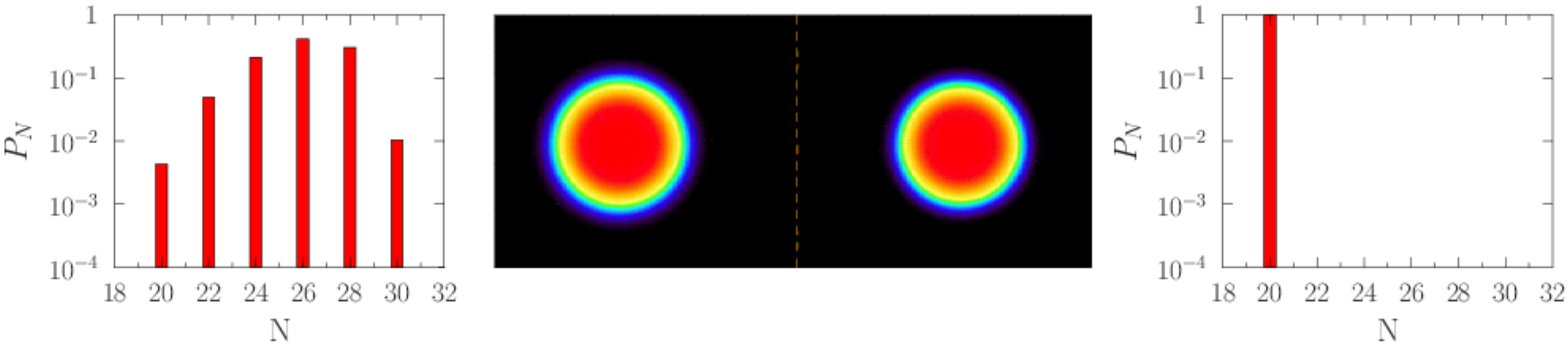


(Courtesy G. Scamps)

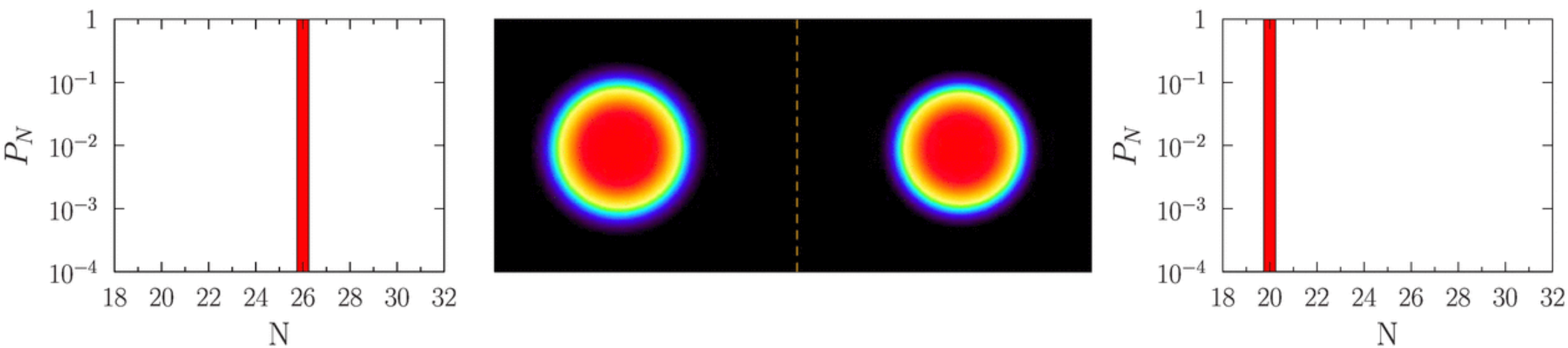
Initial time

Single projection scheme (only on the left side)

$^{46}Ca + ^{40}Ca$

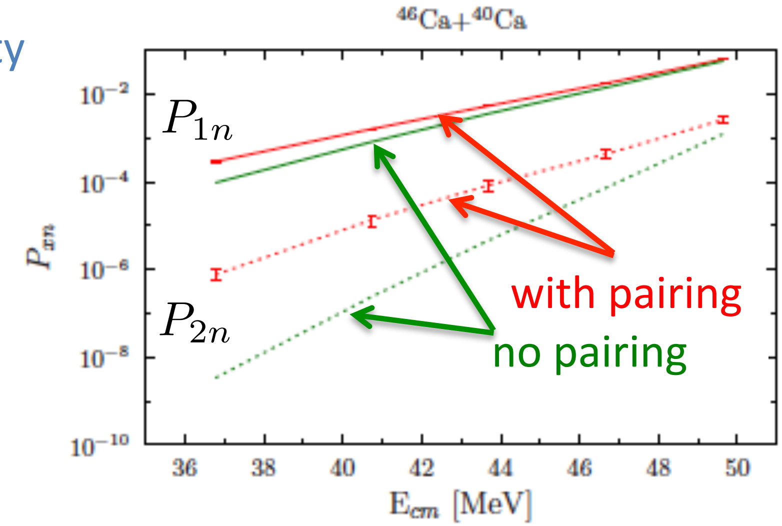


Double projection scheme (total and left side)



(Courtesy G. Scamps)

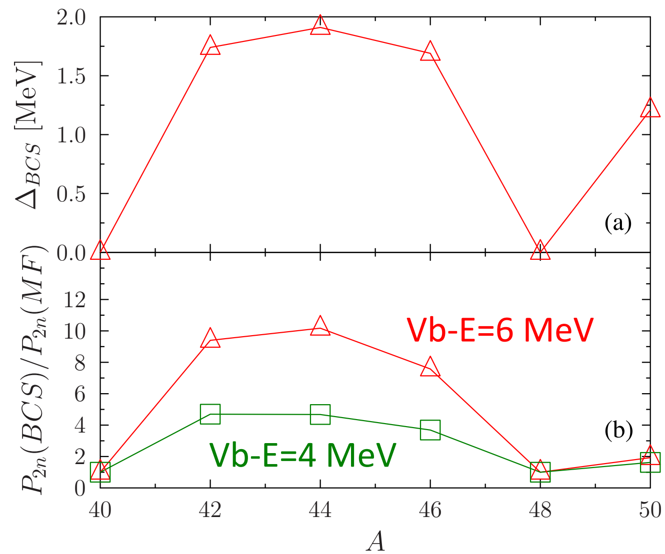
Enhancement of the pair transfer probability



First conclusion

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

Link between pairing strength and pairing gap:

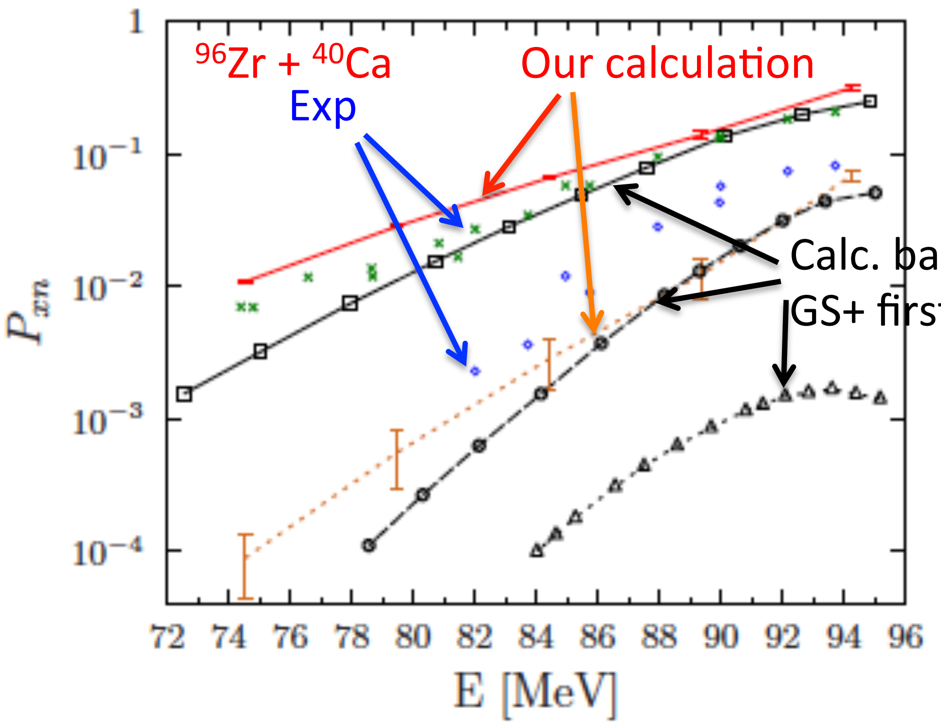


Strong beam energy dependence

Scamps, Lacroix, PRC 87 (2013)

Comparison with experiment

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



Calc. based on HFB GS+ first 2^+ (from Corradi publication)

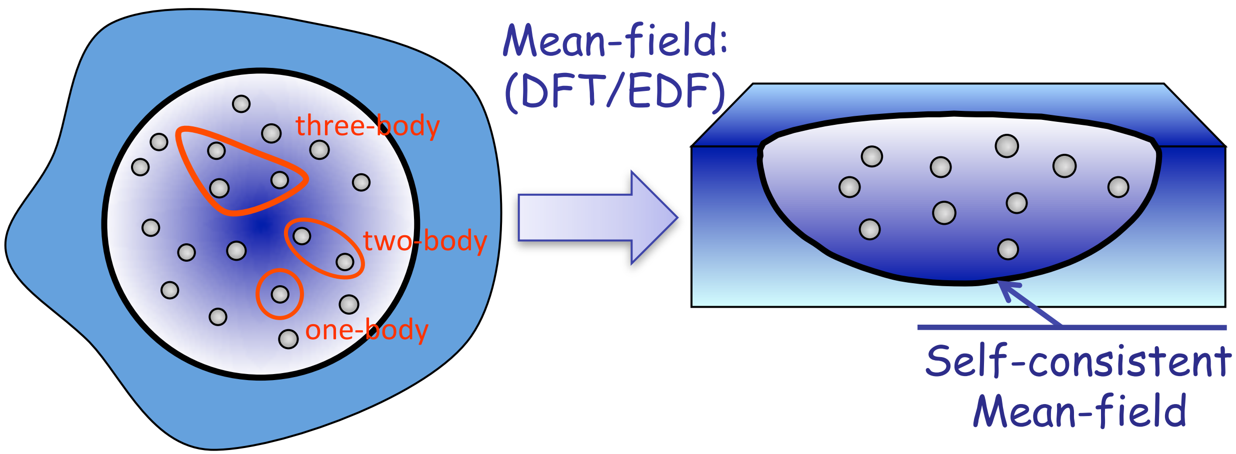
- The dynamical approach is competitive Compared to other approaches
- P_{1n} is not so well reproduces:

(Problem with the single-particle field)

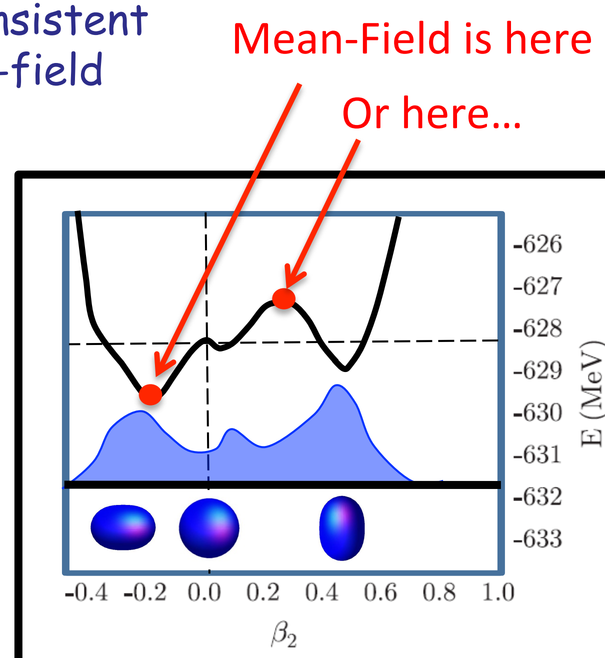
- P_{2n} is underestimated

(Other effects are important!)

Missing quantum effects in collective space

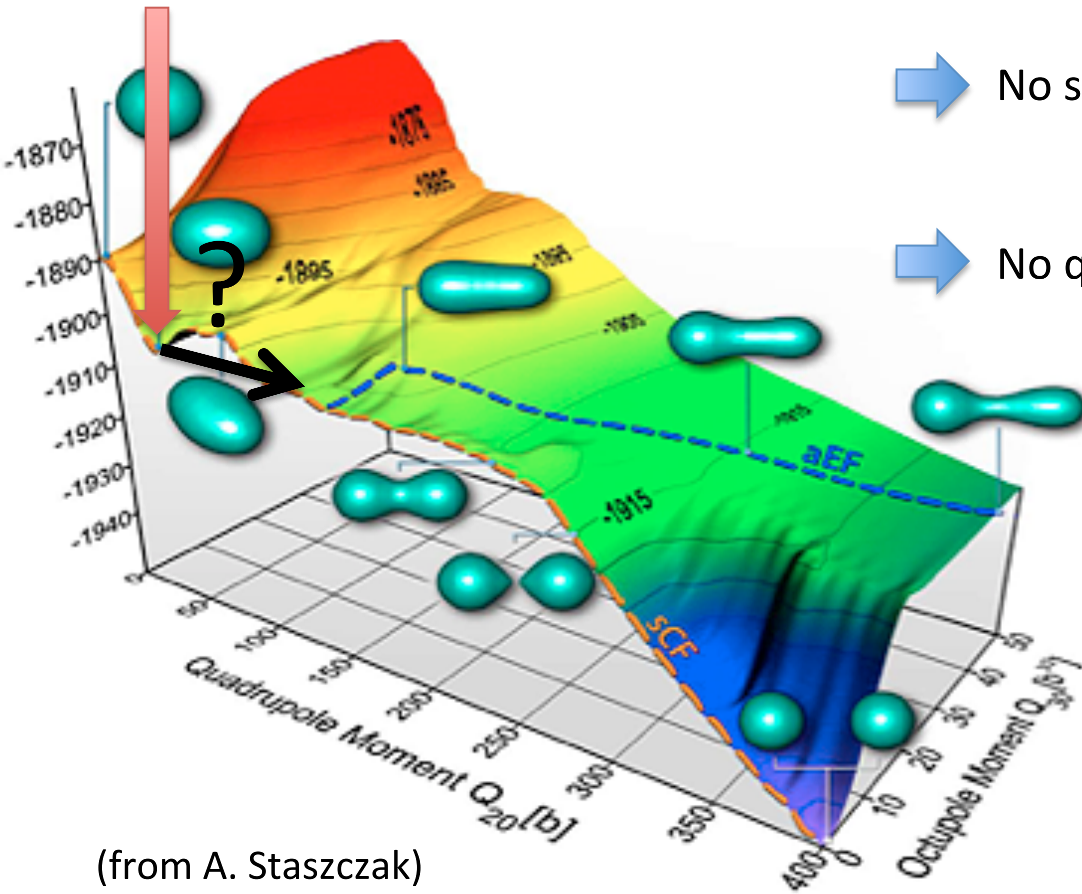


- Single-particle are quantum objects
- Collective DOF are classical objects
- Quantum fluctuations in collective space
  Needs to be introduced beyond the mean-field

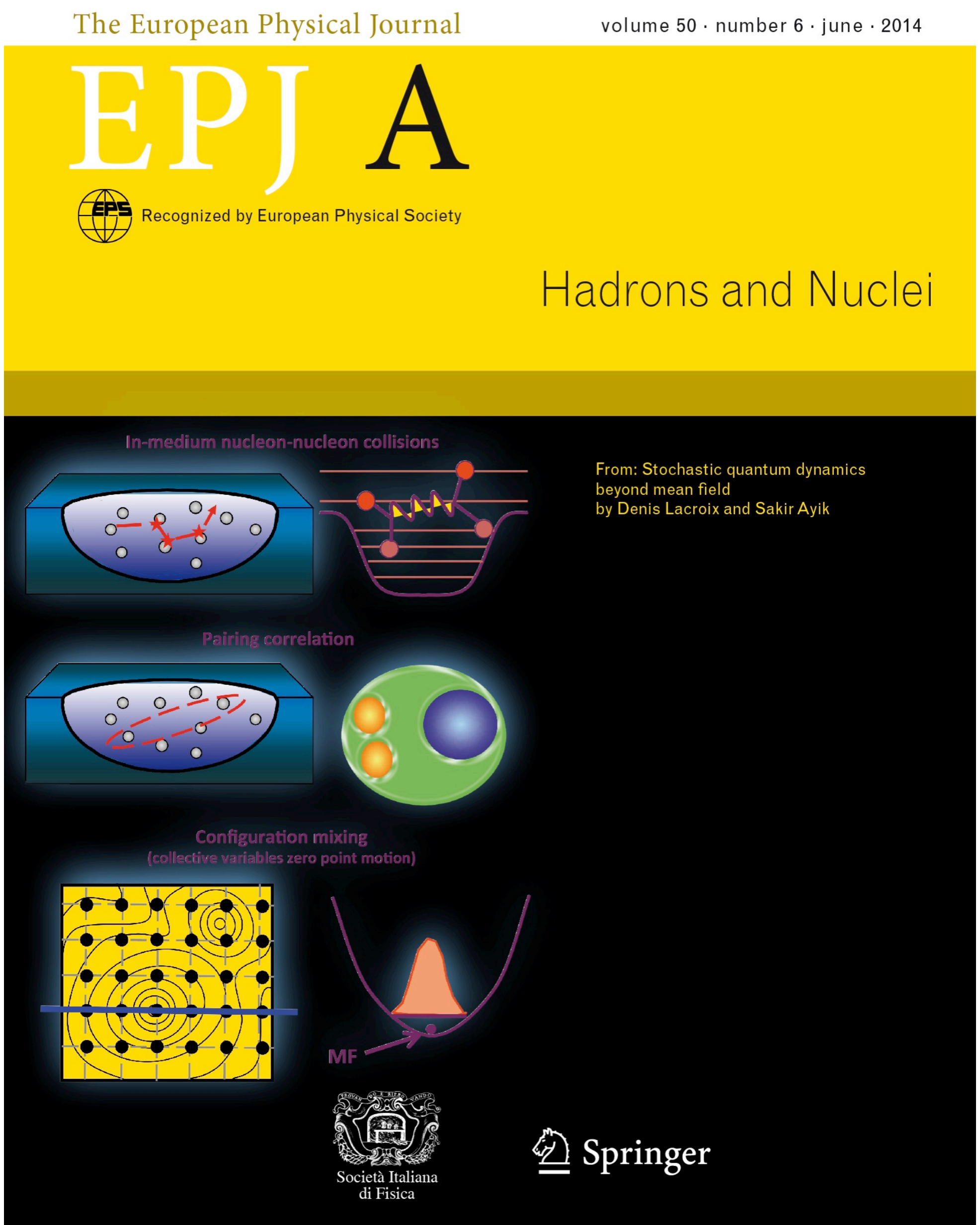


Illustration

- The mean-field dynamic is quasi-classical
- Quantum fluctuations are underestimated
- No spontaneous symmetry breaking
- No quantum tunneling in collective space

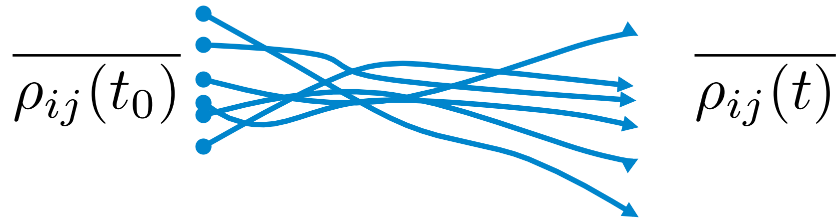


(from A. Staszczak)



The many facets of stochastic methods

Stochastic Mean-Field

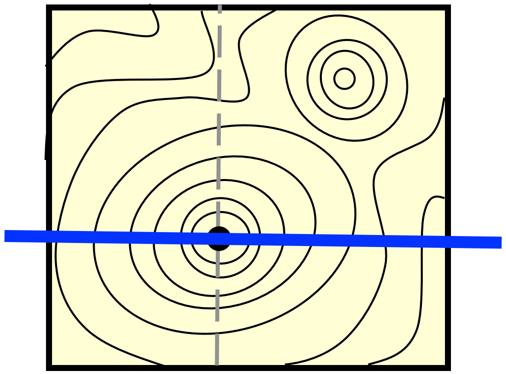


Stochastic TDHF

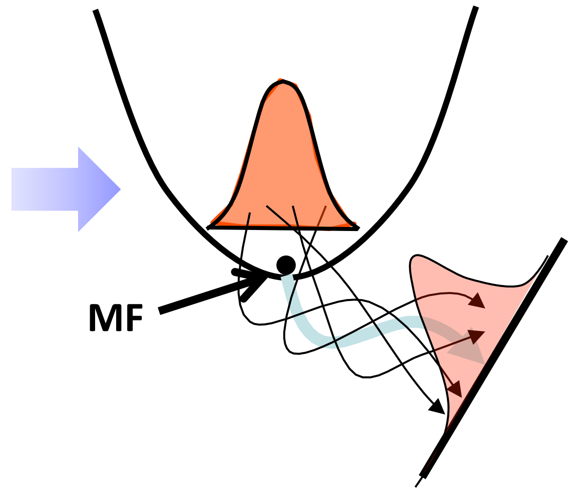
Quantum Monte-Carlo

The stochastic mean-field (SMF) concept applied to many-body problem

Collective phase-space



Quantum fluctuations



The dynamics is described by a set of mean-field evolutions with random initial conditions

Ayik, Phys. Lett. B 658, (2008).

The average properties of initial sampling should identify with properties of the mean-field.

SMF in density matrix space

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

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

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

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

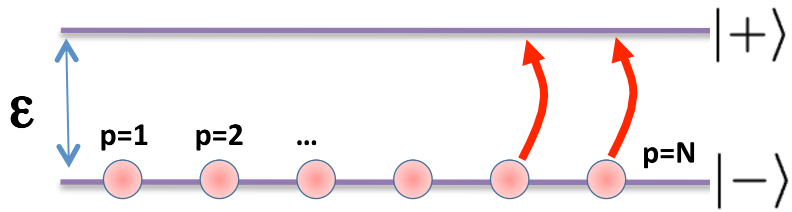
SMF in collective space

$$Q(t_0) \rightarrow Q^\lambda(t_0)$$

$$\overline{Q}^\lambda(t_0) = Q(t_0)$$

$$\sigma_Q(t_0) = \overline{(Q^\lambda(t_0) - \overline{Q^\lambda(t_0)}^2)}$$

Lipkin Model



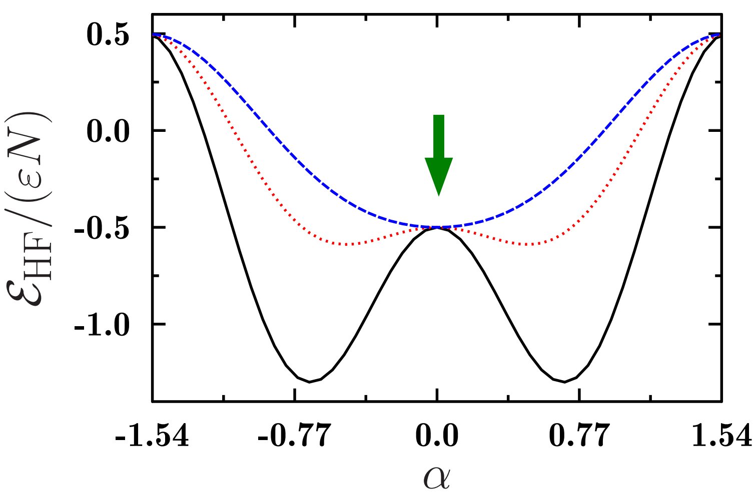
$$H = \varepsilon J_0 - \frac{V}{2}(J_+J_+ + J_-J_-)$$

$$J_0 = \frac{1}{2}\sum_{p=1}^{N}\left(c^\dagger_{+,p}c_{+,p} - c^\dagger_{-,p}c_{-,p}\right) \qquad J_y = \frac{1}{2i}(J_+ - J_-)$$

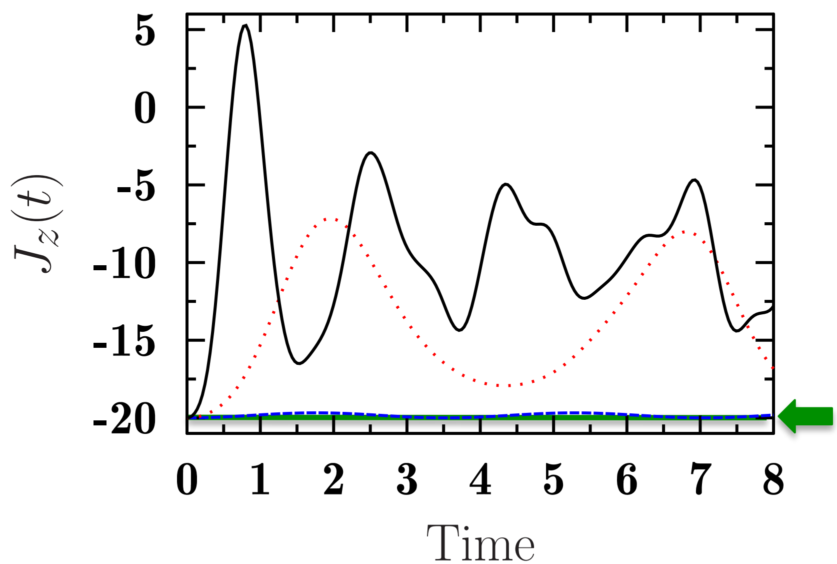
$$J_+ = \sum_{p=1}^{N} c^\dagger_{+,p}c_{-,p}, \quad J_- = J_+^\dagger, \qquad J_x = \frac{1}{2}(J_+ + J_-)$$

See for instance : Ring and Schuck book
Severyukhin, Bender, Heenen, PRC74 (2006)

N=40 particles



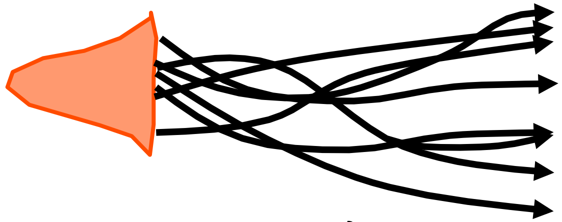
Exact dynamics



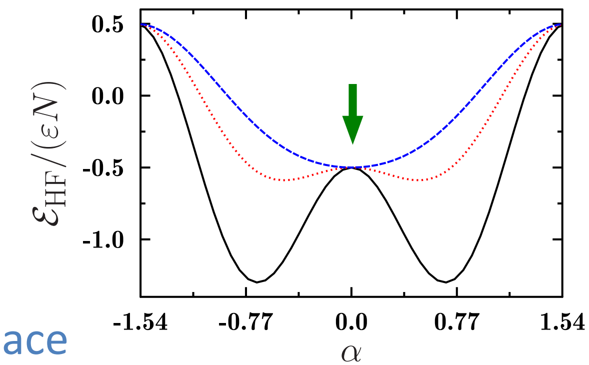
Mean-field is stationary

Description of large amplitude collective motion : symmetry breaking

The stochastic mean-field solution



$\rho \Rightarrow \rho^{\lambda}$



One-body observables

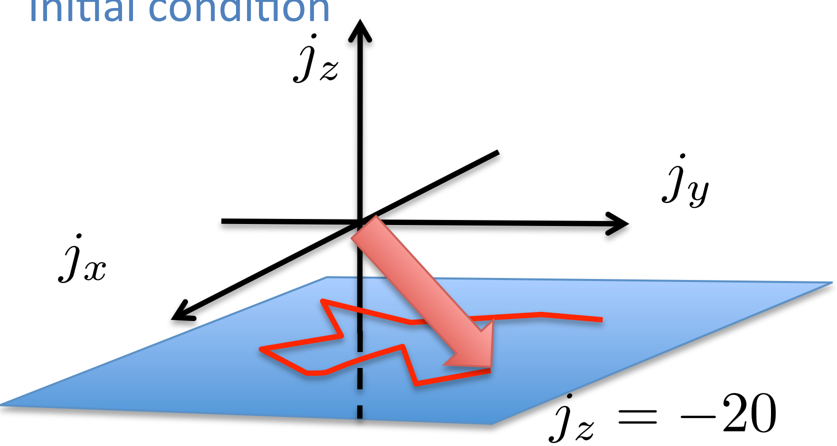
Formulation in quasi-spin space

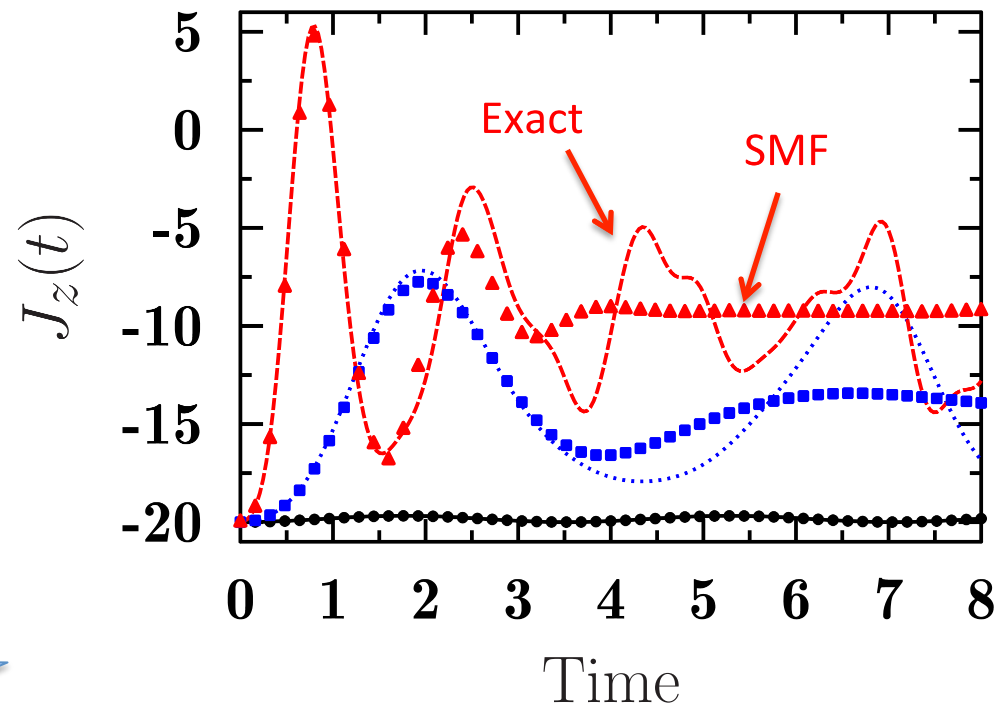
$$j_i \equiv \langle J_i \rangle / N \quad \Rightarrow \quad j_i^{\lambda}$$

$$\overline{j_i^{\lambda}(t_0)} = 0$$

$$\overline{j_x^{\lambda}(t_0) j_x^{\lambda}(t_0)} = \overline{j_y^{\lambda}(t_0) j_y^{\lambda}(t_0)} = \frac{1}{4N}.$$

Initial condition



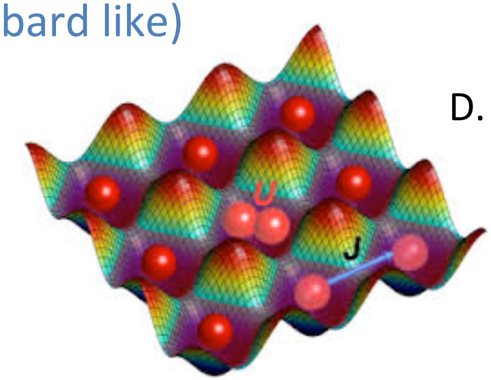


Lacroix, Ayik, Yilmaz, PRC 85 (2012)

- Extension to include pairing correlation

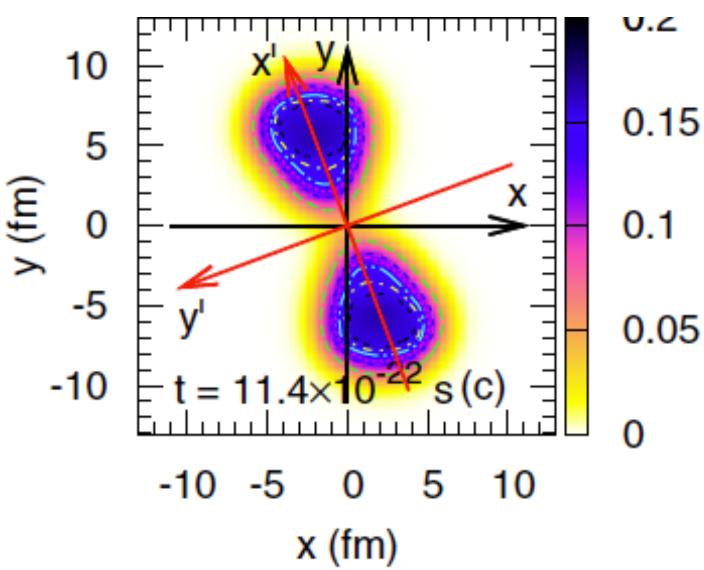
D. Lacroix, D. Gambacurta, S. Ayik, PRC 87 (2013)

- Validation in lattice models (Hubbard like)



D. Lacroix et al, PRB90 (2014)

- Nuclear collisions



B. Yilmaz, S. Ayik, D. Lacroix, O. Yilmaz, PRC90 (2014)

- Project : fission and LACM