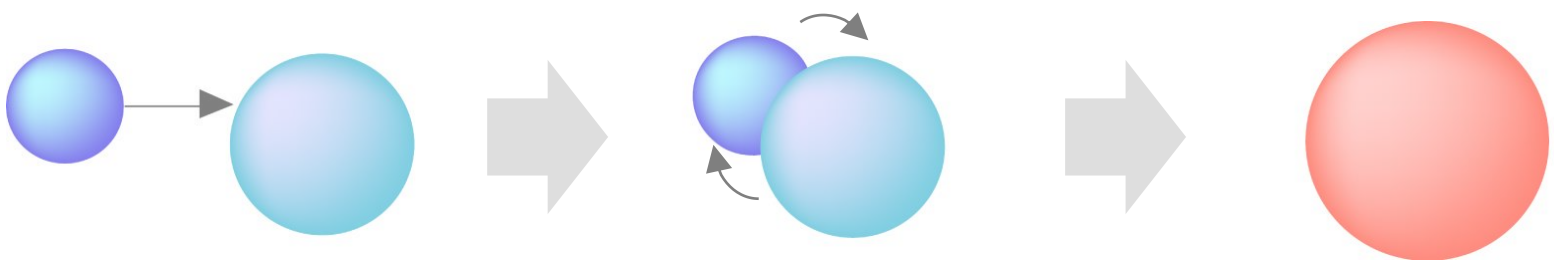
Microscopic description of extra-push energy and fusion dynamics in heavy systems

Kouhei Washiyama (RIKEN Nishina Center, Japan)

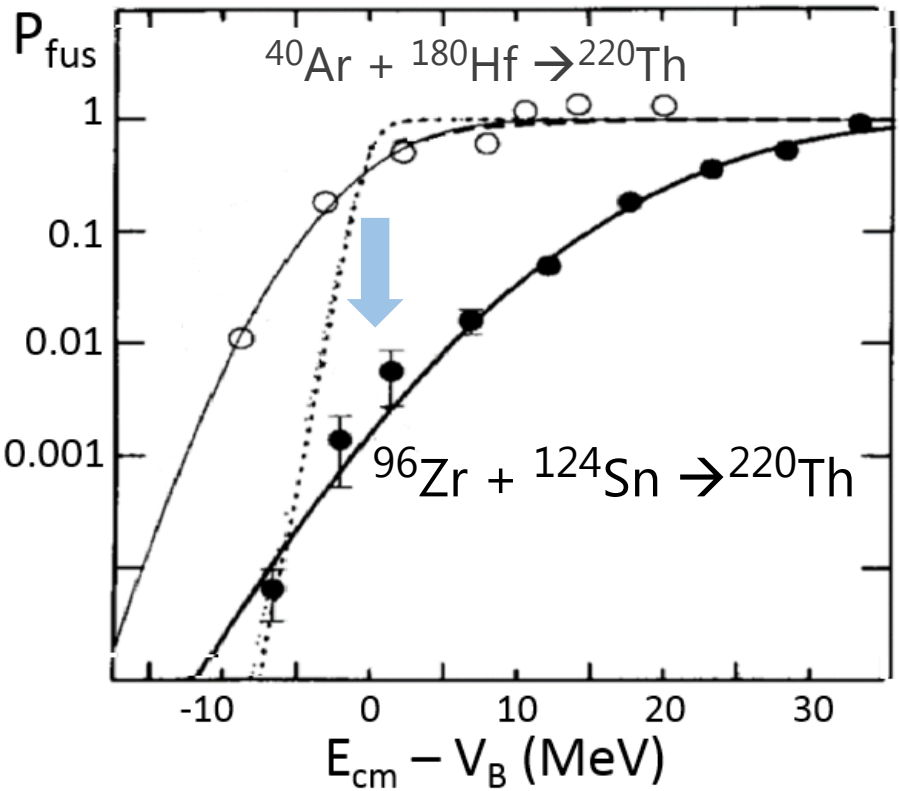
- What is fusion hindrance?
- Analysis by microscopic TDHF
- Nucleus-nucleus potential
- Energy dissipation



Nuclear Fission and Exotic Nuclei, Dec. 3-5, 2014 @ JAEA, Japan

Introduction: What is fusion hindrance?

Fusion probability

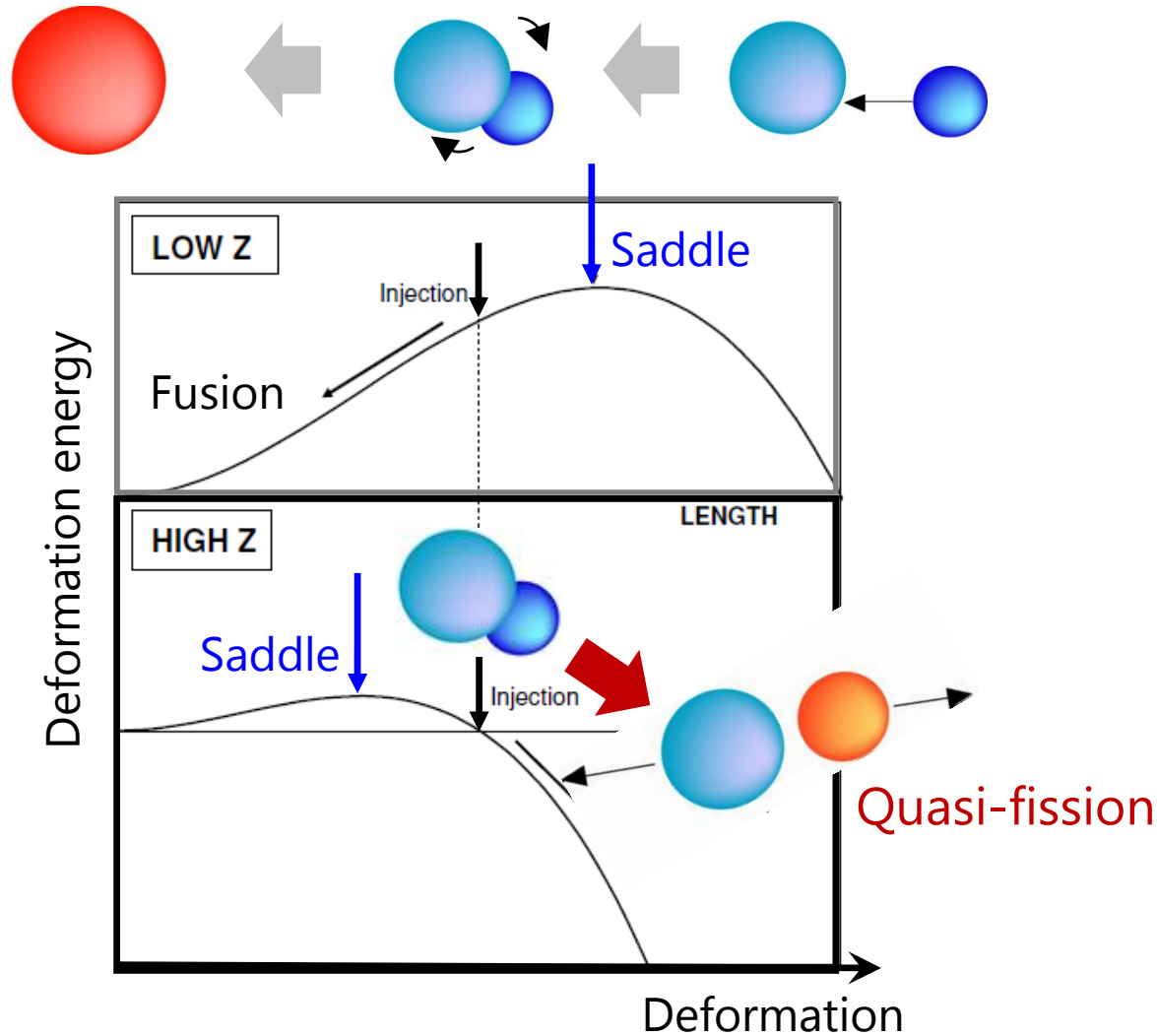


C.-C. Sahm et al., NPA441 (1985) 316

- P_{fus} is hindered in $Z_P Z_T$ >1600 (superheavy elements)
- Extra-push energy is needed for fusion

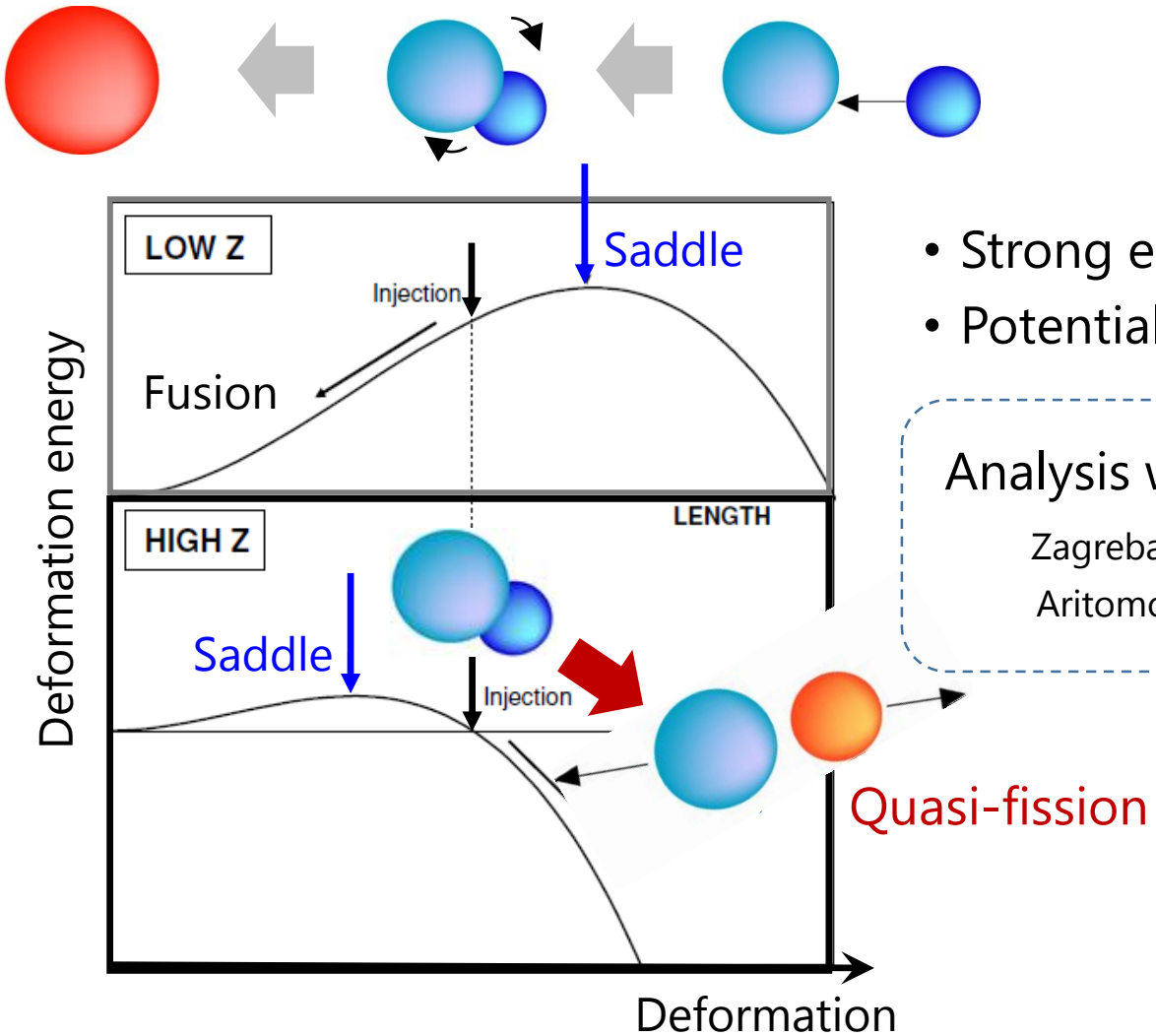
Swiatecki, NPA376 (1982) 275

Quasi-fission in heavy systems



Taken from Swiatecki et al., PRC71(2005)014602

Quasi-fission in heavy systems



- Strong energy dissipation
- Potential energy

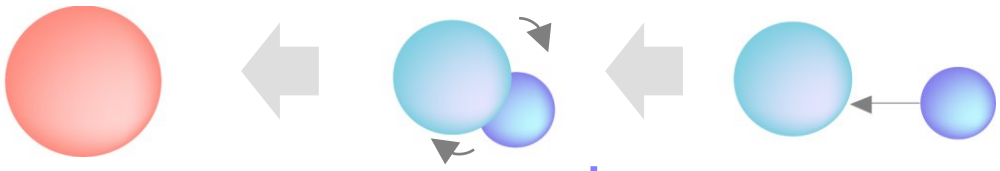
Analysis with Langevin equation

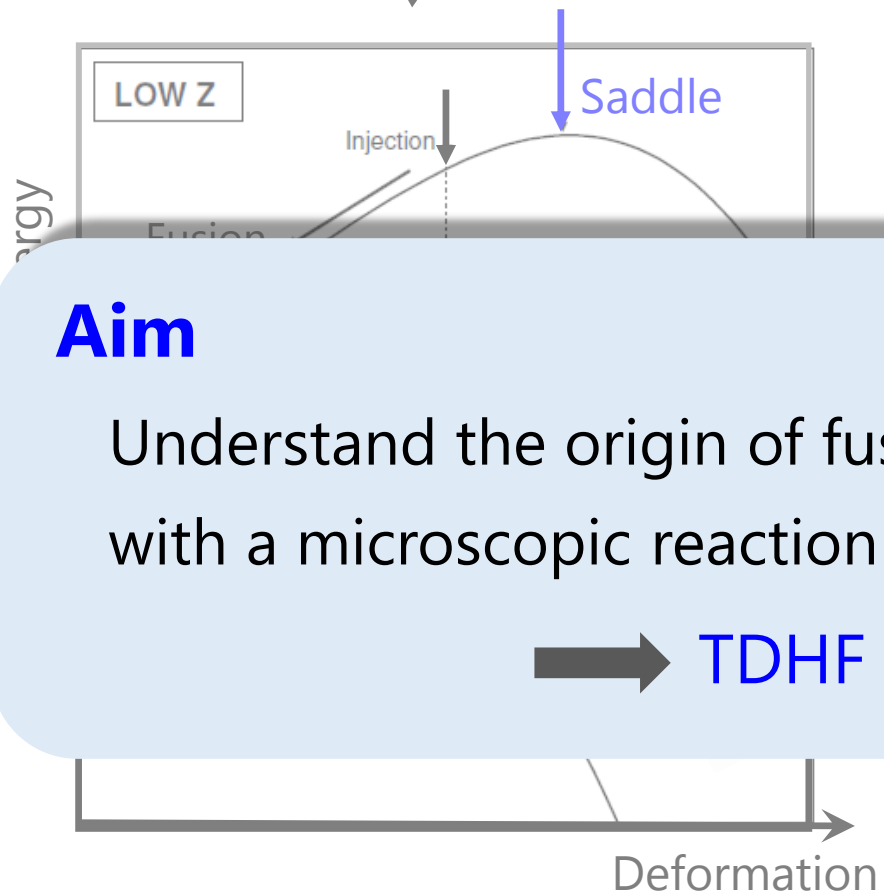
Zagrebaev, Greiner, JPG31(2005) 825

Aritomo et al., PRC85 (2012) 044614

Taken from Swiatecki et al., PRC71(2005)014602

Quasi-fission in heavy systems





- Strong energy dissipation
- Potential energy

equation

005) 825

) 044614

Aim

Understand the origin of fusion hindrance with a microscopic reaction model

→ TDHF

Taken from Swiatecki et al., PRC71(2005)014602

Time-dependent Hartree-Fock (TDHF)

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

h : single-particle Hamiltonian

Bonche et al., PRC 13 (1976)
Flocard et al., PRC 17 (1978)
Kim et al., J. Phys. G 23 (1997)
Simenel et al., PRL 86 (2001)
Nakatsukasa, Yabana, PRC 71 (2005)
Umar, Oberacker, PRC 73 (2006)
Maruhn et al., PRC 74 (2006)

- Self-consistent description for both static and dynamical properties
- Shell effects
- Single-particle: Quantum; Many-body (collective): Classical
- Low energy: mean-field approximation

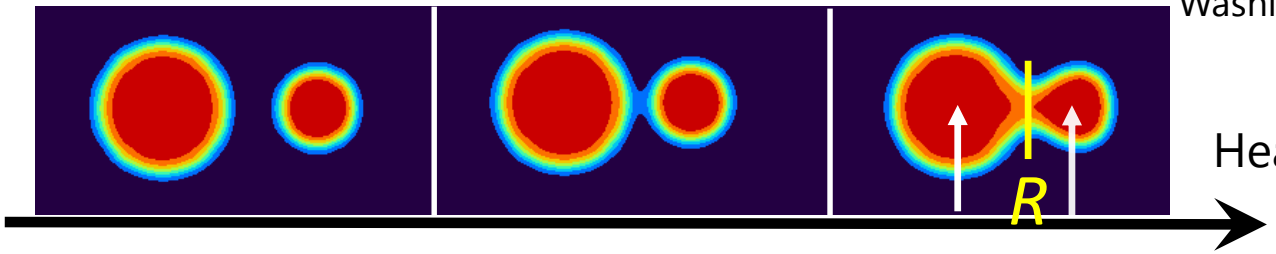
Estimate of extra-push energy with TDHF

Simenel, EPJA48(2012)152

Guo, Nakatsukasa, EPJ. Conf. 38 (2012) 09003

Method: Extract potential and dissipation

Washiyama, Lacroix, PRC78(2008)024610



Head-on collision

TDHF simulation $\longrightarrow$ $\rho(t)$

$\rho(t) \longrightarrow R(t), P(t)$

Assume that $R(t), P(t)$ obey a Newton equation

$$\frac{dP}{dt}, \ \frac{dR}{dt} \Longrightarrow \gamma(R), \ V(R)$$

R : Relative distance

P : Momentum

V : Potential

γ : Friction coefficient

$$\frac{dR}{dt} = \frac{P}{\mu(R)}$$

$$\frac{dP}{dt} = -\frac{dV(R)}{dR} - \frac{d}{dR}\frac{P^2}{2\mu(R)} - \gamma(R)\frac{dR}{dt}$$

Extraction stops when dR/dt ~ 0

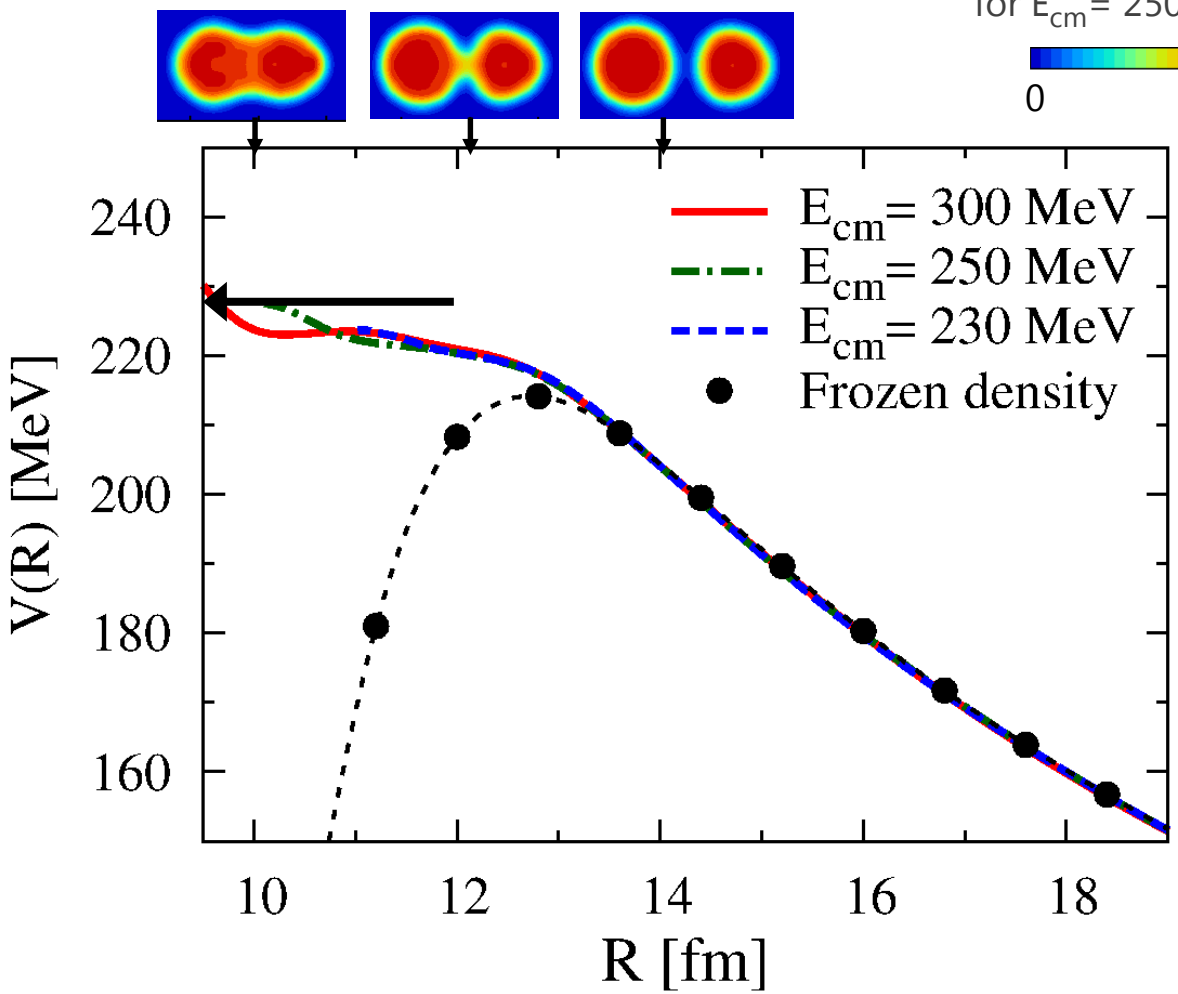
(Overlap of densities becomes large)

Result: Extracted potential

$^{96}Zr + ^{124}Sn$ $Z_P Z_T = 2000$

Density at R=10.0, 12.1, 14.0 fm
for E_{cm}= 250 MeV

0 0.16 (fm^{-3})



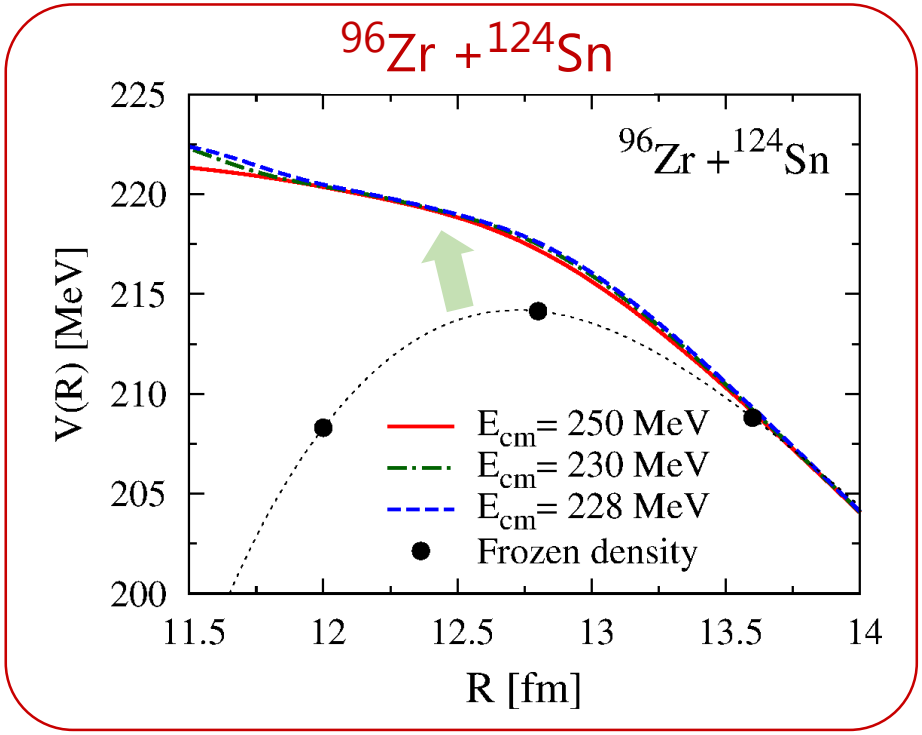
Fusion threshold
= 228 MeV

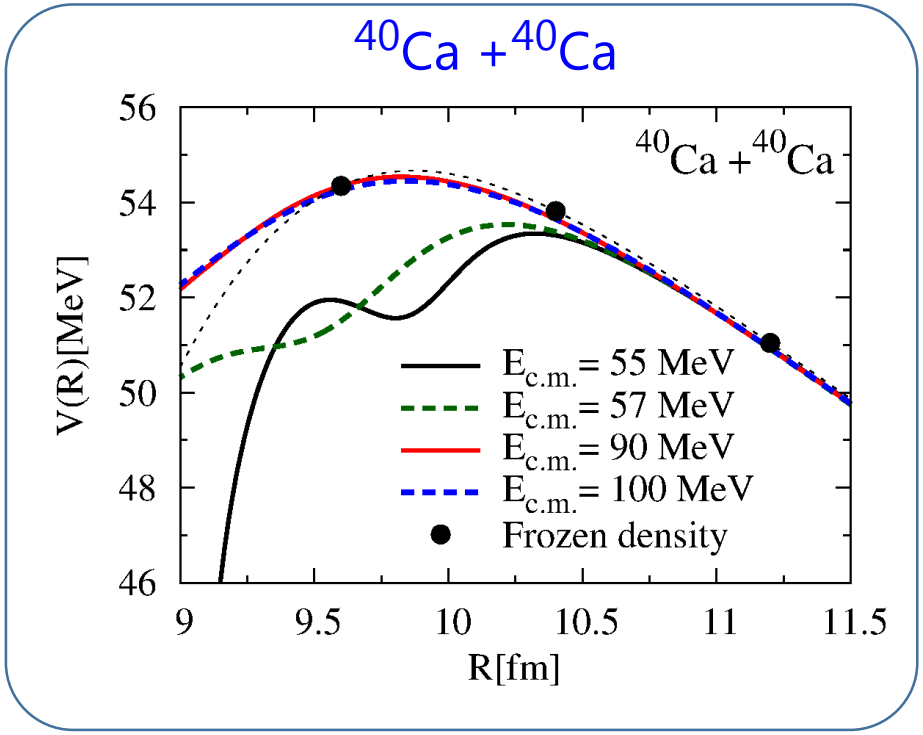
SLy4d Skyrme force
dx = 0.8fm
dt = 0.45fm/c

Washiyama, in preparation

Result: Comparison of potentials

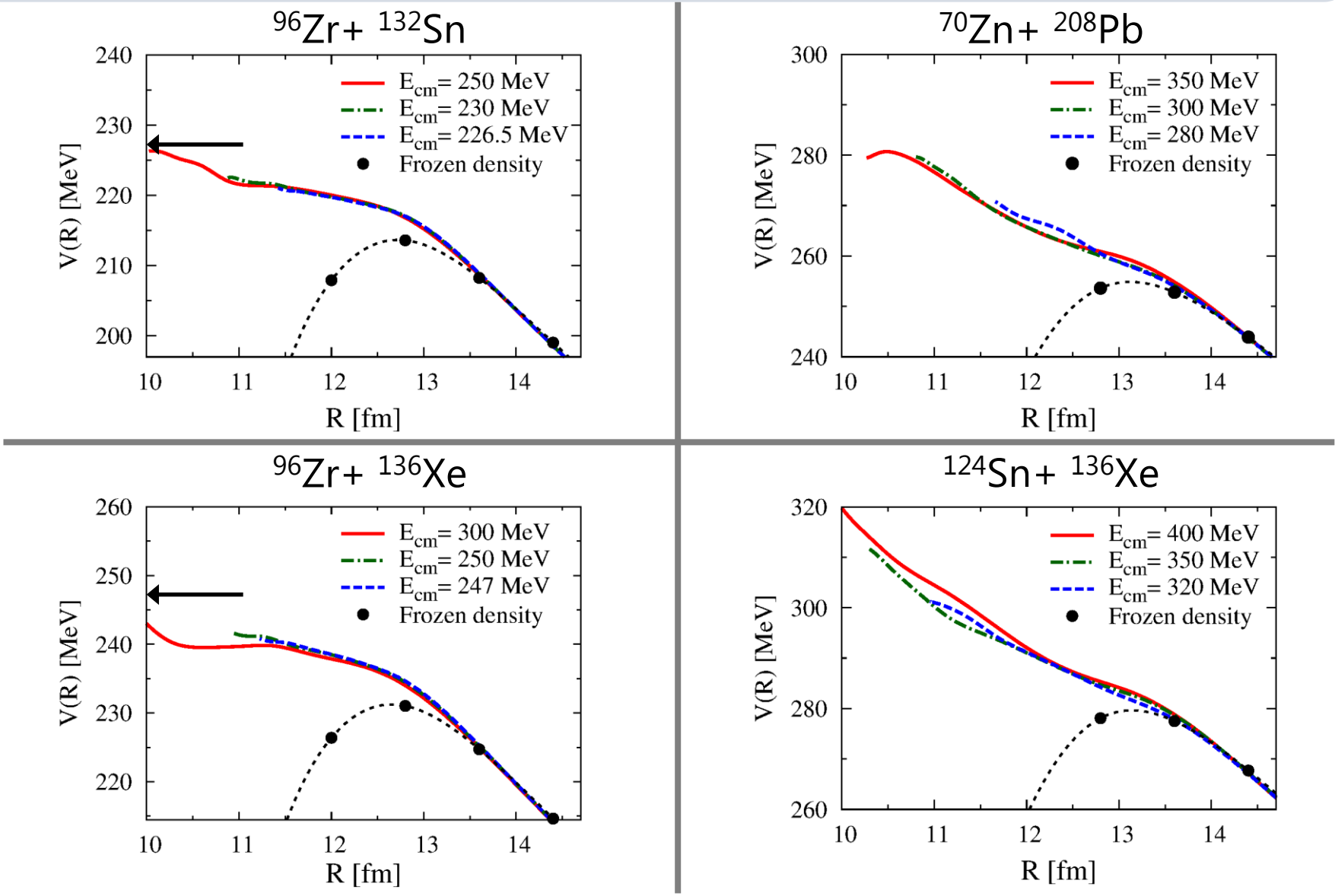
Heavy system vs. Light system



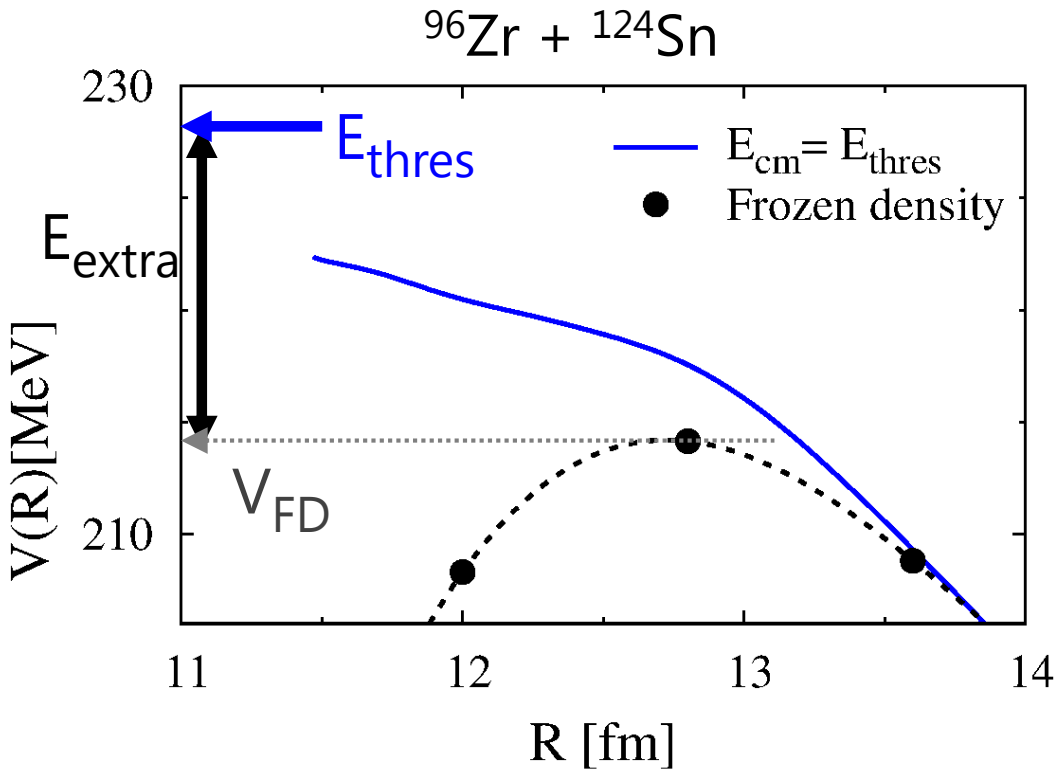


- Potential barrier vanishes by dynamical effect
- Energy dependence of potential is less around the “barrier”

Potentials of heavy systems



Origin of fusion hindrance

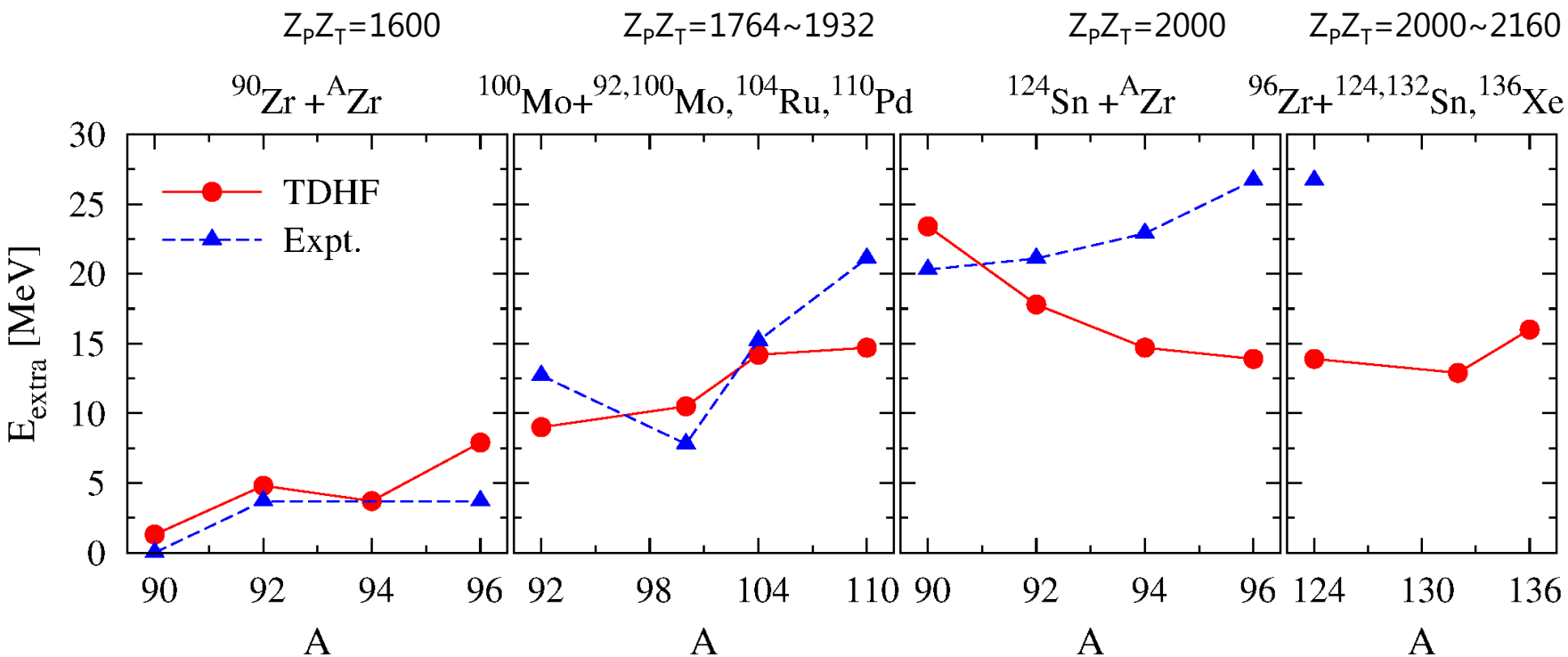


$E_{extra} = E_{thres} - V_{FD}$: Extra-push energy for TDHF

E_{thres} : Fusion threshold energy

V_{FD} : Frozen density barrier

Extra-push energy



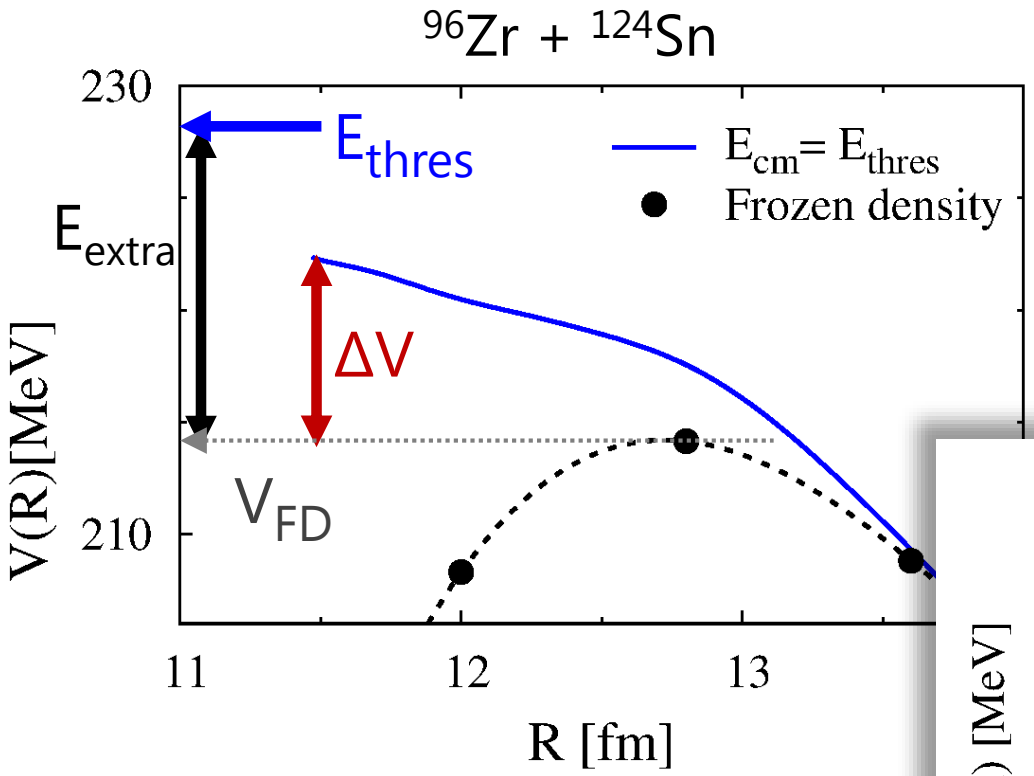
Data from Schmidt, Morawek, Rep.Prog.Phys.54(1991)949

$$E_{extra} = E - V_B$$

$E = E_{expt}$, $V_B = V_{Bass}$ for Expt.

$E = E_{thres}$, $V_B = V_{FD}$ for TDHF

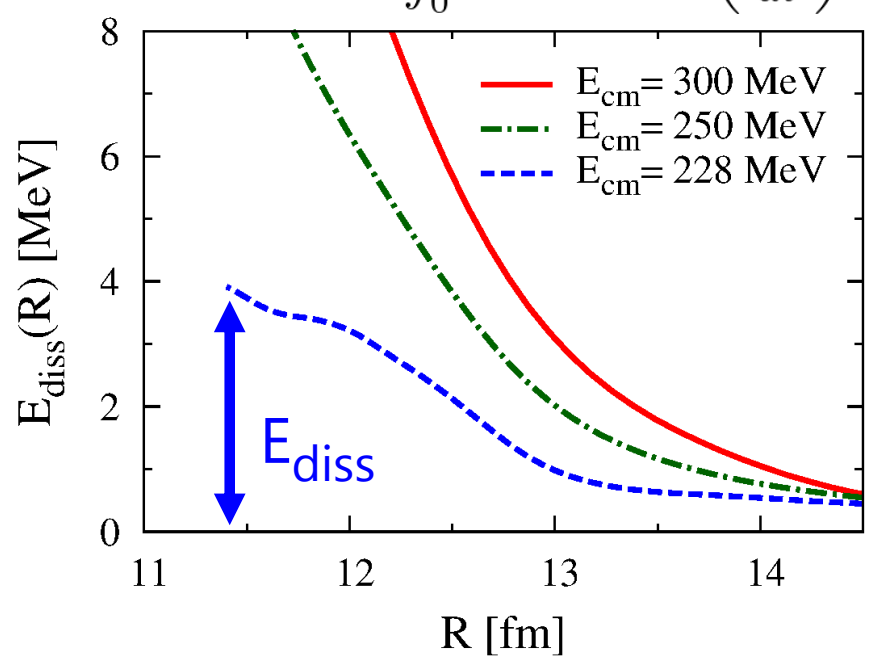
Origin of fusion hindrance



$E_{extra} \sim \Delta V + E_{diss}$

$(E_{cm} \sim E_{kin} + V + E_{diss})$

$$E_{diss}(R) = \int_0^t dt' \, \gamma[R(t')] \left(\frac{dR}{dt}\right)^2$$

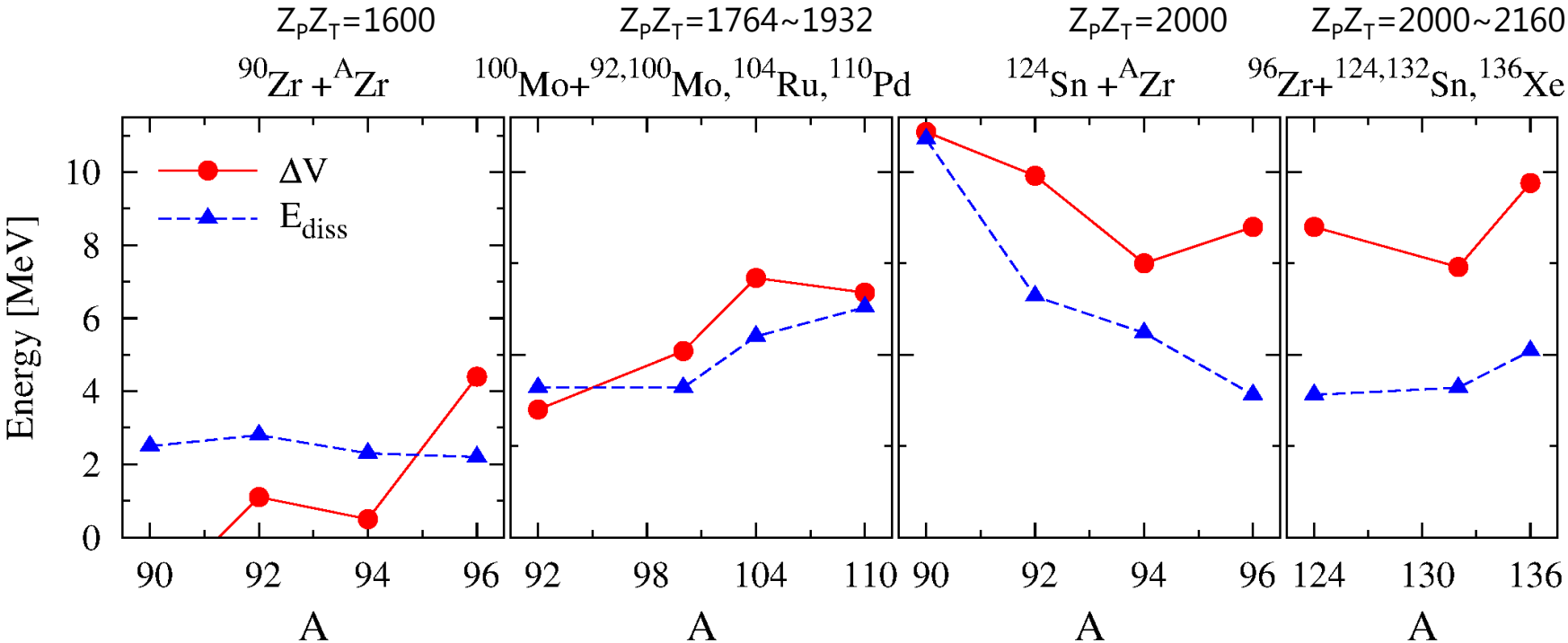


ΔV : Increase in potential from V_{FD}

ΔV is calculated at $E_{cm} = E_{thres}$

Origin of fusion hindrance

$E_{extra} \sim \Delta V + E_{diss}$

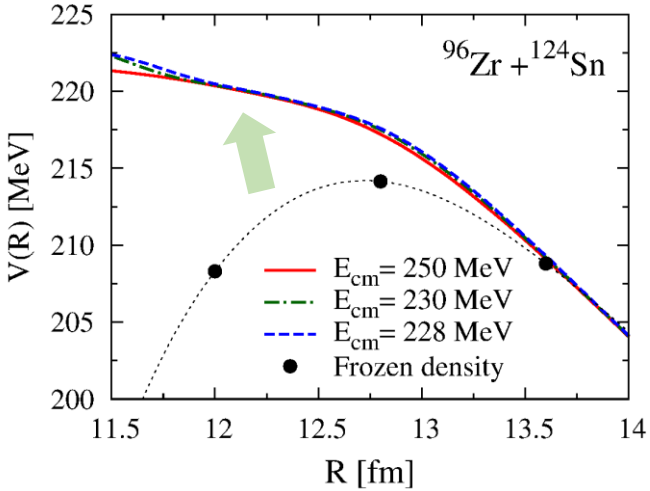


$\Delta V > E_{diss}$ in more systems

➡ Main contribution to fusion hindrance comes from dynamical increase in potential

Summary

- Fusion hindrance in heavy systems
- Potential and energy dissipation are extracted from TDHF
- Change the property of potential
  - No barrier structure
  - Dynamical increase
- Analysis of extra-push energy
- As system becomes heavier, dynamical increase in potential is more significant for the fusion hindrance

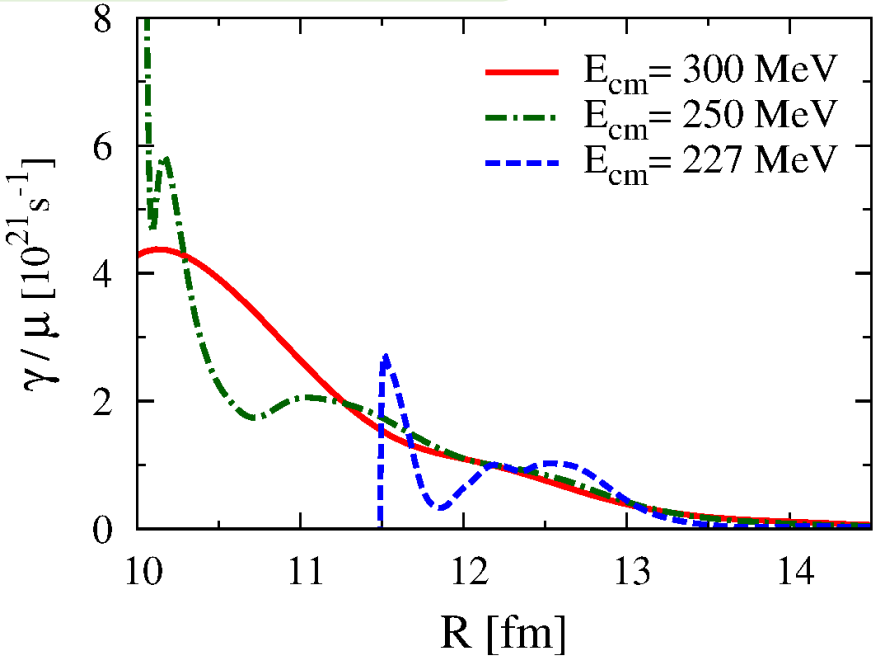


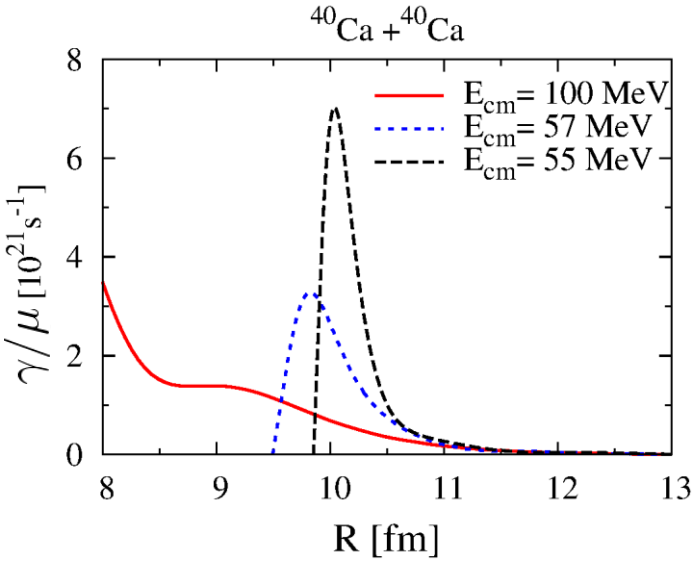
Dissipated energy

Dissipation from the relative motion to the internal excitations

Friction coefficient

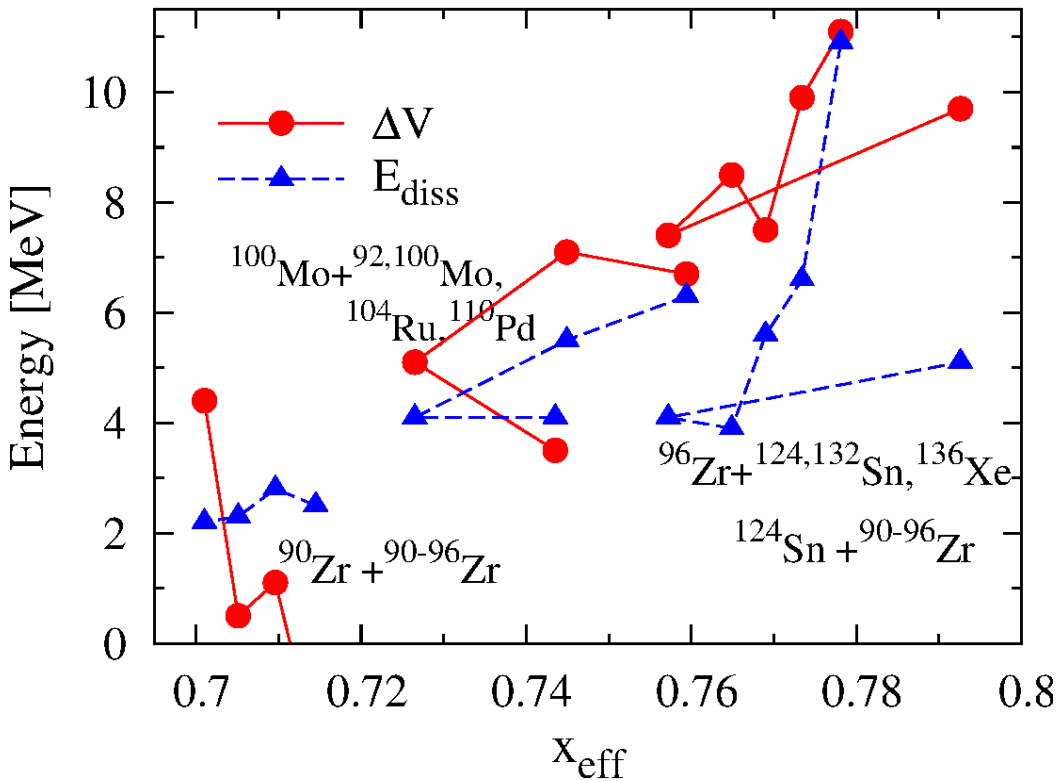
$^{96}Zr + ^{124}Sn$





- The strength and behaviour are similar to lighter systems
- Friction shows a strong R-dependence at dR/dt ~ 0

Origin of fusion hindrance

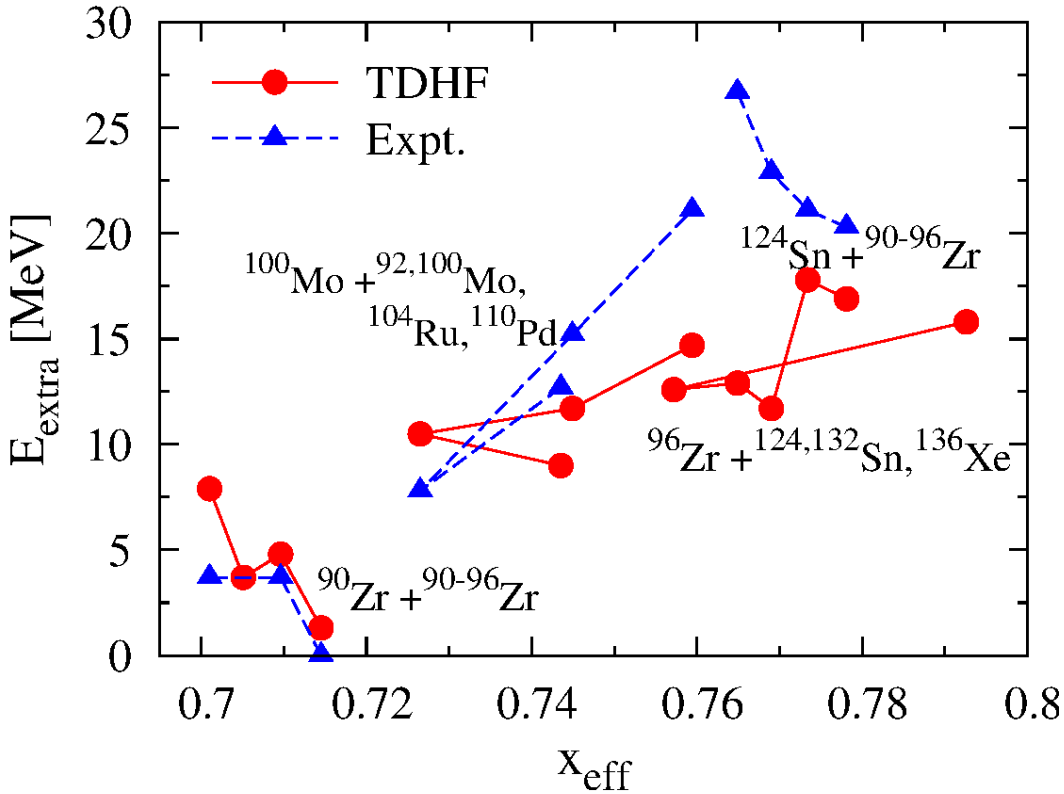


$$x_{\rm eff} = \frac{4Z_1Z_2}{A_1^{1/3}A_2^{1/3}(A_1^{1/3}+A_2^{1/3})} \Big/ (Z^2/A)_{\rm crit}$$

$$(Z^2/A)_{\rm crit} = 50.833(1-1.7826I^2)$$

As x_{eff} becomes larger, contribution from ΔV becomes larger than dissipated energy, $\Delta V > E_{diss}$

Extra-push energy



X_{eff}: size of the system

$$x_{\rm eff} = \frac{4Z_1Z_2}{A_1^{1/3}A_2^{1/3}(A_1^{1/3}+A_2^{1/3})} \Big/ (Z^2/A)_{\rm crit}$$

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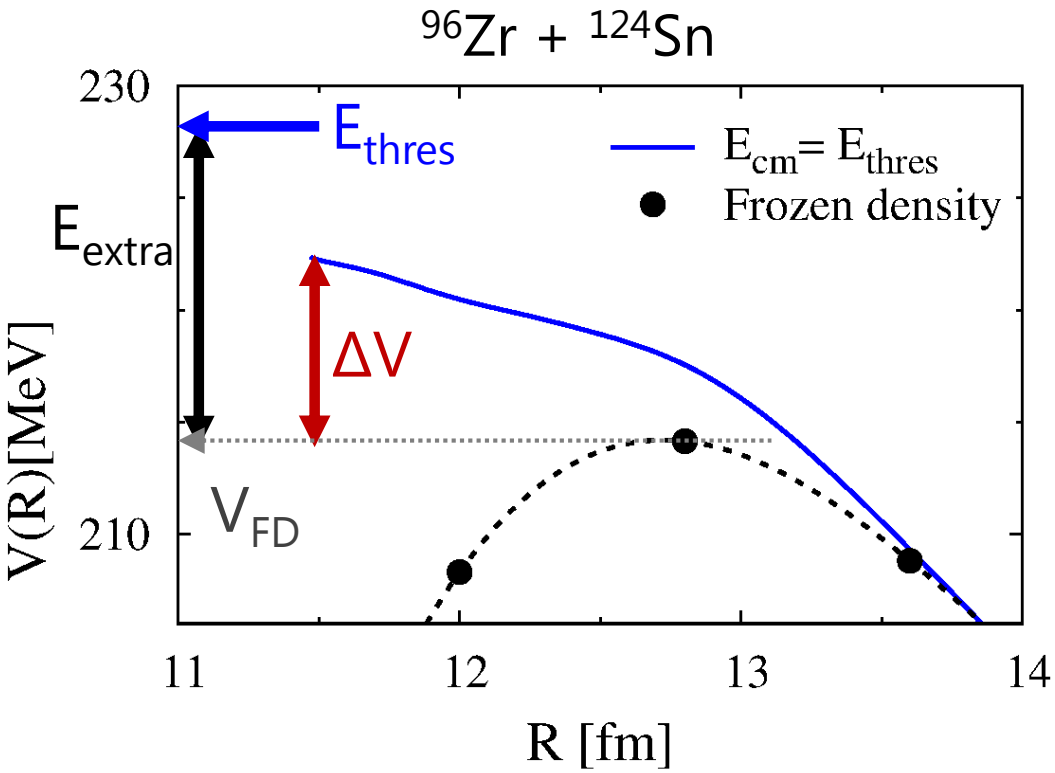

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Dissipated energy

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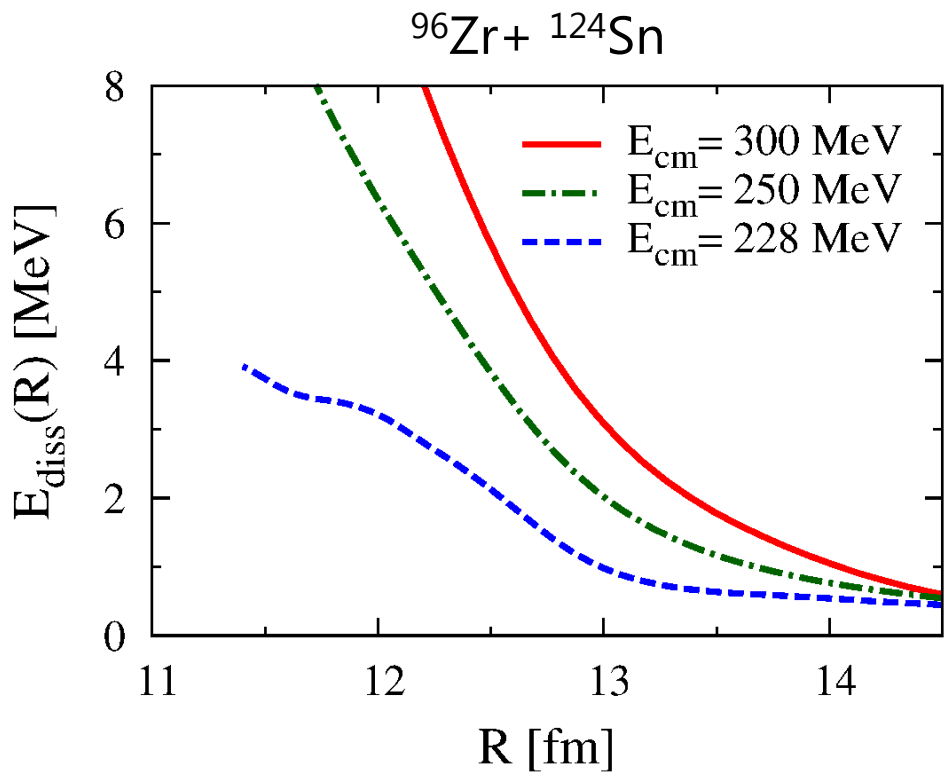

Dissipated energy

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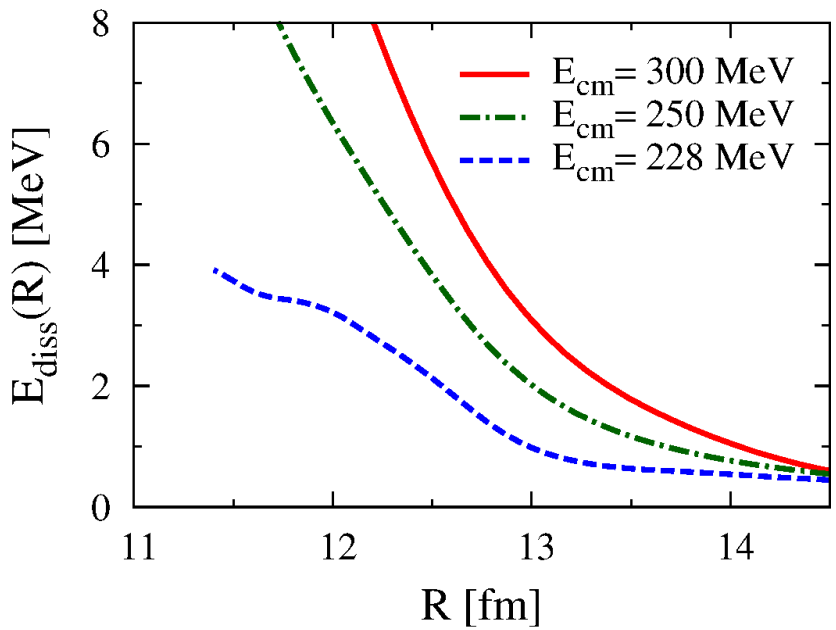
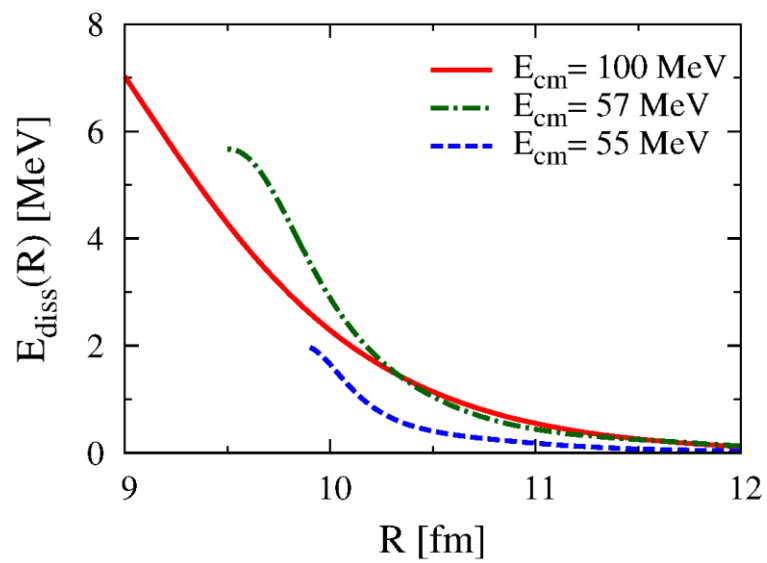
^{96}Zr+ ^{124}Sn



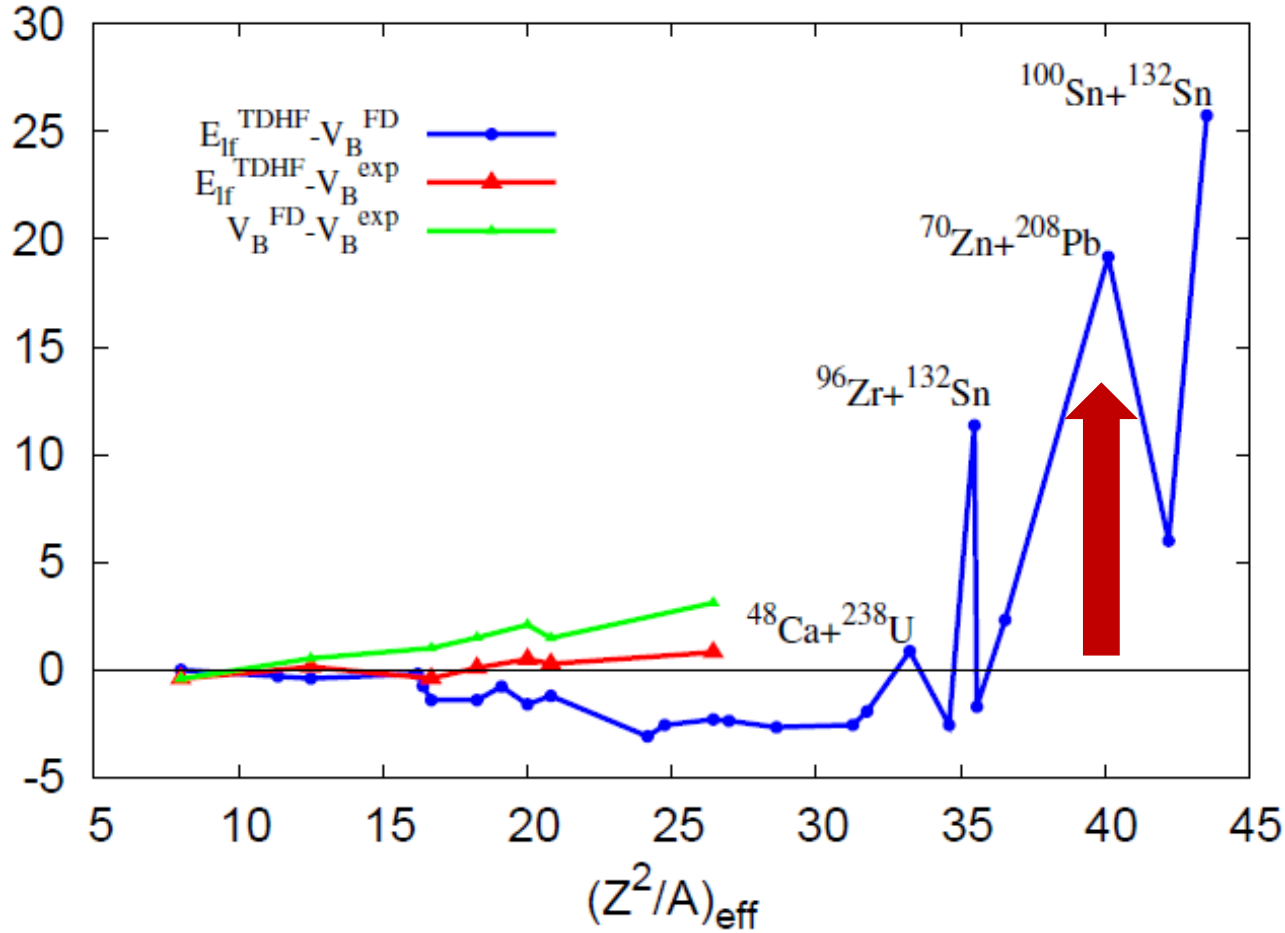
^{40}Ca +^{40}Ca



Fusion threshold energy from TDHF

$E_{extra} = E_{thres} - V_{FD}$ [MeV]

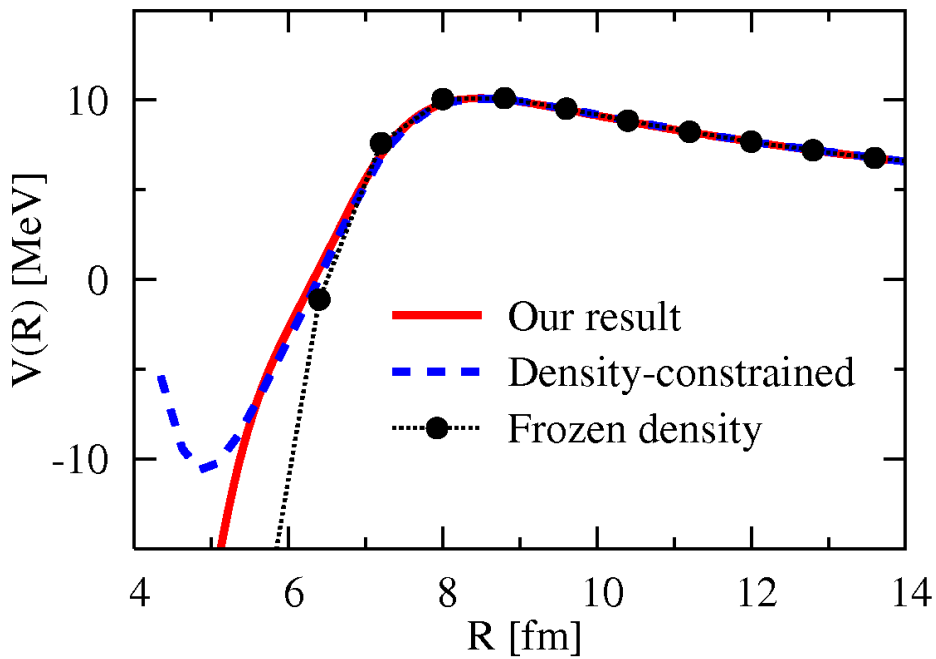
Guo, Nakatsukasa, EPJ.Conf. 38 (2012) 09003



Our method vs. Density-constrained

Washiyama, Lacroix, PRC78 (2008) 024610

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



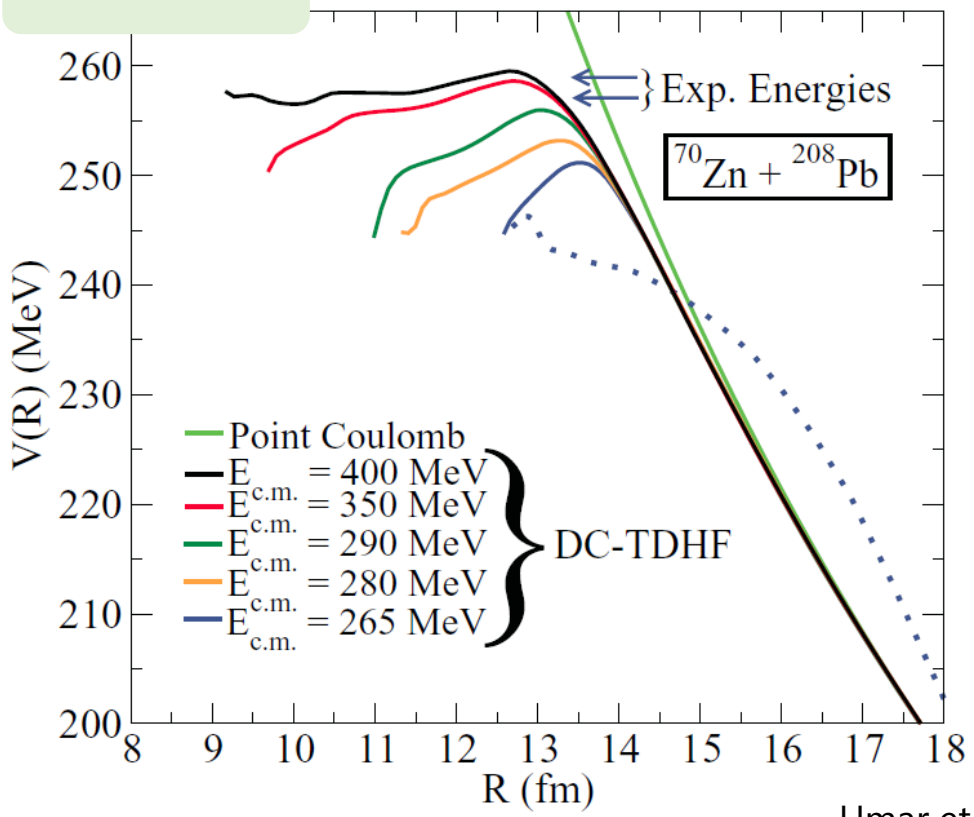
- Agree with each model
- Validation of our model

Density-constrained TDHF

Umar, Oberacker, PRC74(2006)021601

$\mathcal{E}_{\mathrm{DC}}[\rho(t)](R)$ from minimization of $\hat{H} - \int d^3r\lambda(r)\hat{\rho}(r)$

Potential



Potential is obtained as a function of R

Umar et al., PRC81(2010)064607

Energy density functional

- Skyrme energy density functional

$$\mathcal{E}_{\rm Sk} \equiv \int d^3r \sum_{t=0,1} \mathcal{H}_t(\boldsymbol{r}) \qquad \begin{aligned} \rho_{t=0} &= \rho_n + \rho_p \\ \rho_{t=1} &= \rho_n - \rho_p \end{aligned}$$

$$\mathcal{H}_t = C_t^\rho \rho_t^2 + C_t^{\Delta\rho} \rho_t \Delta \rho_t + C_t^\tau \rho_t \tau_t + C_t^{\nabla\cdot J} \rho_t \nabla \cdot \boldsymbol{J}_t - C_t^T \sum_{\mu,\nu=x,y,z} J_{t,\mu\nu} J_{t,\mu\nu} \cdots$$

$$+ C_t^s \boldsymbol{s}_t^2 + C_t^{\Delta s} \boldsymbol{s}_t \cdot \Delta \boldsymbol{s}_t - C_t^\tau \boldsymbol{j}_t^2 + C_t^{\nabla\cdot J} \boldsymbol{s}_t \cdot \nabla \times \boldsymbol{j}_t + C_t^T \boldsymbol{s}_t \cdot \boldsymbol{T}_t + \cdots$$

$$\rho_q(\boldsymbol{r}) = \rho_q(\boldsymbol{r},\boldsymbol{r}')|_{\boldsymbol{r}=\boldsymbol{r}'}, \quad \tau_q(\boldsymbol{r}) = \nabla\cdot\nabla' \rho_q(\boldsymbol{r},\boldsymbol{r}')|_{\boldsymbol{r}=\boldsymbol{r}'}, \quad J_{q,\mu\nu}(\boldsymbol{r}) = -\frac{i}{2}(\nabla_\mu - \nabla'_\mu) s_{q,\nu}(\boldsymbol{r},\boldsymbol{r}')|_{\boldsymbol{r}=\boldsymbol{r}'}$$

$$\boldsymbol{s}_q(\boldsymbol{r}) = \boldsymbol{s}_q(\boldsymbol{r},\boldsymbol{r}')|_{\boldsymbol{r}=\boldsymbol{r}'}, \quad \boldsymbol{T}_q(\boldsymbol{r}) = \nabla\cdot\nabla' \boldsymbol{s}_q(\boldsymbol{r},\boldsymbol{r}')|_{\boldsymbol{r}=\boldsymbol{r}'}, \quad \boldsymbol{j}_q(\boldsymbol{r}) = -\frac{i}{2}(\nabla - \nabla')\rho_q(\boldsymbol{r},\boldsymbol{r}')|_{\boldsymbol{r}=\boldsymbol{r}'}$$

$$\rho_q(\boldsymbol{r},\boldsymbol{r}') = \sum_{\sigma=\pm1} \rho_q(\boldsymbol{r}\sigma,\boldsymbol{r}'\sigma) = \sum_{\sigma=\pm1}\sum_k n_k \phi_k(\boldsymbol{r}\sigma q)\phi_k^*(\boldsymbol{r}'\sigma q)$$

$$\boldsymbol{s}_q(\boldsymbol{r},\boldsymbol{r}') = \sum_{\sigma,\sigma'=\pm1} \rho_q(\boldsymbol{r}\sigma,\boldsymbol{r}'\sigma')\langle\sigma'|\hat{\boldsymbol{\sigma}}|\sigma\rangle$$

Bender, Heenen, Reinhard, Rev. Mod. Phys. 75 (2003) 121