Macroscopic collision dynamics by time-dependent energy density functional theory

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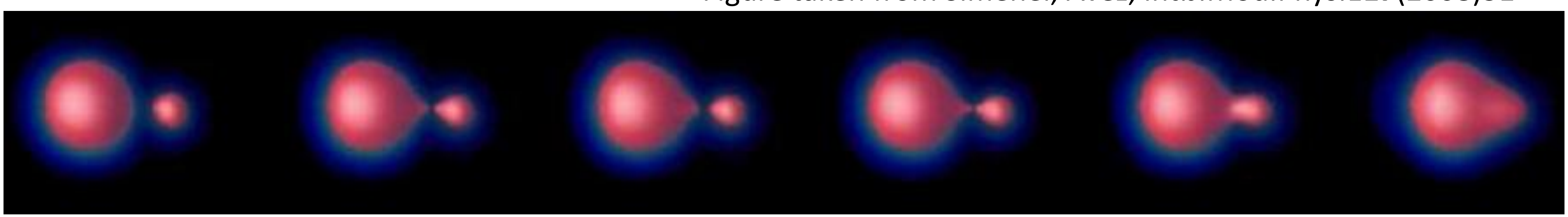
Denis Lacroix (GANIL), Sakir Ayik (Tennessee Tech. Univ)

Mean-field dynamics

- Microscopic $\longleftrightarrow$ Macroscopic
- Nucleus-nucleus potential
- Energy dissipation

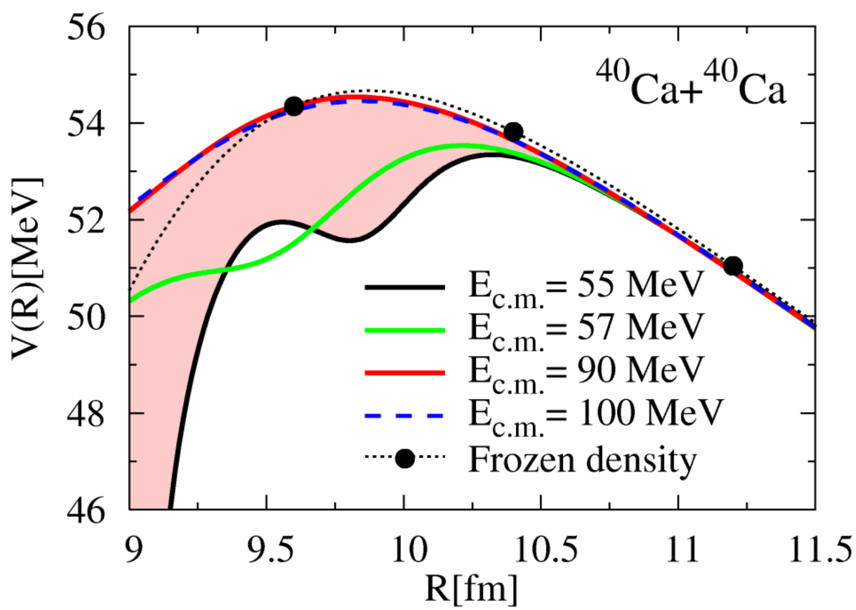
Figure taken from Simenel, Avez, Int.J.Mod.Phys.E**17**(2008)31



DCEN2011, Oct. 28, 2011, Kyoto

Plan of the talk

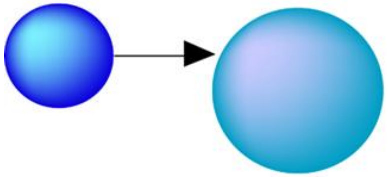
- Introduction
- Macroscopic and microscopic nuclear reaction
- Time-dependent energy density functional (TDHF)
- Nucleus-nucleus potential, energy dissipation
- Fluctuation around mean field: Width of mass distribution
- Stochastic mean-field approach
- Summary



Introduction: macroscopic, microscopic

(Energy < 10 MeV/A)

□Macroscopic nuclear reaction



- Collective degrees of freedom
- Coupled-channels, CDCC
- Nucleus-nucleus potential

■ Nucleus-nucleus potential

- Phenomenological potential (Woods-Saxon)
- Double folding potential with realistic nuclear density

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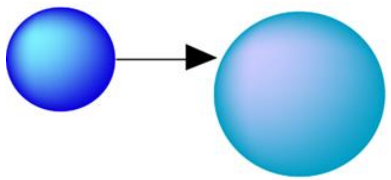

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□Microscopic nuclear reaction: TDHF

- Microscopic degrees of freedom
  (single-particle wave functions in TDHF)
- No collective degrees of freedom is explicitly considered

Introduction: TDHF

- Nuclear structure and dynamics in a unified framework
- Dynamical effect (vibration, rotation, transfer, ...) automatically included
- Single-particle motion: quantum.   Collective motion: classical
- Full Skyrme forces including spin-orbit and time-odd terms
- No fitted parameter for dynamics

Predictive power of TDHF

- Bonche et al., PRC13 (1976)
- Flocard et al., PRC17 (1978)
- Kim et al., J. Phys. G23 (1997)
- Simenel et al., PRL86 (2001)
- Nakatsukasa et al., PRC71 (2005)
- Umar et al., PRC73 (2006)
- Maruhn et al., PRC74 (2006)

3D-TDHF code by P. Bonche (Kim, Otsuka, Bonche, J.Phys.G23(1997)1267)

- $i\hbar\dot{\varphi}_\alpha = \hat{h}\varphi_\alpha$, *h*: self-consistent mean field
- Three dimensional box (mesh size: 0.8 fm, time step: 0.45 fm/c)
- Skyrme energy density functional (SLy4d)

Introduction: macroscopic, microscopic

Macroscopic aspects $\Longleftrightarrow$ Microscopic model

Nucleus-nucleus potential and ....

Microscopic potentials based on EDF

□Frozen density approximation

Denisov, Norenberg, EPJA15(2002)375

- Energy density functional of projectile and target
- Density is frozen to ground-state density at each R

$$V^{FD}(R) = \mathcal{E}[\rho_{P+T}](R) - \mathcal{E}[\rho_T] - \mathcal{E}[\rho_P]$$

$\mathcal{E}$: Skyrme energy density functional

□Density-constrained TDHF

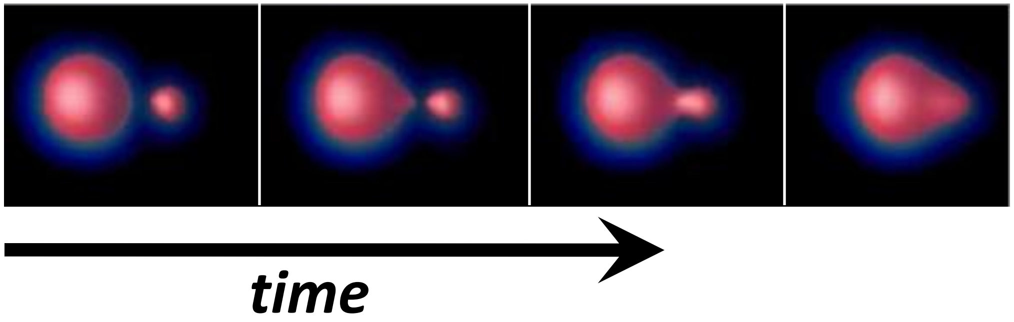
Umar, Oberacker, PRC74(2006)021601

- Density from TDHF trajectory
- Minimization of energy: constraint HF on this density

$$\hat{H} \to \hat{H} + \int d^3 r \lambda(r) \hat{\rho}(r)$$

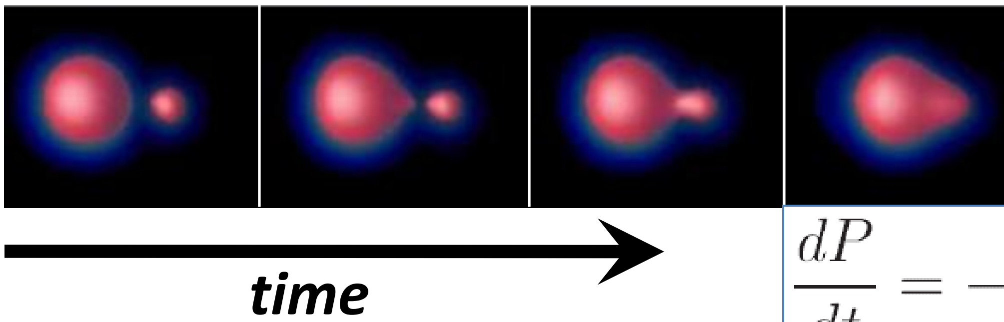
$$V(R) \to E_{DC}(R) - E_{A_1} - E_{A_2}$$

From TDHF to macroscopic dynamics (fusion)



Central collision

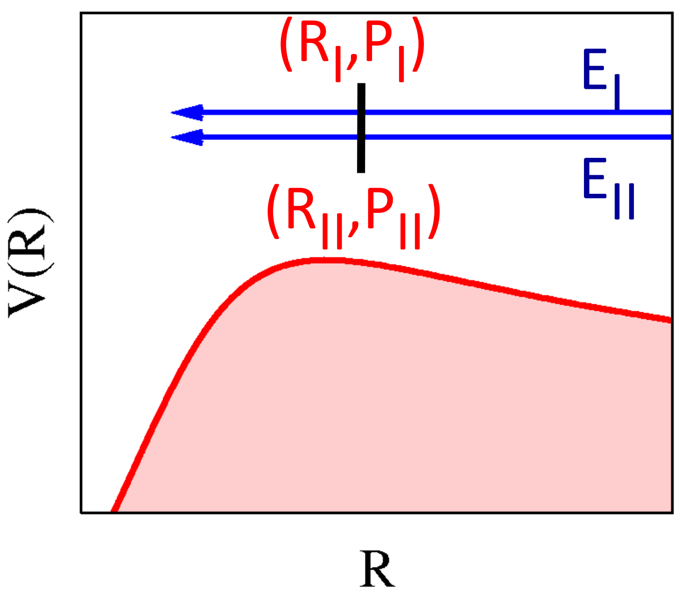
From TDHF to macroscopic dynamics (fusion)



Mapping

$$\frac{dP}{dt} = -\frac{dV(R)}{dR} - \gamma(R)\frac{dR}{dt}$$

R: relative distance
P: momentum
V: potential
γ: friction coefficient



- Two trajectories (R_I, P_I), (R_{II}, P_{II}) at two slightly different energies (E_I, E_{II})

$$\Rightarrow \gamma(R) = -\frac{dP_I/dt - dP_{II}/dt}{dR_I/dt - dR_{II}/dt}$$

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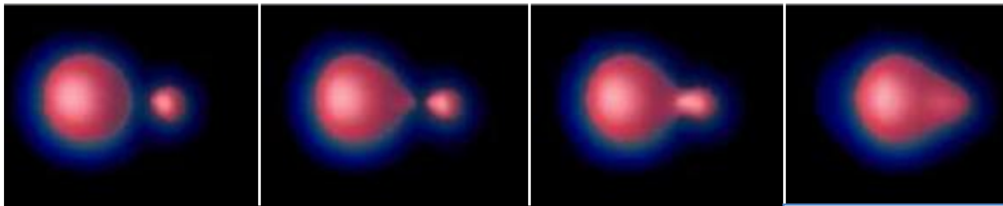

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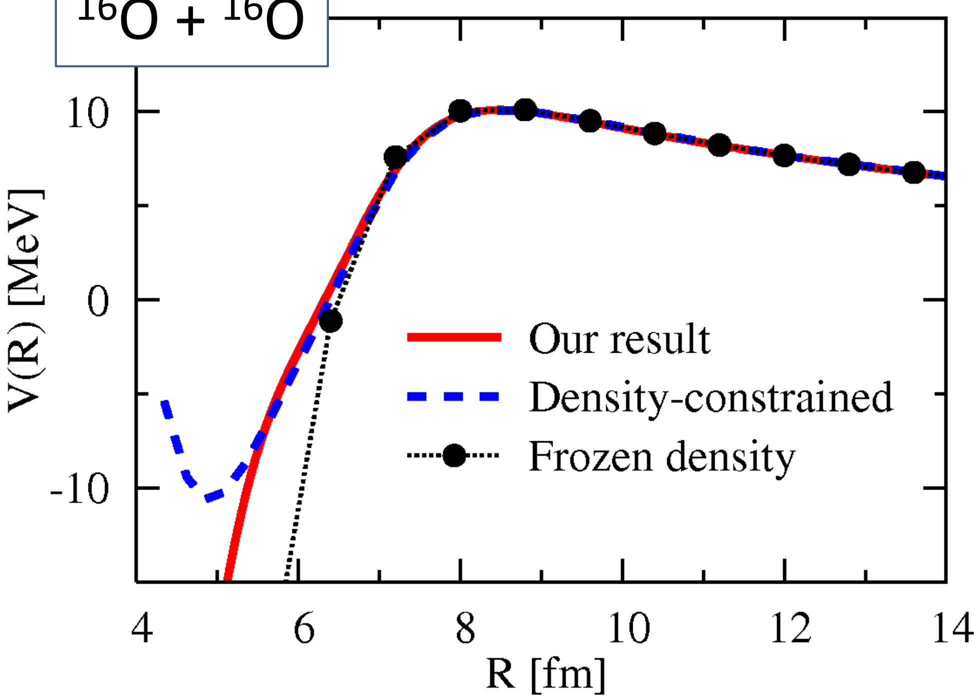
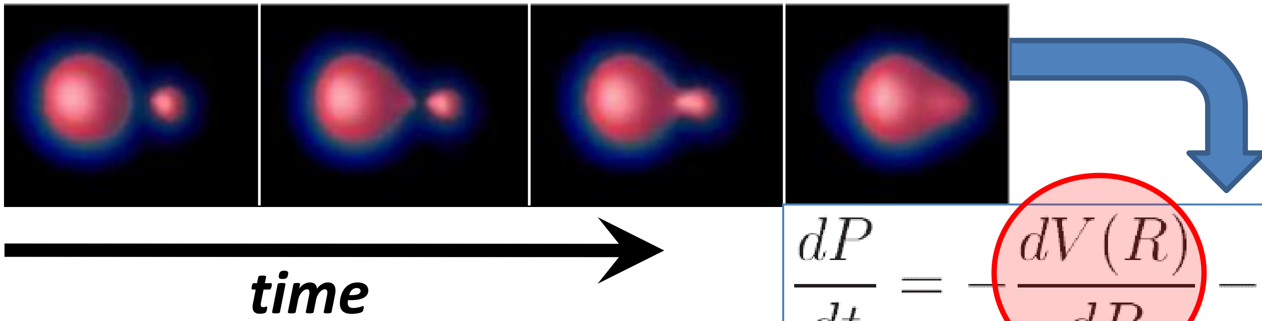
$^{16}O + ^{16}O$



Washiyama, Lacroix, PRC78(2008)024610

Energy dependence of potential



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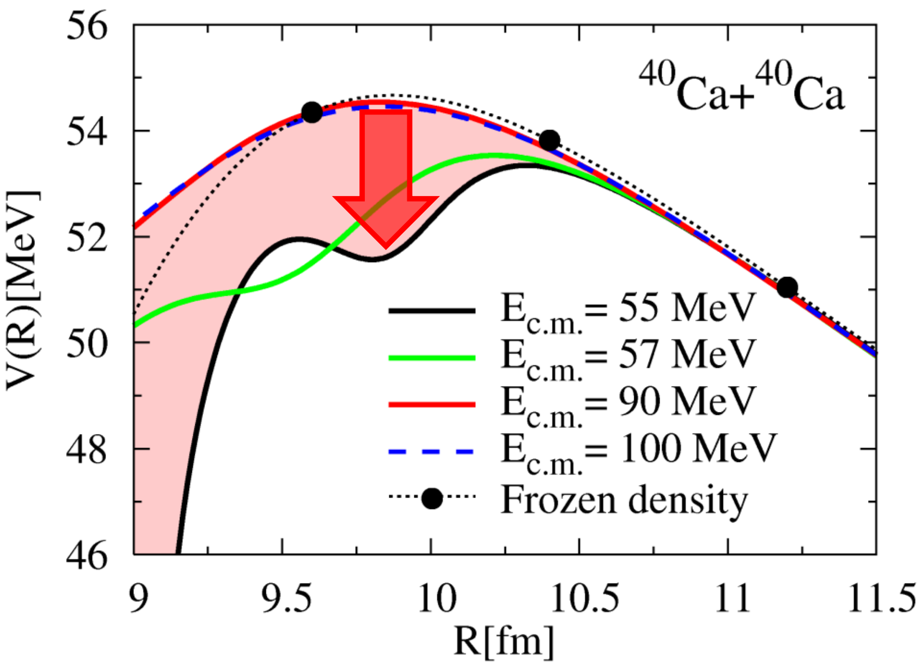

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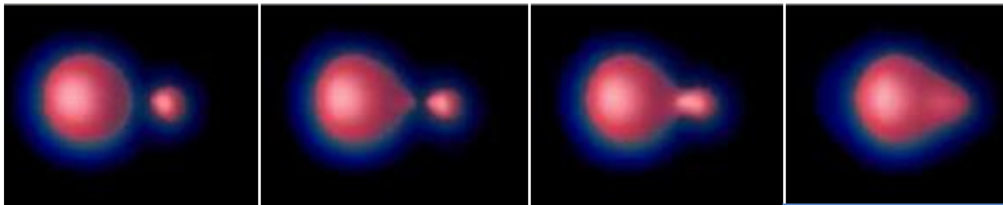

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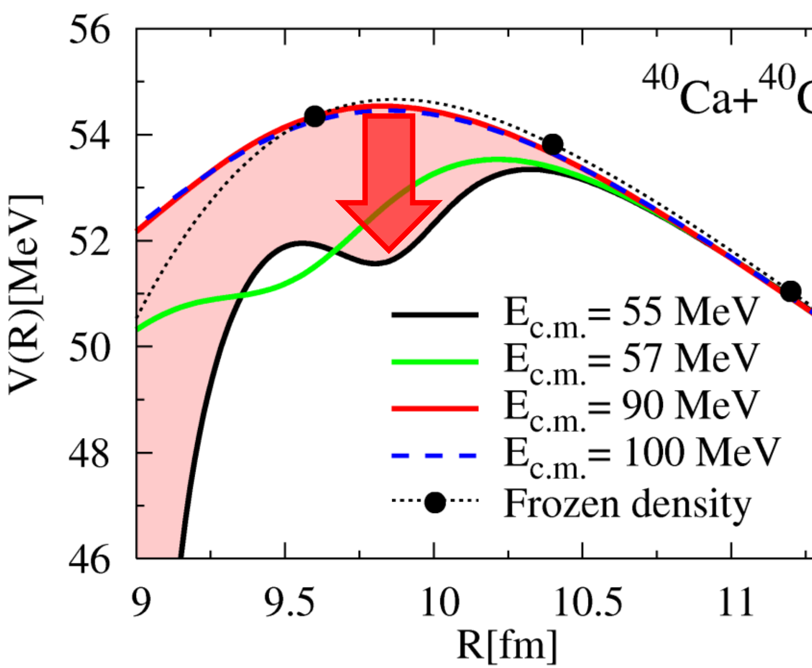

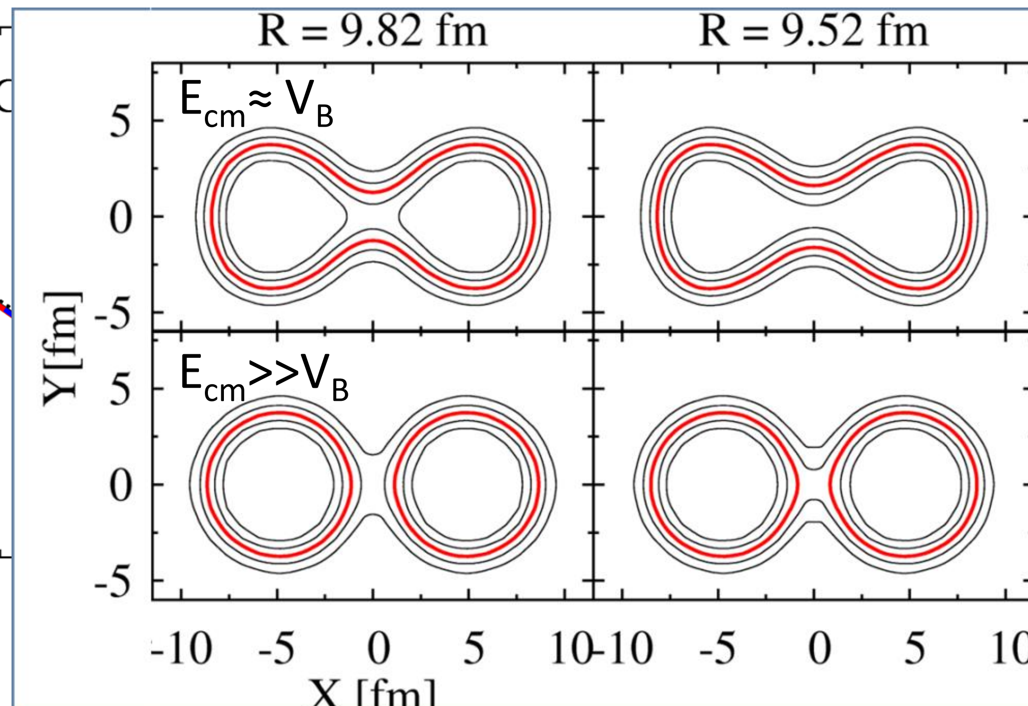

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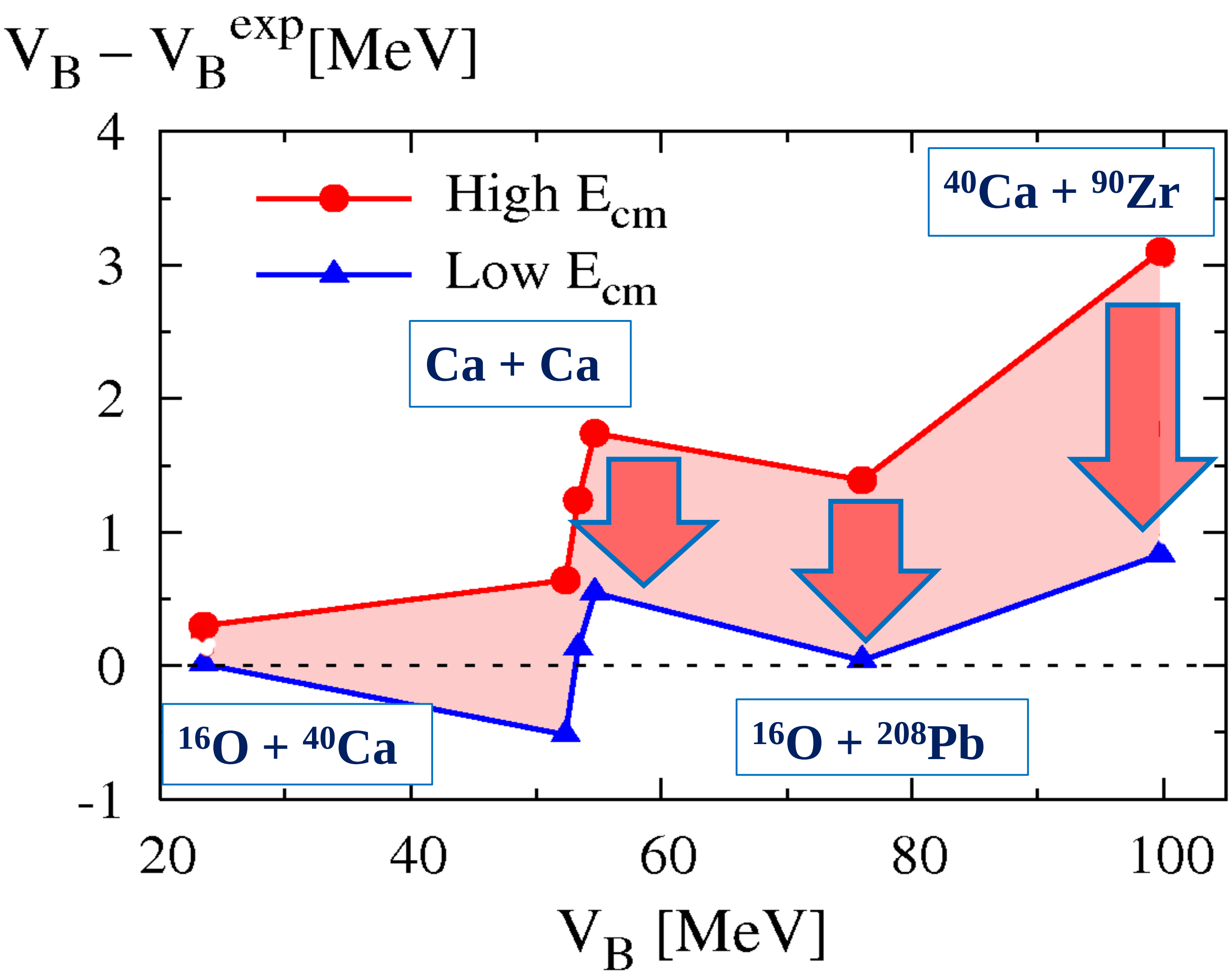
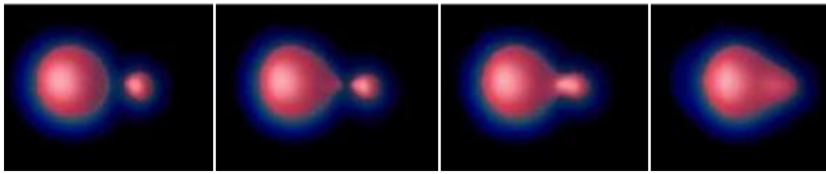


Nuclear friction: energy dissipation



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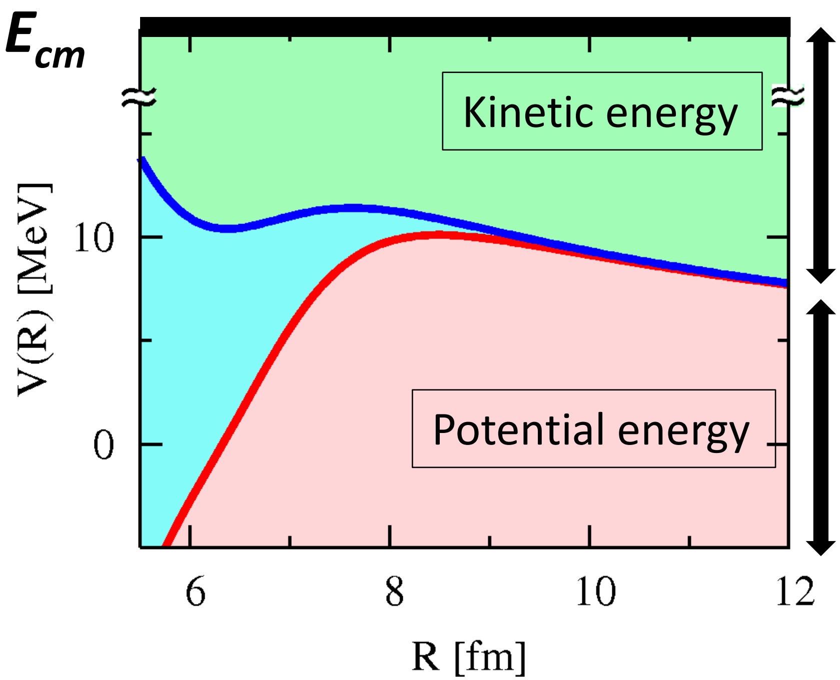
$$E_{cm} = P^2/2\mu + V$$



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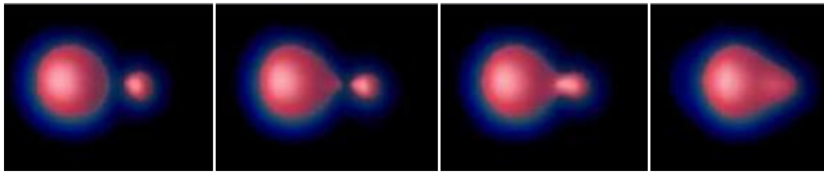

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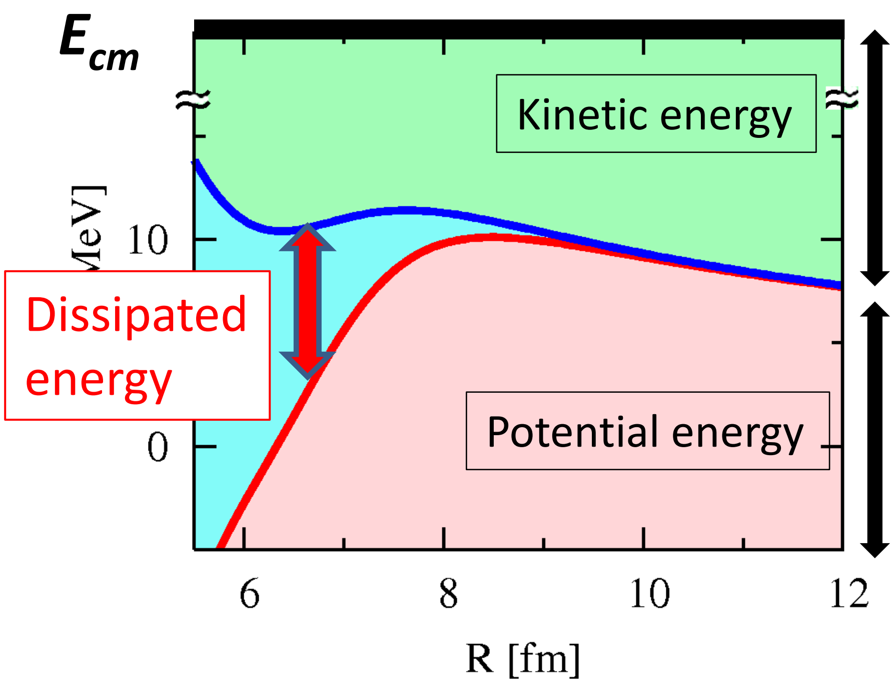
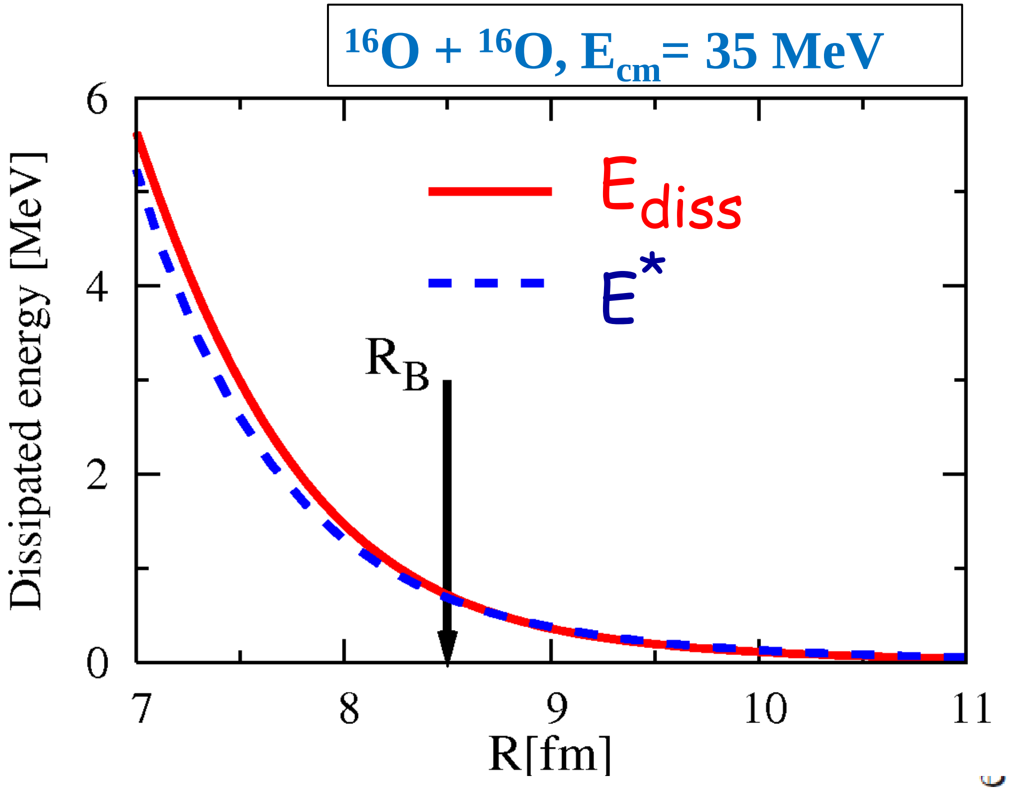
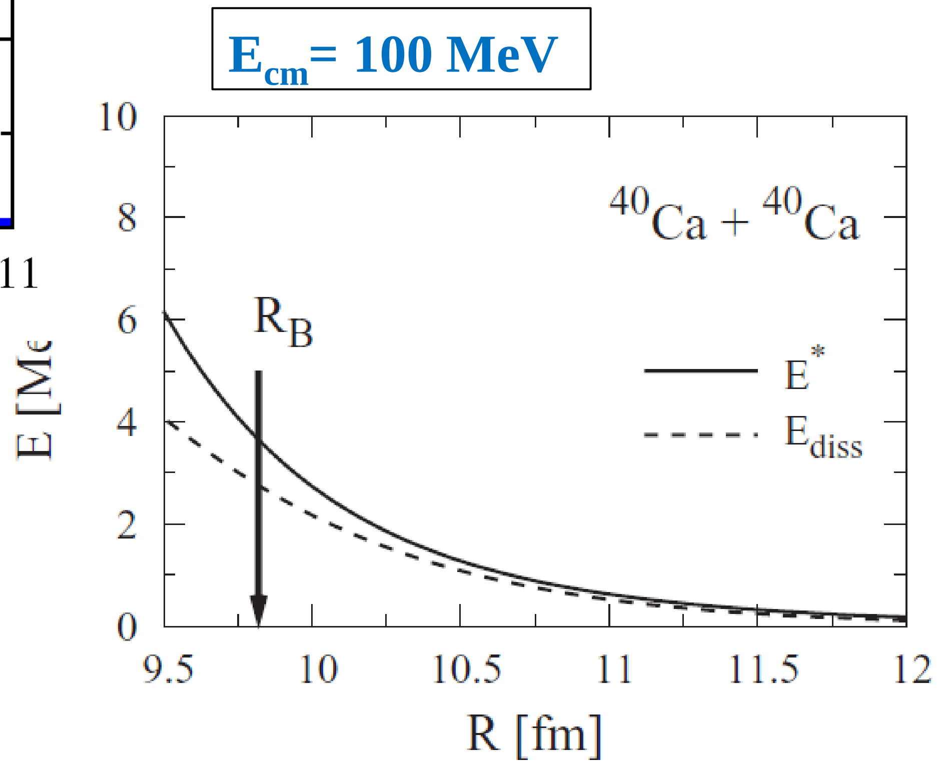


Nuclear friction: dissipated energy





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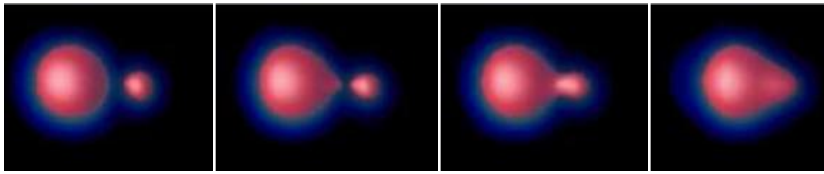

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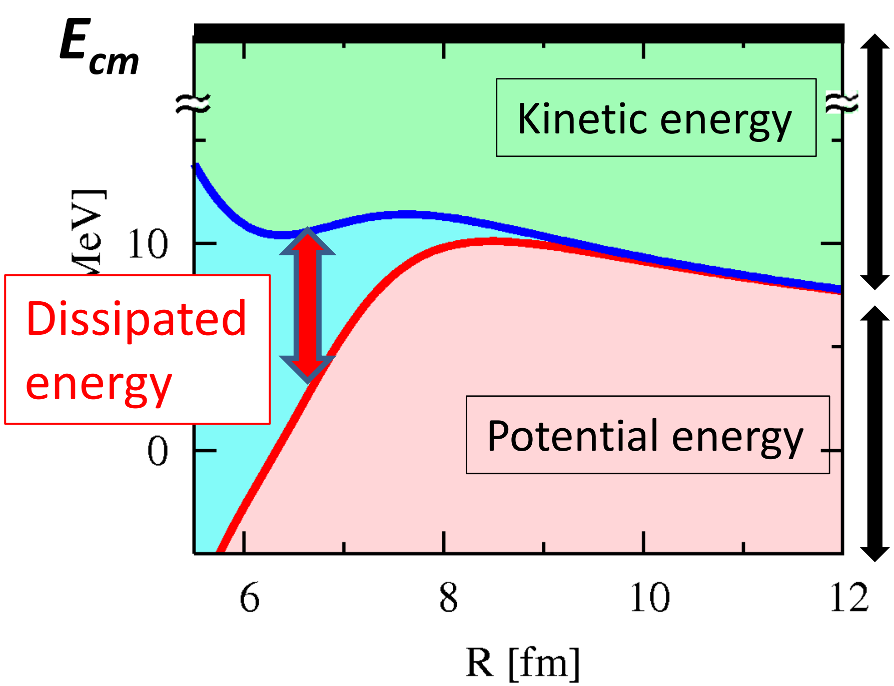
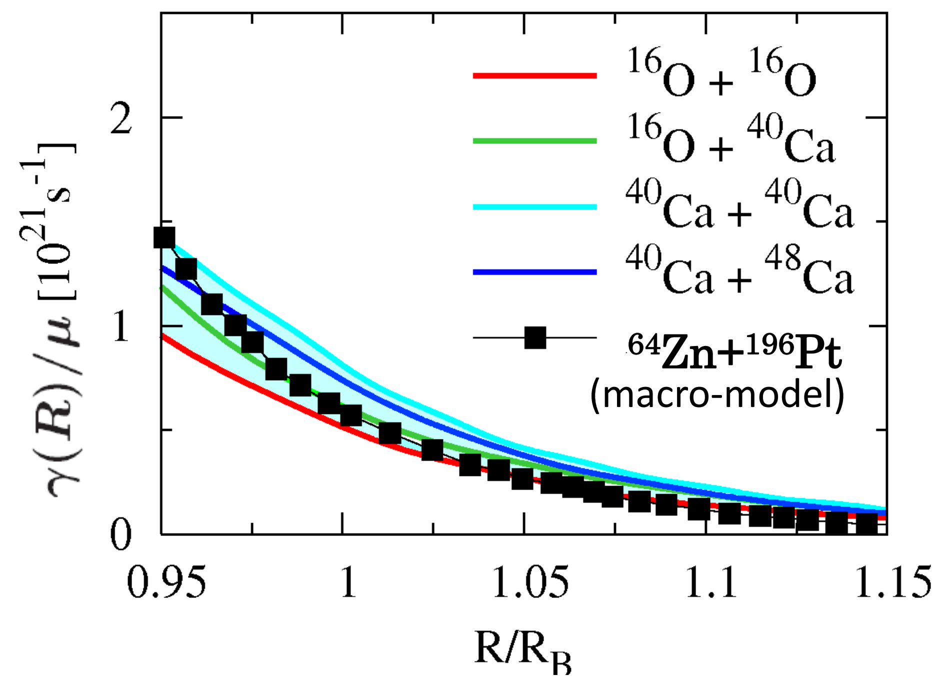
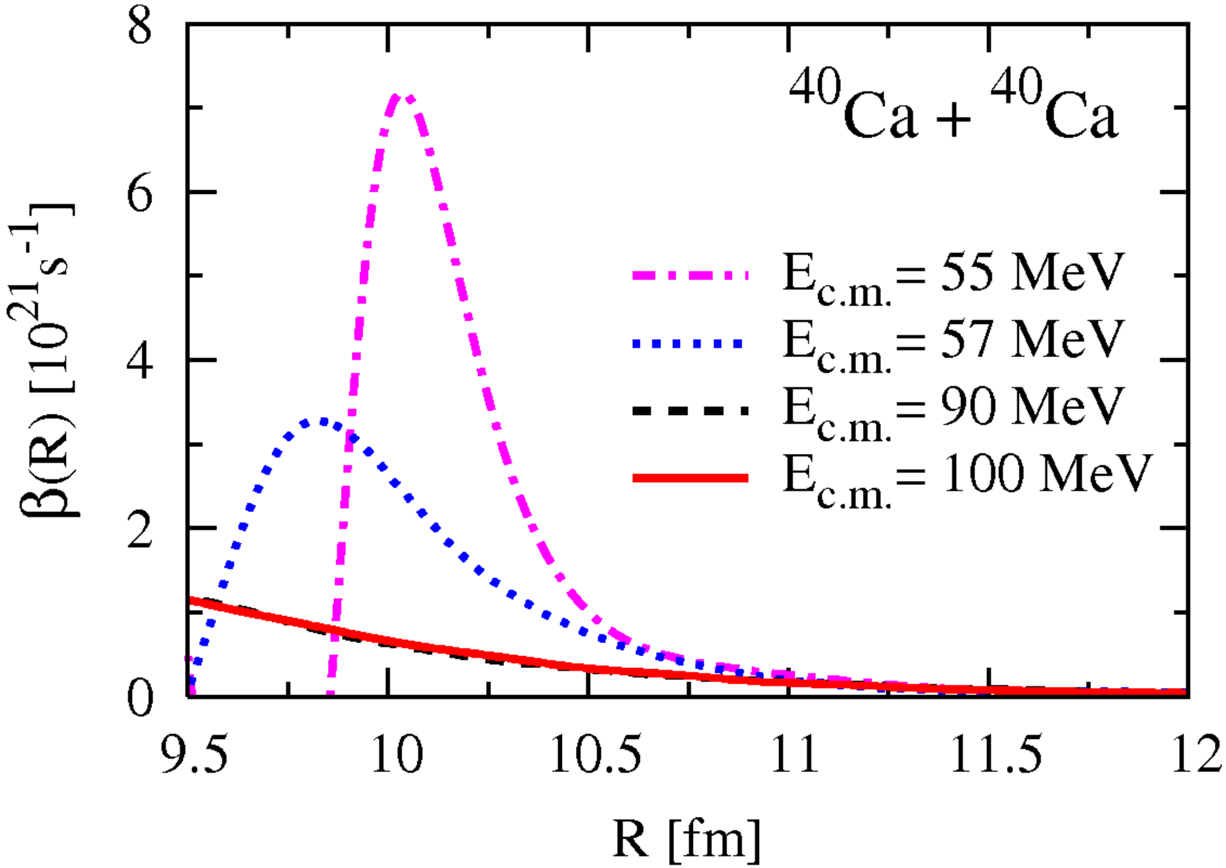




Washiyama, Lacroix, Ayik, PRC79(2009)024609

Energy dependence of nuclear friction



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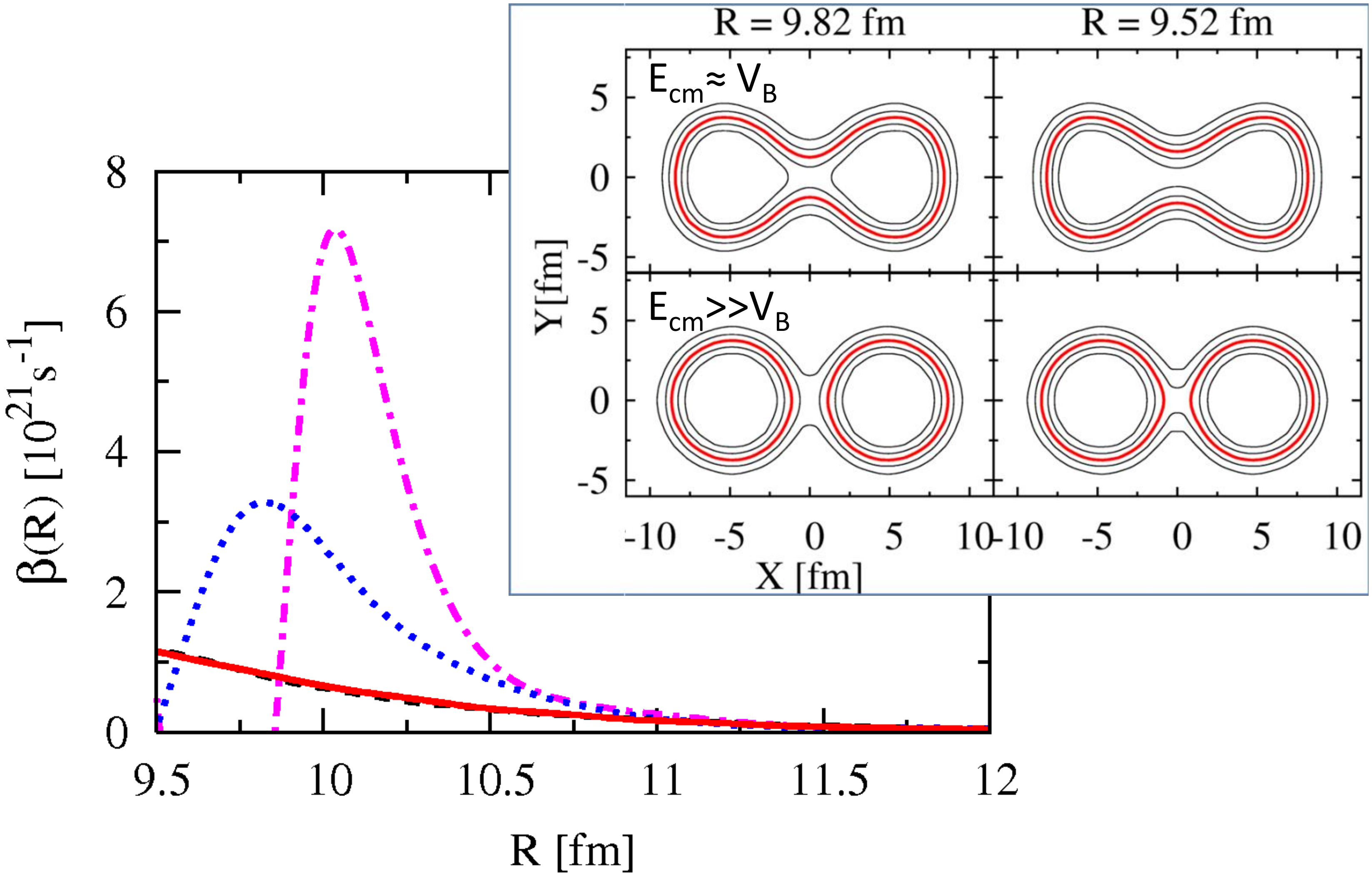

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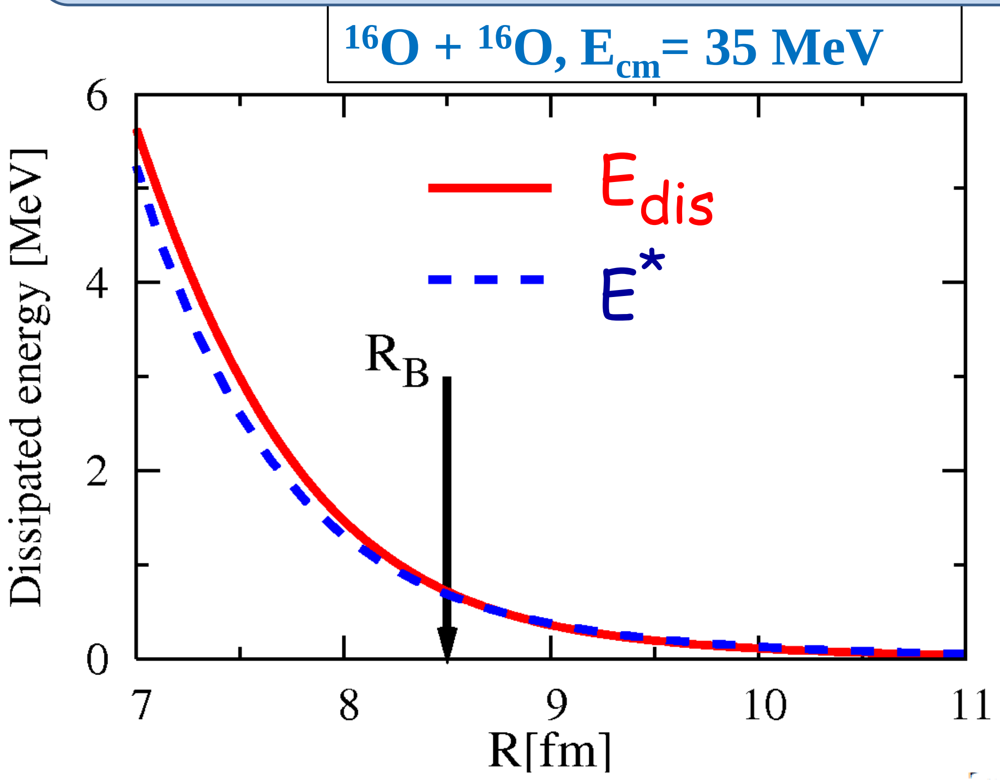
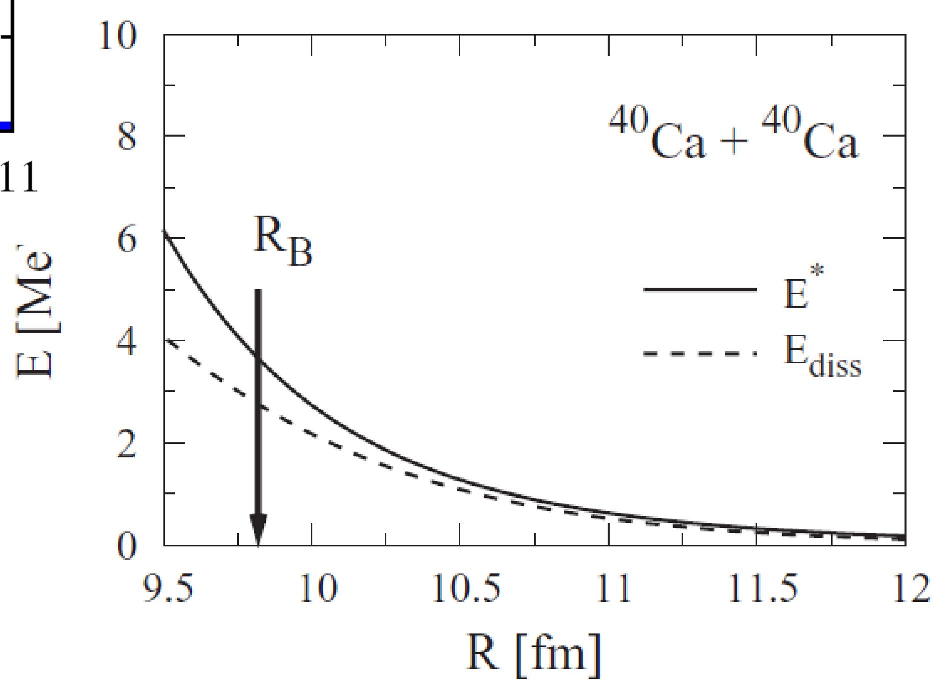
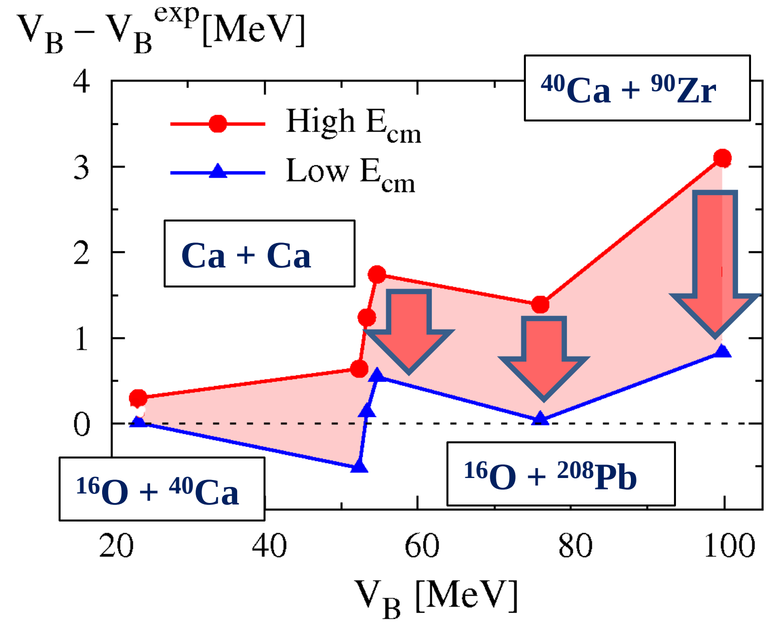


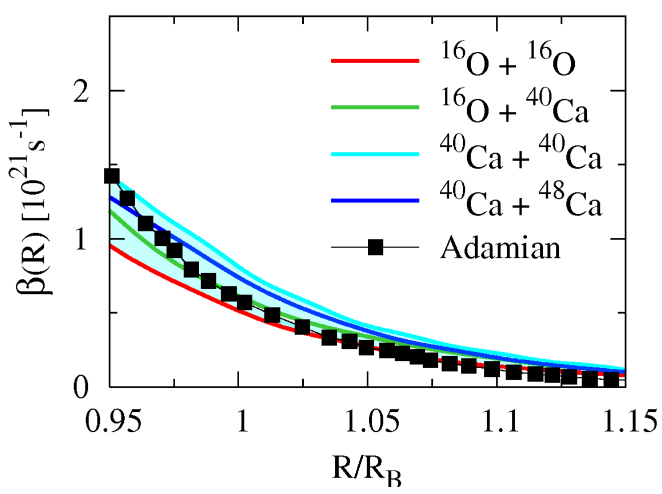


Summary

- Nucleus-nucleus potentials are systematically extracted from TDHF.
- Dynamical reduction of potential energy close to the Coulomb barrier energy
- Extracted potentials agree with exp. data



- One-body energy dissipation are extracted from microscopic theory
- Universal property of extracted friction
- Energy dependence of friction



Mean-field (one-body) fluctuations

Mean-field dynamics

- ➢good description for average evolution
- ➢fluctuations are underestimated

- Bonche et al., PRC13 (1976)
- Flocard et al., PRC17 (1978)
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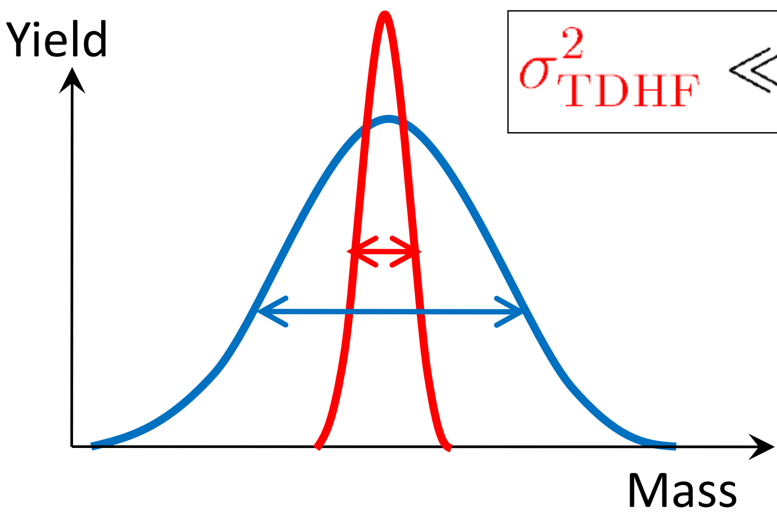
Width of mass distribution in DIC



$$\sigma^2_{\mathrm{TDHF}} \ll \sigma^2_{\mathrm{exp}}$$

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◆(semi-)Classical models

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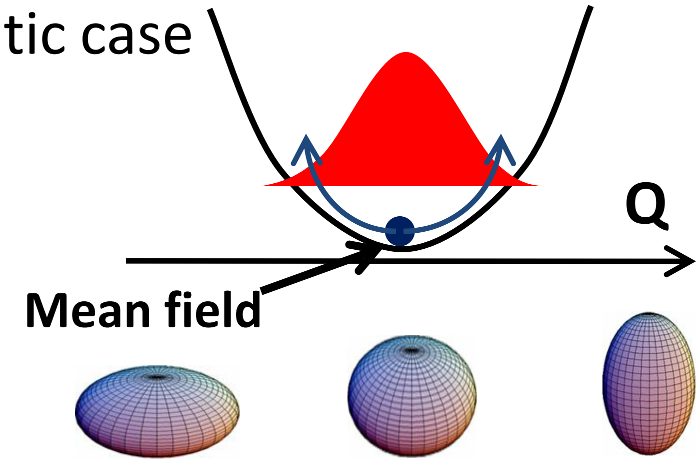
➡ Beyond mean field with a stochastic method

Stochastic Mean Field

- Static case



Configuration mixing calculation
(Generator coordinate method)

$$|\Psi\rangle = \int dQ f(Q) \, |\Phi(Q)\rangle$$

Stochastic Mean Field

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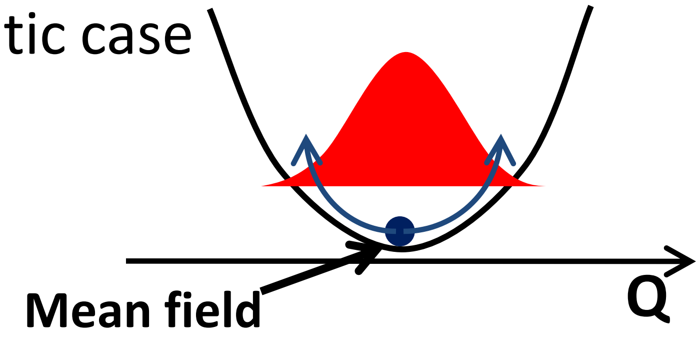

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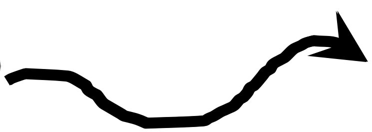
- Dynamical case

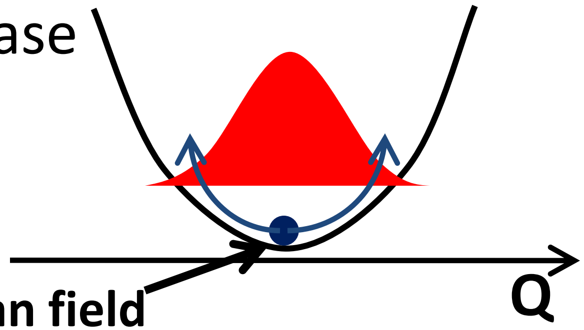
Mean Field

$|\Psi(t_0)\rangle$  $|\Psi(t_1)\rangle$

$$i\hbar \frac{\partial}{\partial t}\rho = [h(\rho), \rho]$$

Stochastic Mean Field

● Static case



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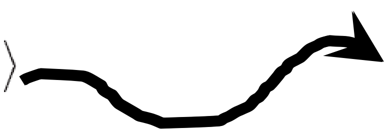

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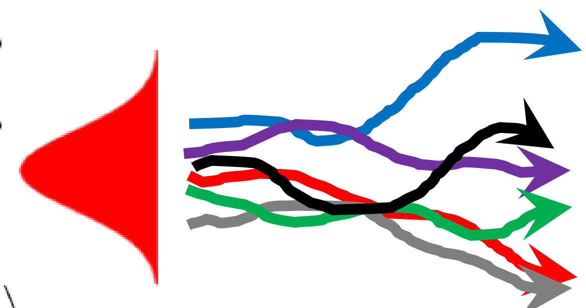
Stochastic Mean Field

$|\Psi^{\lambda=1}(t_0)\rangle$

$|\Psi^{\lambda=2}(t_0)\rangle$

$\vdots$

$|\Psi^{\lambda=N}(t_0)\rangle$



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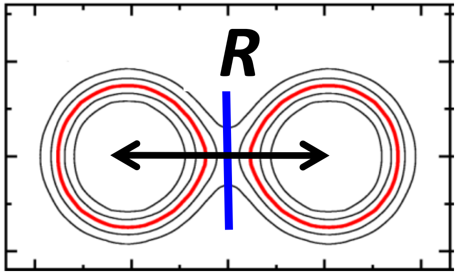
$$i\hbar \frac{\partial}{\partial t}\rho^{\lambda} = [h(\rho^{\lambda}), \rho^{\lambda}]$$

Ayik, PLB658, 174(2008)

Ayik, Washiyama, Lacroix, PRC79, 054906(2009)

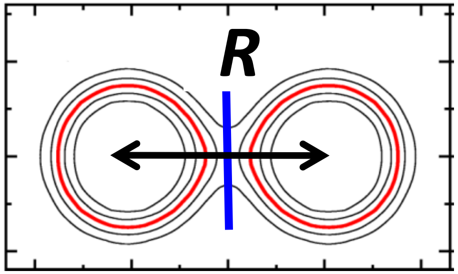
Application to fusion reaction



Mean-field

$$\frac{d}{dt}P = -\frac{d}{dR}U(R) - \gamma(R)\dot{R}$$

Application to fusion reaction



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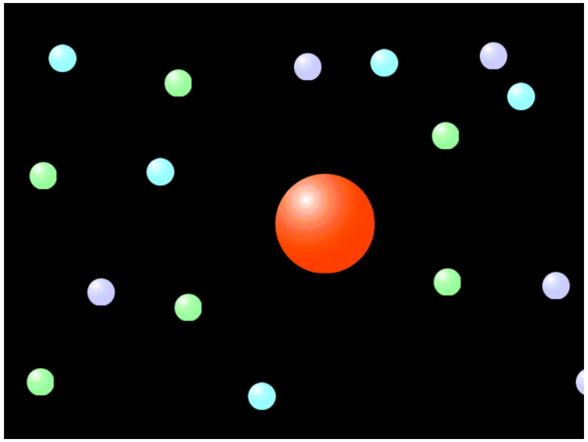
Stochastic mean-field

$$\frac{d}{dt}P^{\lambda} = -\frac{d}{dR^{\lambda}}U(R^{\lambda}) - \gamma(R^{\lambda})\dot{R}^{\lambda} + \xi_P^{\lambda}(t)$$

cf. Brownian motion



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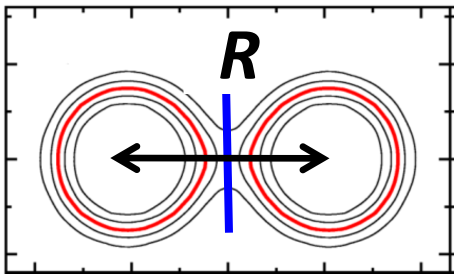

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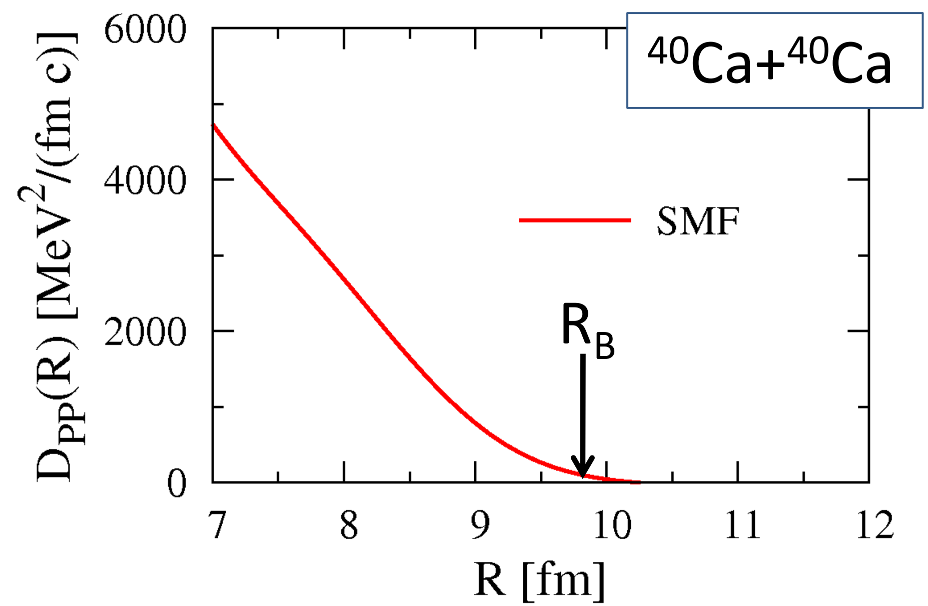
cf. Brownian motion

$$\overline{\xi_P^{\lambda}(t)\xi_P^{\lambda}(t')} = 2\delta(t-t')D_{PP}(R)$$



Ayik, Washiyama, Lacroix, PRC79, 054906(2009)

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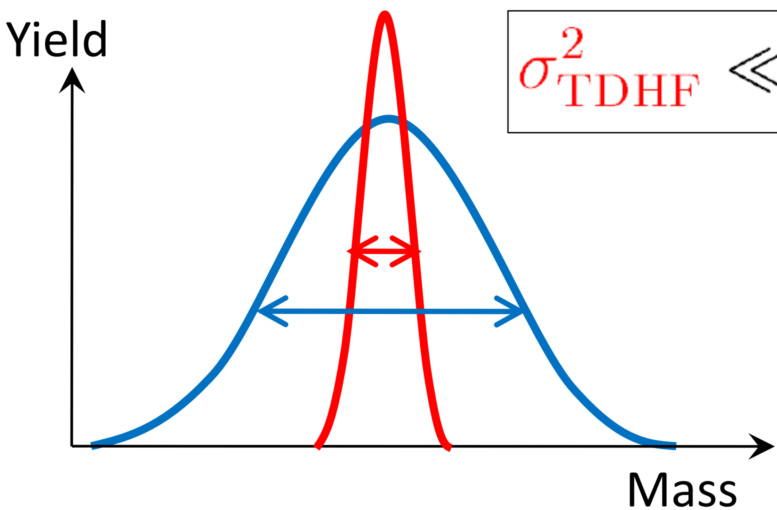

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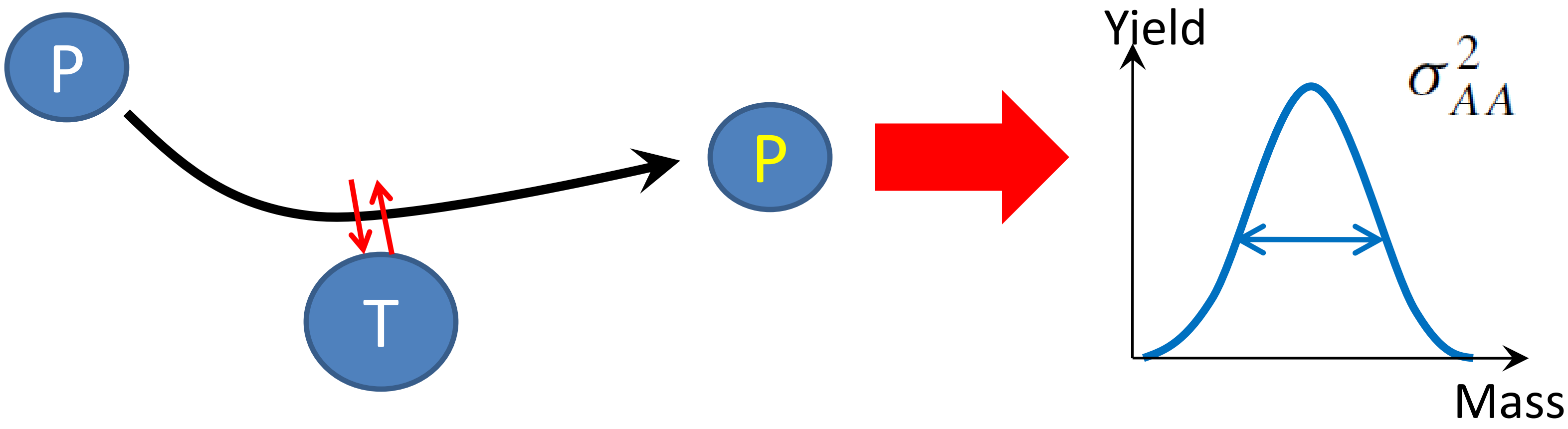
Failure of TDHF for mass variance



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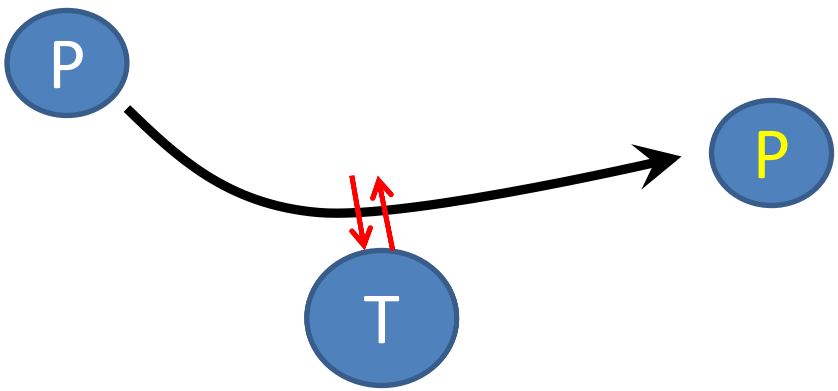
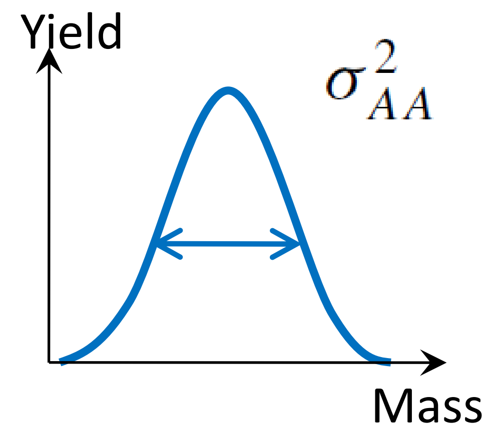


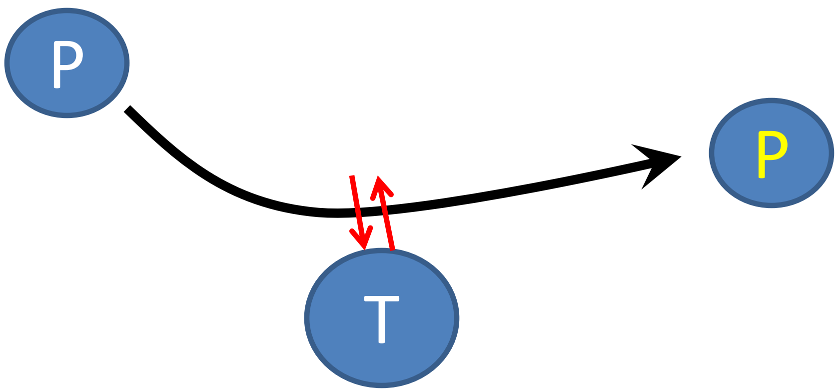


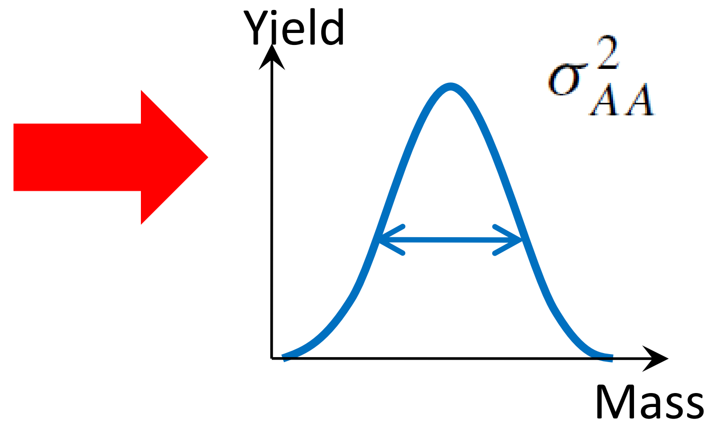
- Analysis based on phenomenological classical model

$$\sigma_{AA}^2(t) \simeq N_{\rm exc}(t)$$ ($N_{\rm exc}$: the number of exchanged nucleons)

Freiesleben, Kratz, Phys.Rep. 106(1984)1

Failure of TDHF for mass variance





- Analysis based on phenomenological classical model

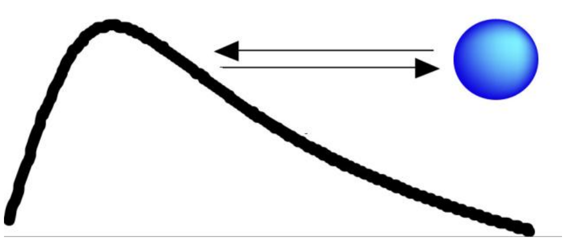
$$\sigma^2_{AA}(t) \simeq N_{\mathrm{exc}}(t)$$

(N_{exc}: the number of exchanged nucleons)

Freiesleben, Kratz, Phys.Rep. 106(1984)1

V_B=53.4 MeV

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



$E_{c.m.}$(MeV)	σ^2_{TDHF}		N_{exc}
51.0	0.004	≪	0.432
52.5	0.008	≪	1.441
53.0	0.008	≪	3.634

Mass fluctuations and exchanged nucleons

Stochastic mean-field

$$\frac{d}{dt}A_P^\lambda = v\left(A_P^\lambda, t\right) + \xi_A^\lambda(t)$$

$$\overline{\xi_A^\lambda(t)\xi_A^\lambda(t')} = 2\delta(t-t')D_{AA}$$

$$\sigma_{AA}^2(t) \simeq 2\int_0^t D_{AA}(s)ds$$

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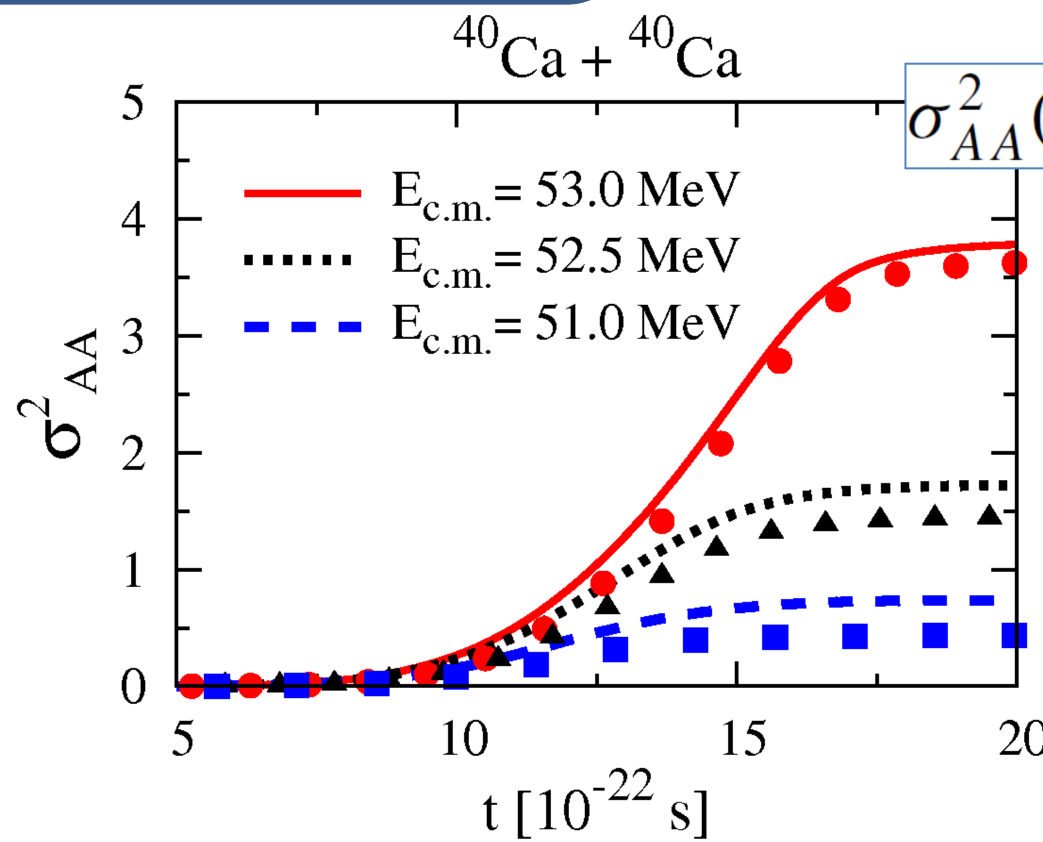

$$\sigma_{AA}^2(t) \simeq N_{\rm exc}(t)$$

$N_{\rm exc}$

Washiyama, Ayik, Lacroix, PRC80, 031602(R) (2009)

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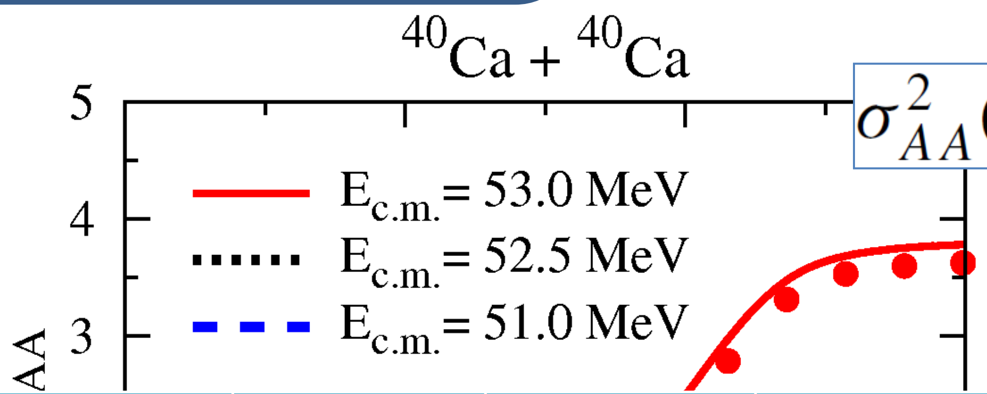
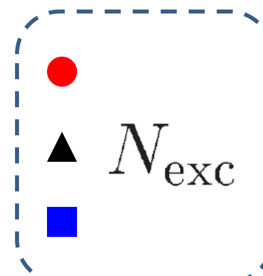


$$\sigma_{AA}^2(t) \simeq N_{\rm exc}(t)$$

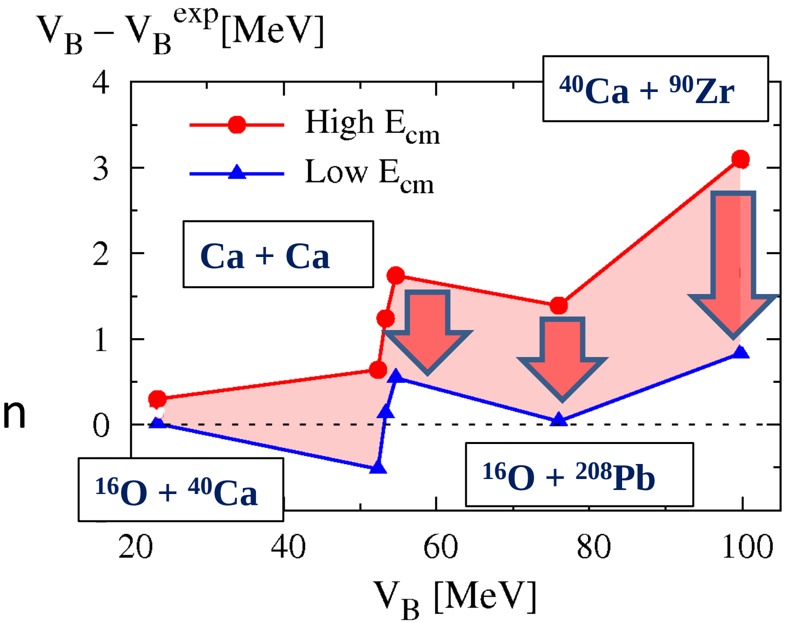
$E_{c.m.}$(MeV)	σ^2_{TDHF}	N_{exc}	σ^2_{AA}
51.0	0.004	0.432	**0.730**
52.5	0.008	1.441	**1.718**
53.0	0.008	3.634	**3.790**



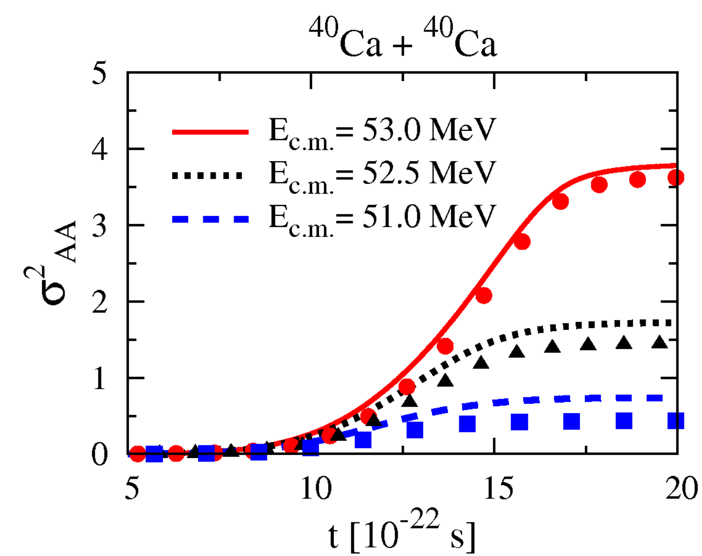
Washiyama, Ayik, Lacroix, PRC80, 031602(R) (2009)

Summary

- Mean-field dynamics
  - Dynamical reduction in potential
  - Good agreement with experiments
  - Universal behavior of Energy dissipation



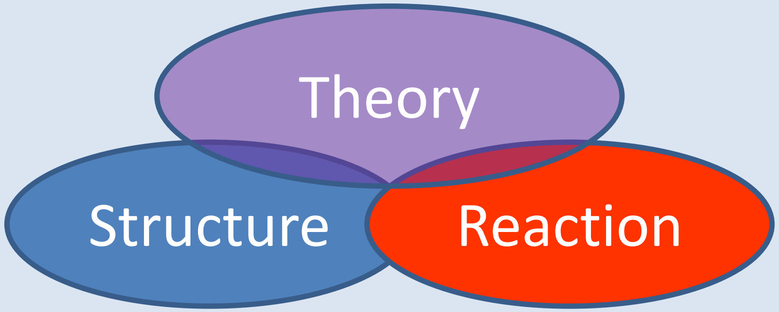
- Beyond mean field
  - Stochastic mean field
  - Good description for mass variance σ^2_{AA}
  - Fluctuation for other collective variables



Introduction: Low energy nuclear dynamics

(Energy < 10 MeV/A)

□Goal: Unified microscopic theory for nuclear structure and dynamics



- Whole nuclear chart including unstable nuclei
- Three dimensional coordinate