5th International Symposium on Nuclear Symmetry Energy (NuSym15)
(29th June – 2nd July, 2015 at Kraków, Poland)

Toward high-density nuclear matter from nucleus-nucleus elastic scattering

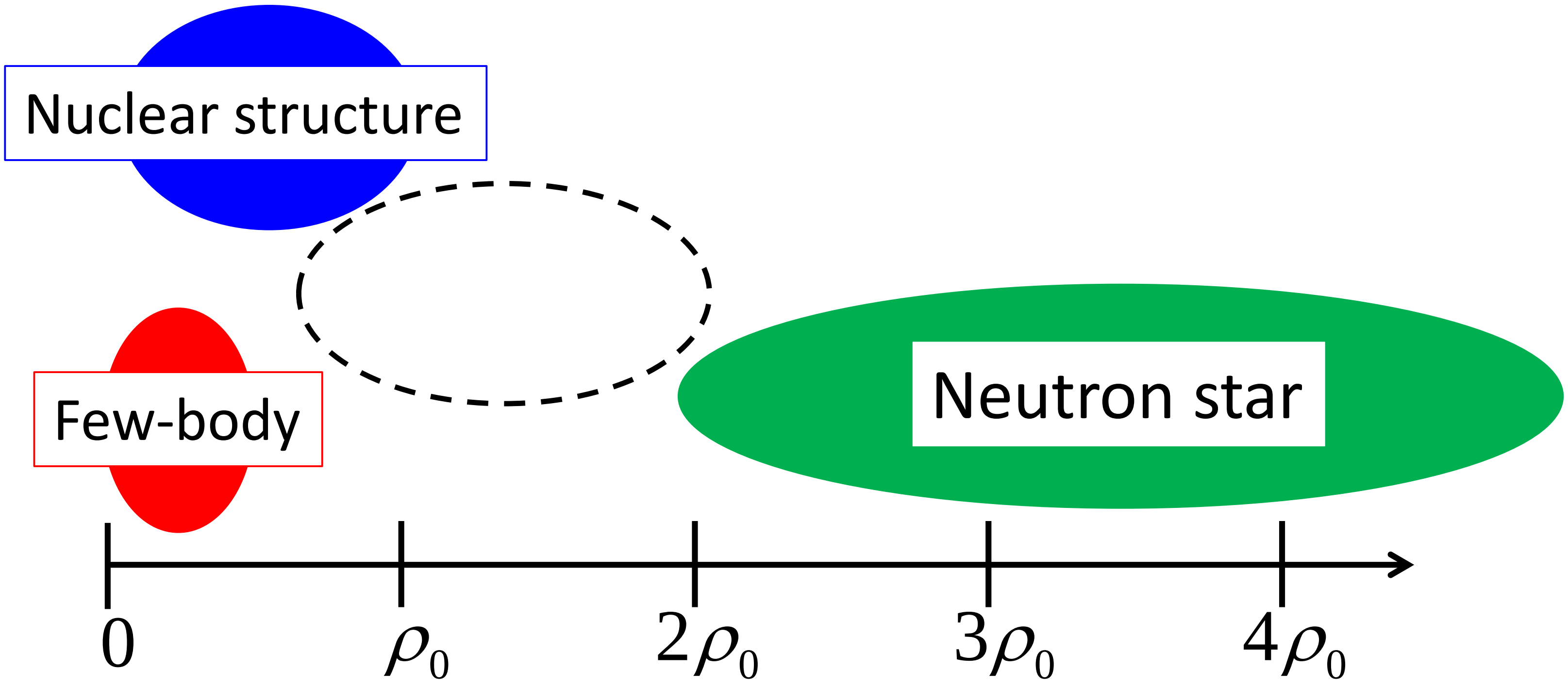
Takenori Furumoto
(National Institute of Technology, Ichinoseki College)

Collaborators
Y. Sakuragi (Osaka City Univ.)
Y. Yamamoto (RIKEN Nishina Center)

Contents

Purpose

- **Toward nuclear matter from the experimental data**



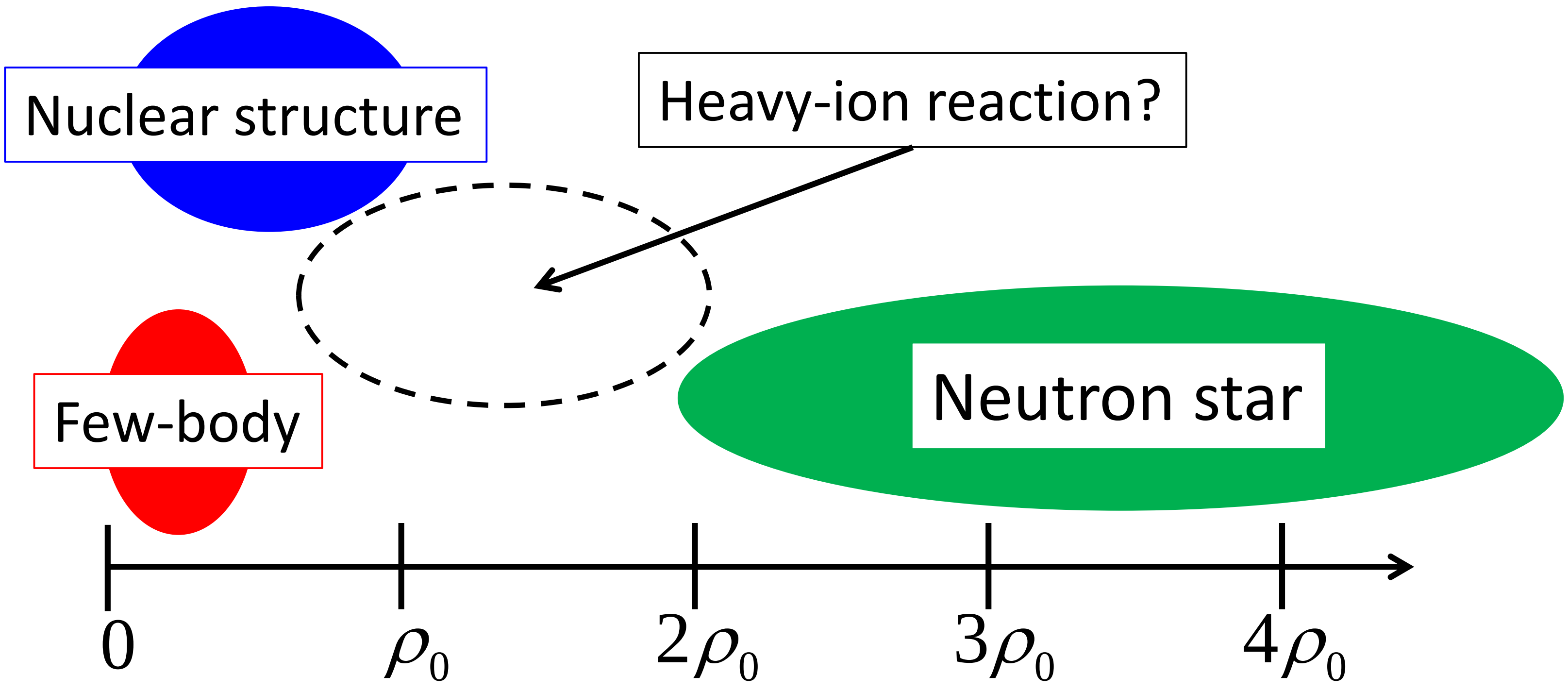
Nuclear structure

Few-body

Neutron star

Purpose

- **Toward nuclear matter from the experimental data**



Nuclear structure

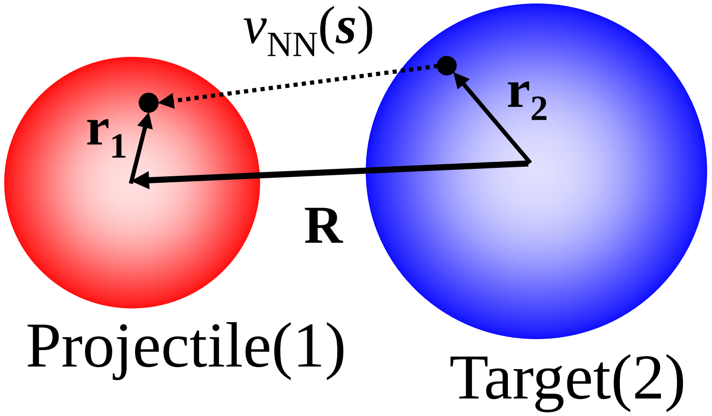
Heavy-ion reaction?

Few-body

Neutron star

0 ρ_0 $2\rho_0$ $3\rho_0$ $4\rho_0$

Double Folding Potential (DF Potential)



$$
\begin{aligned}
U(\mathbf{R}) &= \int \rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2)v_D(\mathbf{s};\rho,E)\,\mathrm{d}\mathbf{r}_1\mathrm{d}\mathbf{r}_2 \\
&+ \int \rho_1(\mathbf{r}_1,\mathbf{r}_1-\mathbf{s})\rho_2(\mathbf{r}_2,\mathbf{r}_2+\mathbf{s})v_{EX}(\mathbf{s};\rho,E)\exp\left[i\frac{\mathbf{K}\cdot\mathbf{s}}{M}\right]\mathrm{d}\mathbf{r}_1\mathrm{d}\mathbf{r}_2 \\
&= V_{DFM}(\mathbf{R}) + iW_{DFM}(\mathbf{R})
\end{aligned}
$$

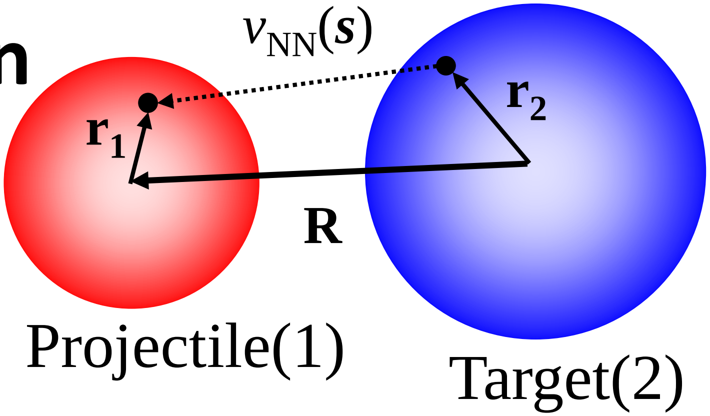
Frozen-density approx. (FDA)

$$\rho = \rho_1 + \rho_2$$

Complex G-matrix interaction (CEG07)

$$v_{D,EX} = v_{D,EX}^{(real)} + iv_{D,EX}^{(imag)}$$

Frozen Density Approximation (FDA)



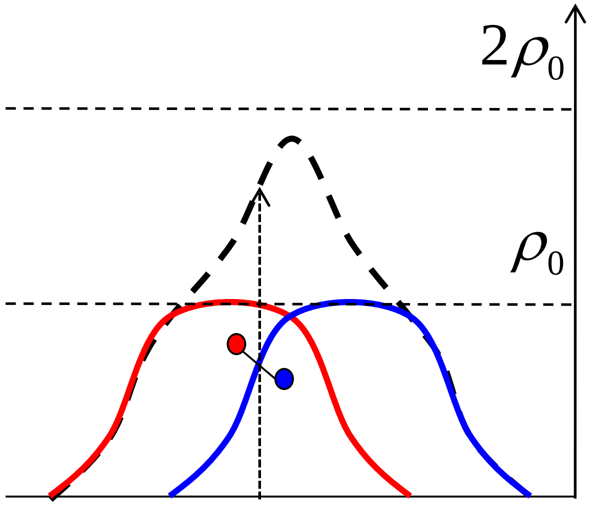
$$U(\mathbf{R}) = \int \rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2)v_D(\mathbf{s};\rho,E)\,\mathrm{d}\mathbf{r}_1\mathrm{d}\mathbf{r}_2$$

$$+\int \rho_1(\mathbf{r}_1,\mathbf{r}_1-\mathbf{s})\rho_2(\mathbf{r}_2,\mathbf{r}_2+\mathbf{s})v_{EX}(\mathbf{s};\rho,E)\exp\left[i\frac{\mathbf{K}\cdot\mathbf{s}}{M}\right]\mathrm{d}\mathbf{r}_1\mathrm{d}\mathbf{r}_2$$

$$= V_{DFM}(\mathbf{R}) + iW_{DFM}(\mathbf{R})$$

Frozen-density approx. (FDA)

$$\rho = \rho_1 + \rho_2$$

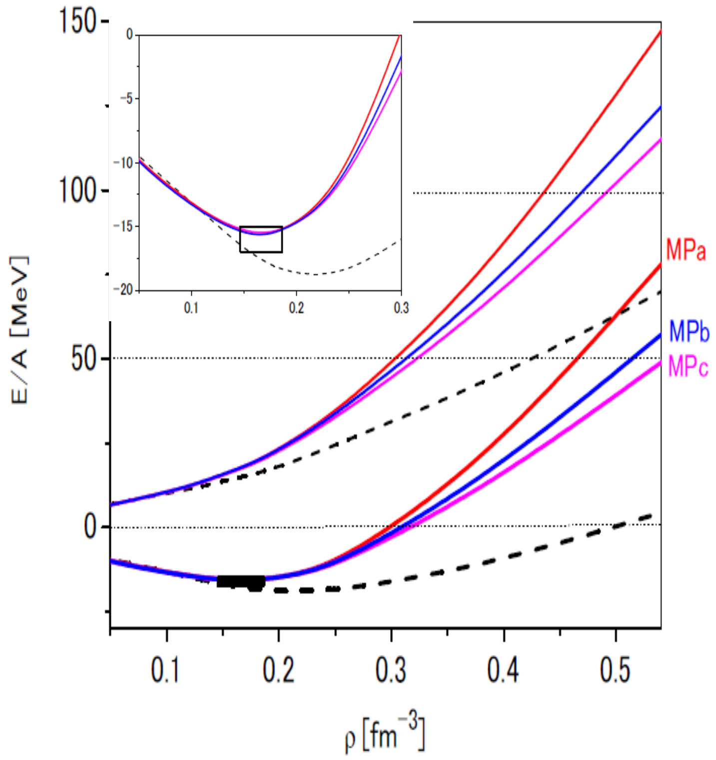


Recent

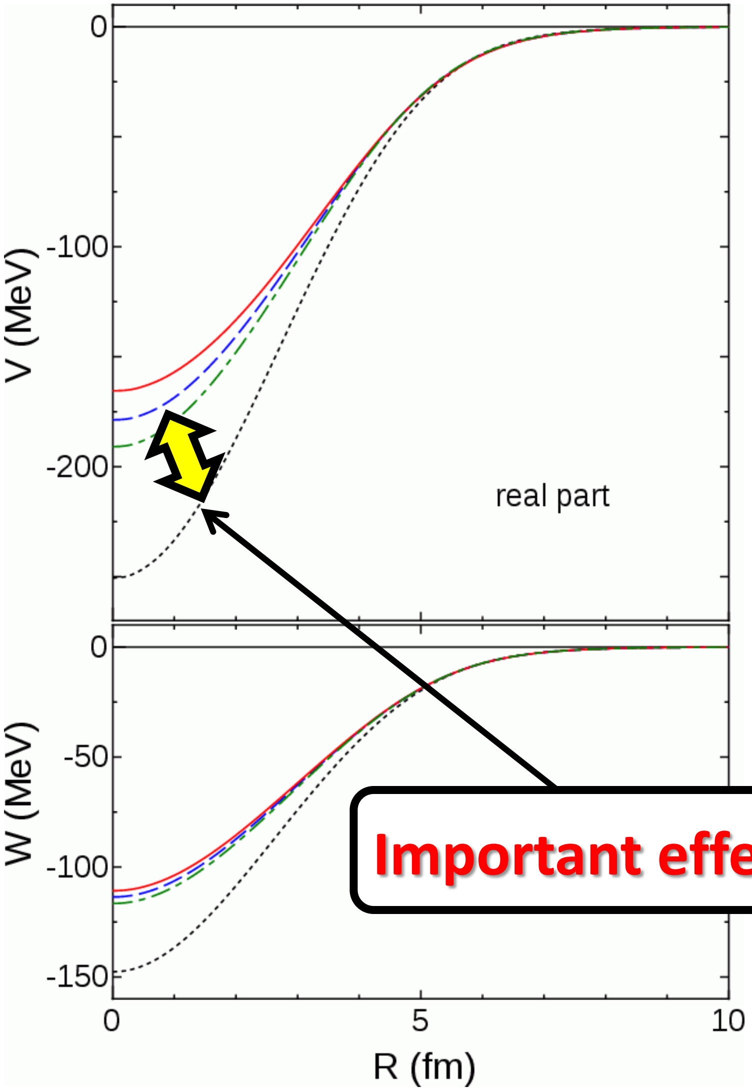
We have proposed the **complex G-matrix folding model**
- the complex G-matrix is derived from the ESC08 NN interaction
- includes the effect of **the multi-body repulsive force**
- consist from the repulsive and attractive parts

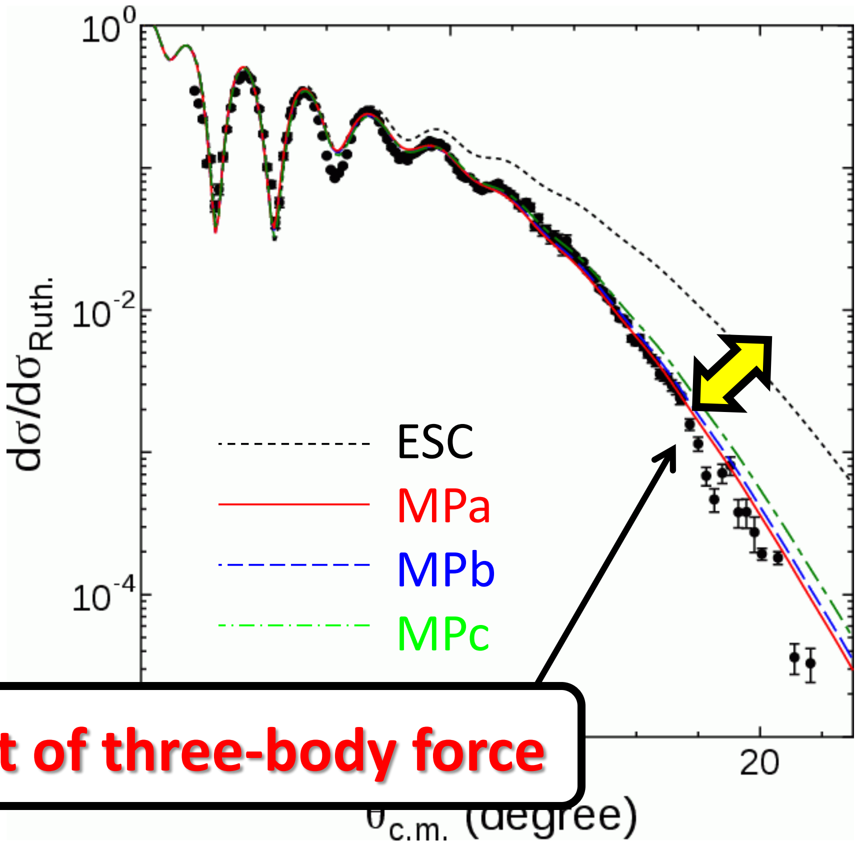
ESC : two-body only
MPa : with three- & four-body forces
MPb : with three-body forces
MPc : with three-body forces

Y. Yamamoto, T. Furumoto, N. Yasutake, and Th. A. Rijken, Phys. Rev. C90, 045805 (2014)



^{16}O + ^{16}O elastic scattering cross section at E/A = 70 MeV



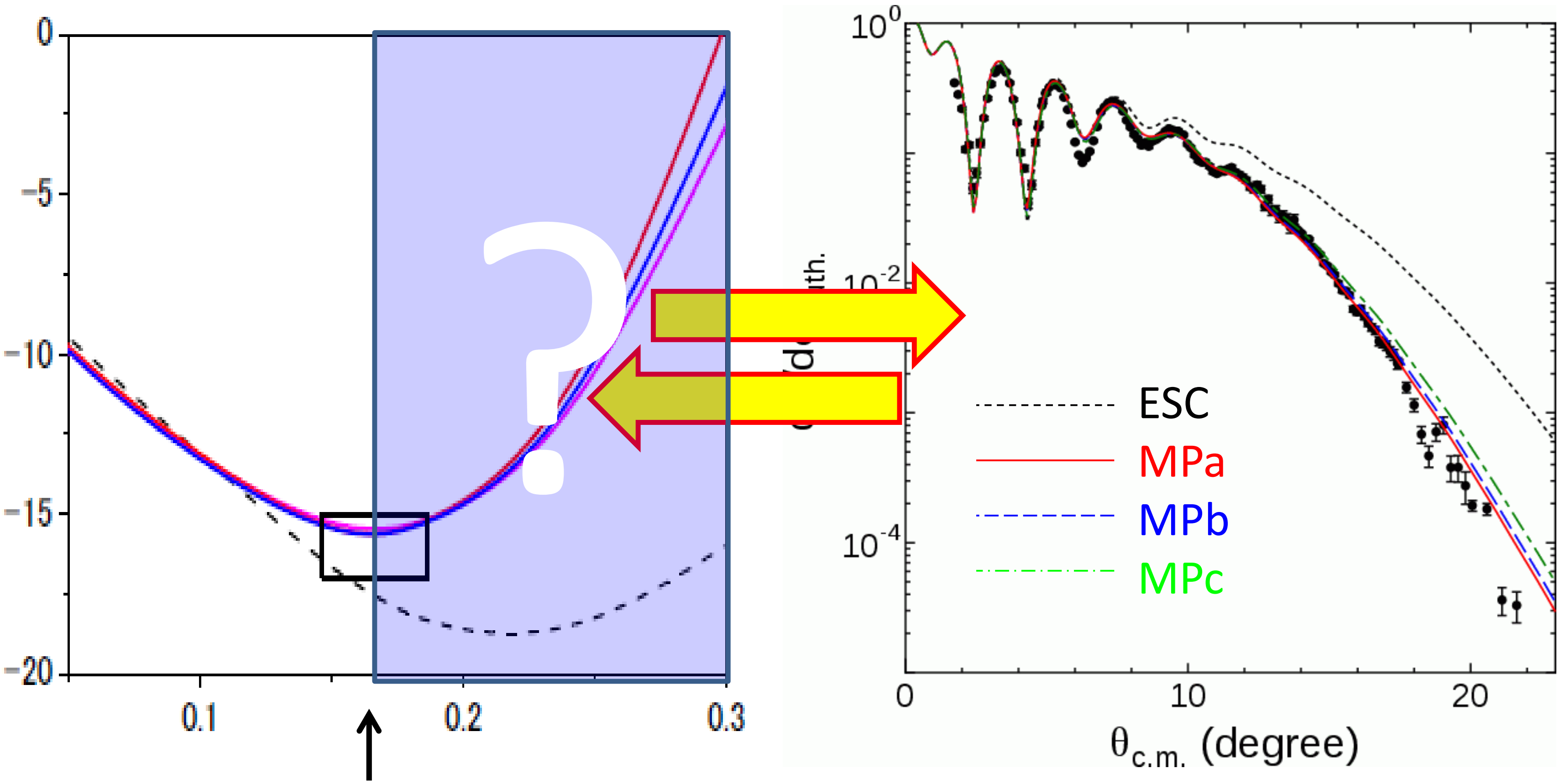


Important effect of three-body force

Y. Yamamoto, <u>T. Furumoto</u>, N. Yasutake, and Th. A. Rijken, Phys. Rev. C90, 045805 (2014)

Introduction of the investigation methods

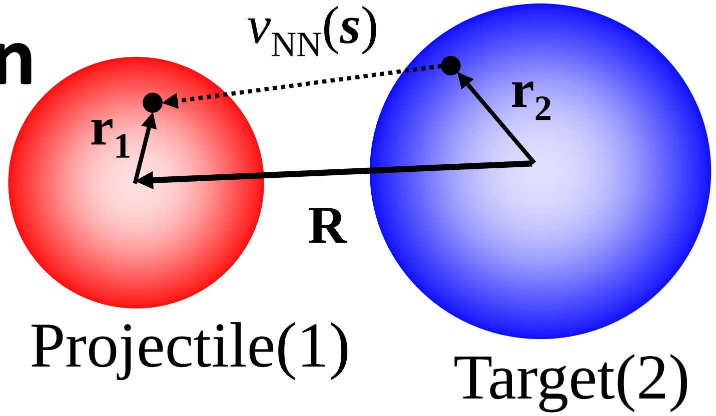
1. Where is the visible region for the cross section?



normal density

Y. Yamamoto, T. Furumoto, N. Yasutake and Th. A. Rijken,
Phys. Rev. C90, 045805 (2014)

Frozen Density Approximation (FDA)



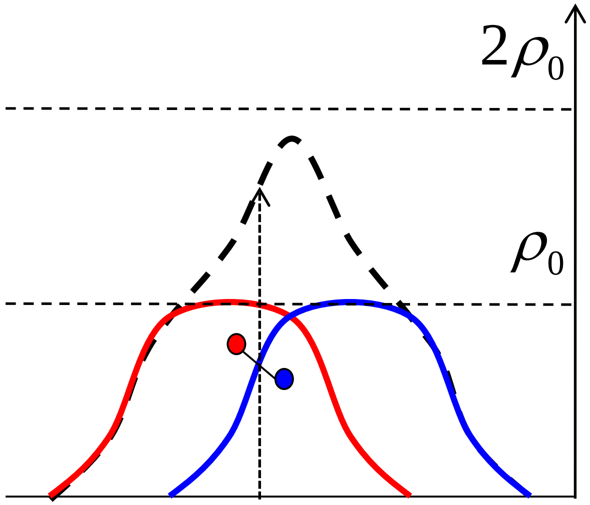
$$U(\mathbf{R}) = \int \rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2)v_D(\mathbf{s};\rho,E)\mathrm{d}\mathbf{r}_1\mathrm{d}\mathbf{r}_2$$

$$+\int \rho_1(\mathbf{r}_1,\mathbf{r}_1-\mathbf{s})\rho_2(\mathbf{r}_2,\mathbf{r}_2+\mathbf{s})v_{EX}(\mathbf{s};\rho,E)\exp\left[i\frac{\mathbf{K}\cdot\mathbf{s}}{M}\right]\mathrm{d}\mathbf{r}_1\mathrm{d}\mathbf{r}_2$$

$$=V_{DFM}(\mathbf{R})+iW_{DFM}(\mathbf{R})$$

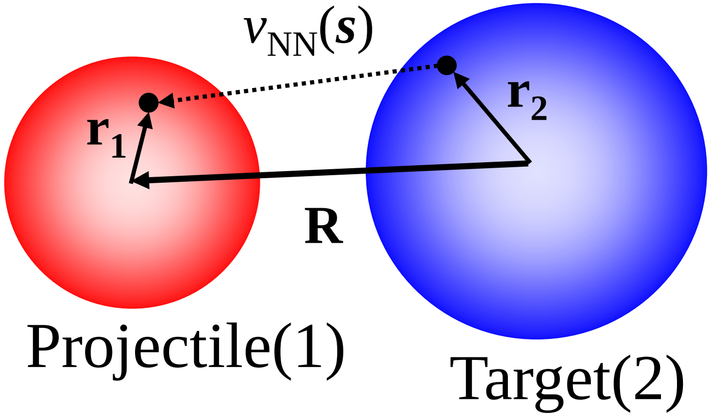
Frozen-density approx. (FDA)

$$\rho = \rho_1 + \rho_2$$



Method 1

cut the local density

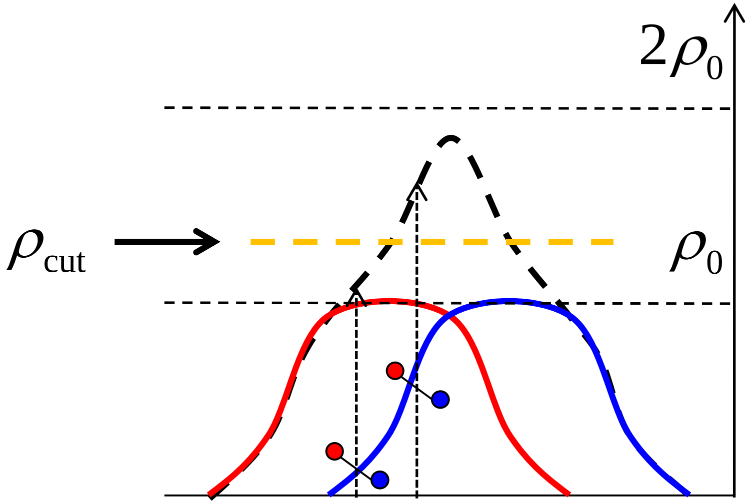


$$U(\mathbf{R}) = \int \rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2) v_D(\mathbf{s};\rho,E)\,\mathrm{d}\mathbf{r}_1\mathrm{d}\mathbf{r}_2$$

$$+\int \rho_1(\mathbf{r}_1,\mathbf{r}_1-\mathbf{s})\rho_2(\mathbf{r}_2,\mathbf{r}_2+\mathbf{s}) v_{EX}(\mathbf{s};\rho,E)\exp\left[i\frac{\mathbf{K}\cdot\mathbf{s}}{M}\right]\mathrm{d}\mathbf{r}_1\mathrm{d}\mathbf{r}_2$$

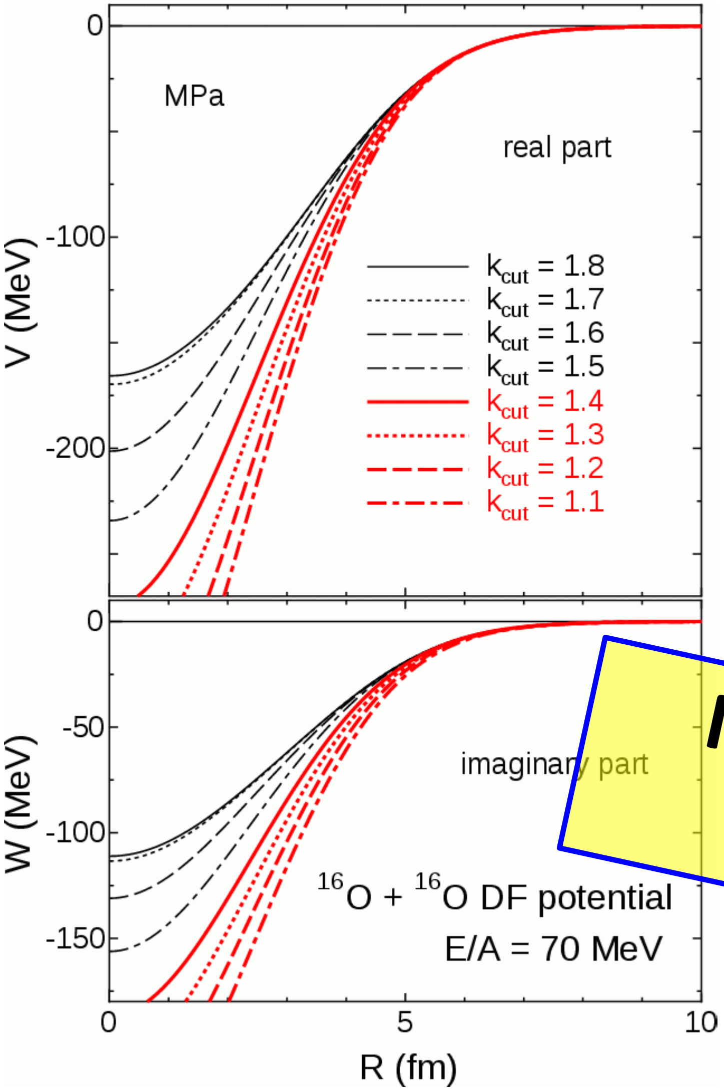
$$= V_{DFM}(\mathbf{R}) + iW_{DFM}(\mathbf{R})$$

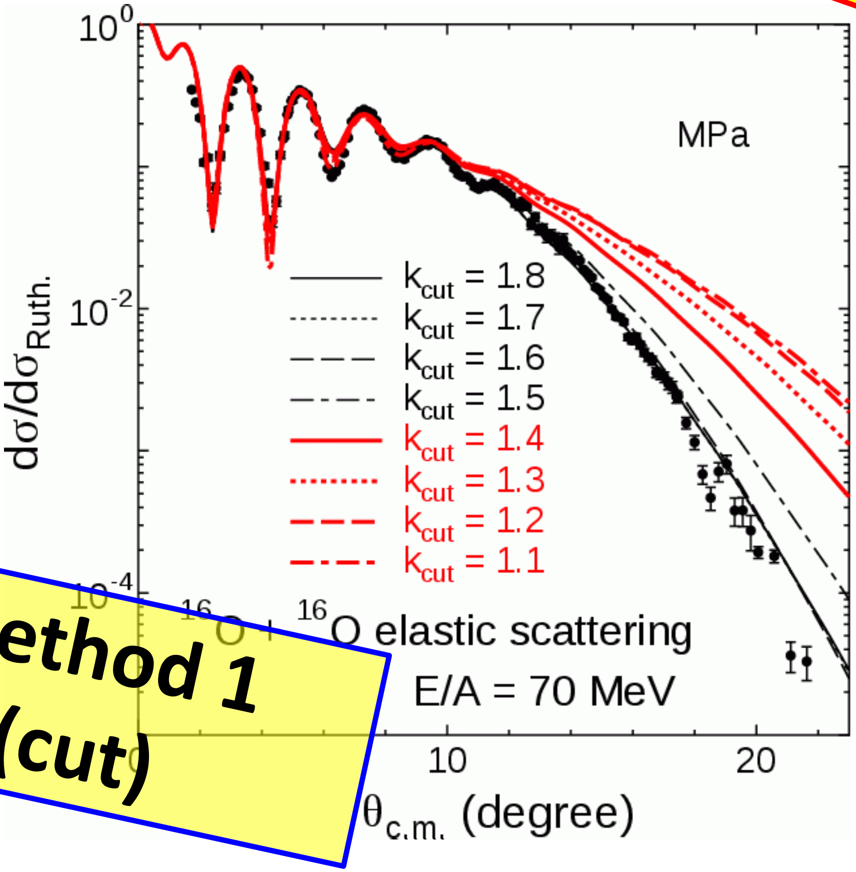
$$\rho = \begin{cases} \rho_1+\rho_2 & (\rho_1+\rho_2 \le \rho_{\mathrm{cut}}) \\ \rho_{\mathrm{cut}} & (\rho_1+\rho_2 > \rho_{\mathrm{cut}}) \end{cases}$$



^{16}O + ^{16}O elastic scattering cross section at E/A = 70 MeV

MPa



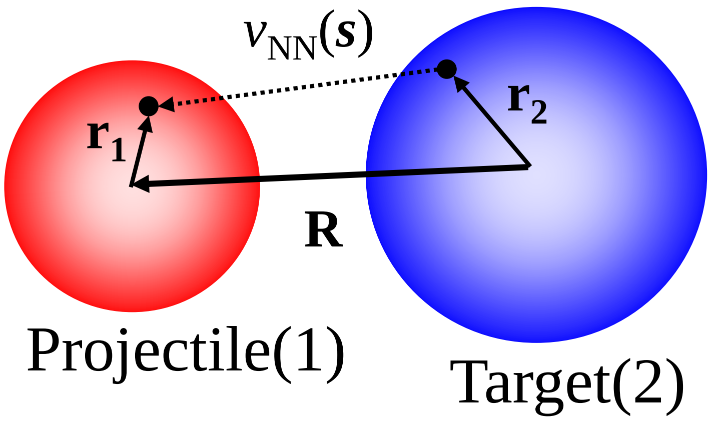


Method 1 (cut)

T. Furumoto, Y. Sakuragi and Y. Yamamoto, Phys. Rev. C90, 041601(R) (2014)

Method 2

replace the interaction

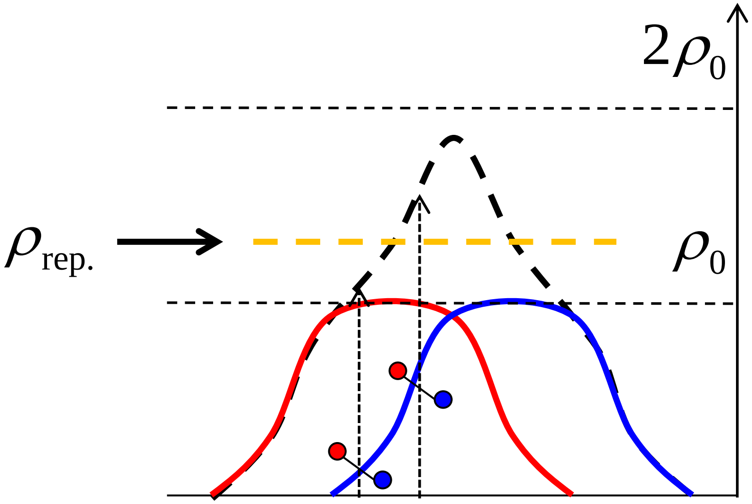


$$U(\mathbf{R}) = \int \rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2)\boxed{v_D(\mathbf{s};\rho,E)}\,d\mathbf{r}_1 d\mathbf{r}_2$$

$$+\int \rho_1(\mathbf{r}_1,\mathbf{r}_1-\mathbf{s})\rho_2(\mathbf{r}_2,\mathbf{r}_2+\mathbf{s})\boxed{v_{EX}(\mathbf{s};\rho,E)}\exp\left[i\frac{\mathbf{K}\cdot\mathbf{s}}{M}\right]d\mathbf{r}_1 d\mathbf{r}_2$$

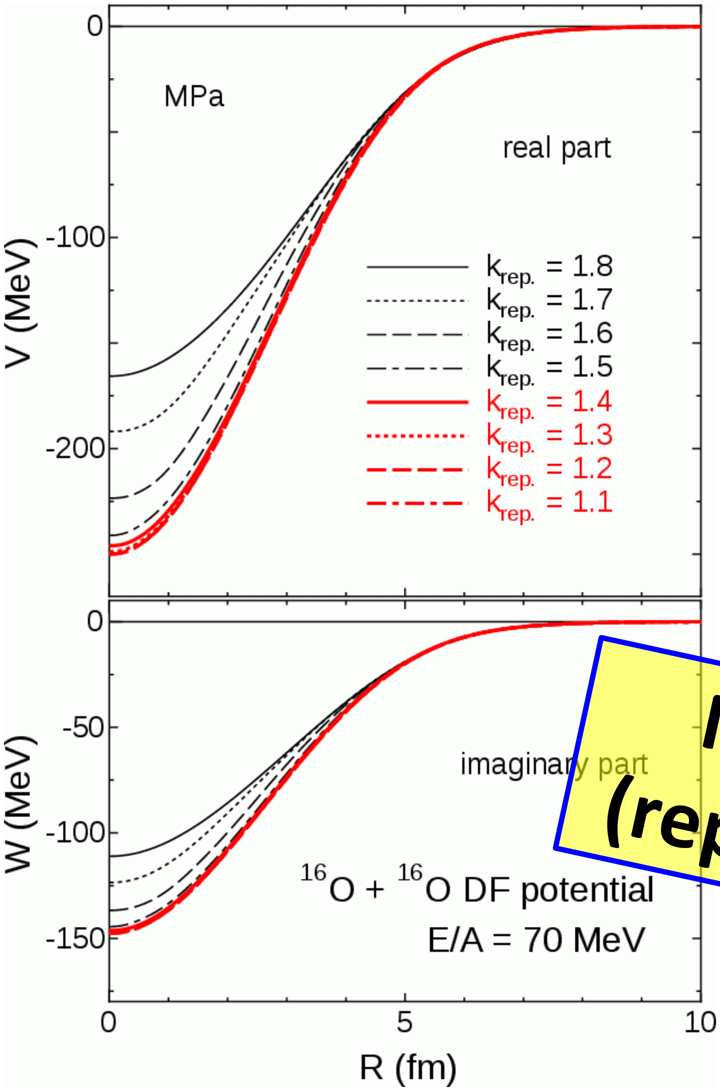
$$= V_{DFM}(\mathbf{R}) + iW_{DFM}(\mathbf{R})$$

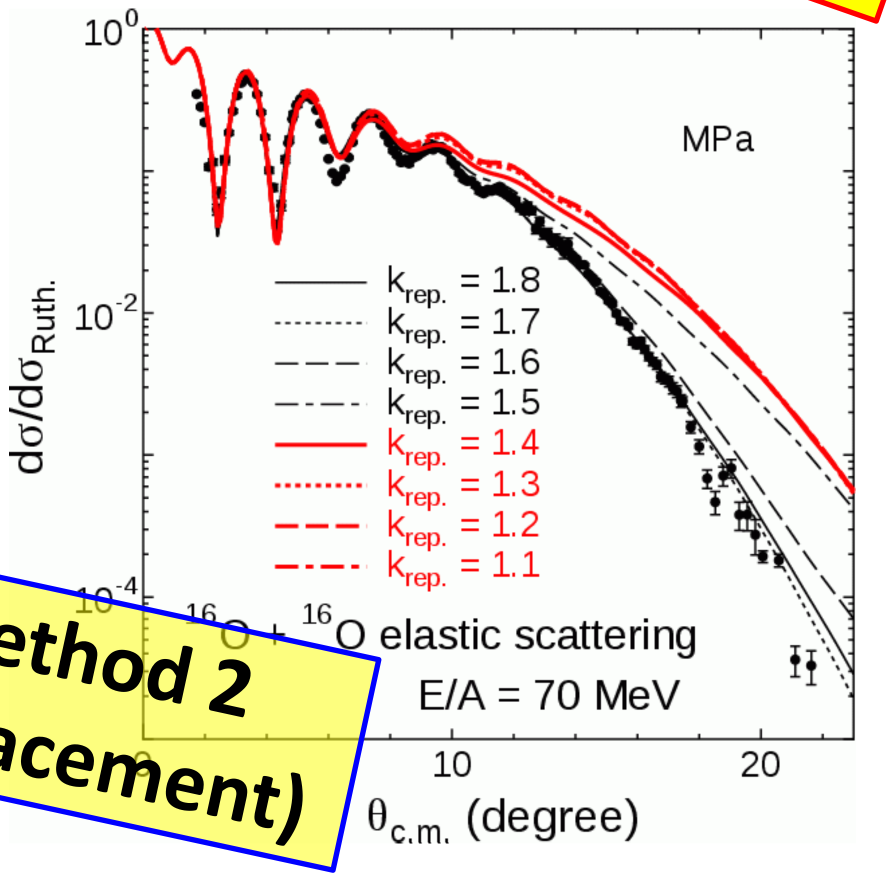
$$v = \begin{cases} \boxed{\mathrm{MPa}\ \ (\rho = \rho_1 + \rho_2 \le \rho_{\mathrm{rep.}})} \\ \boxed{\mathrm{ESC}\ \ (\rho = \rho_1 + \rho_2 > \rho_{\mathrm{rep.}})} \end{cases}$$



^{16}O + ^{16}O elastic scattering cross section at E/A = 70 MeV

MPa



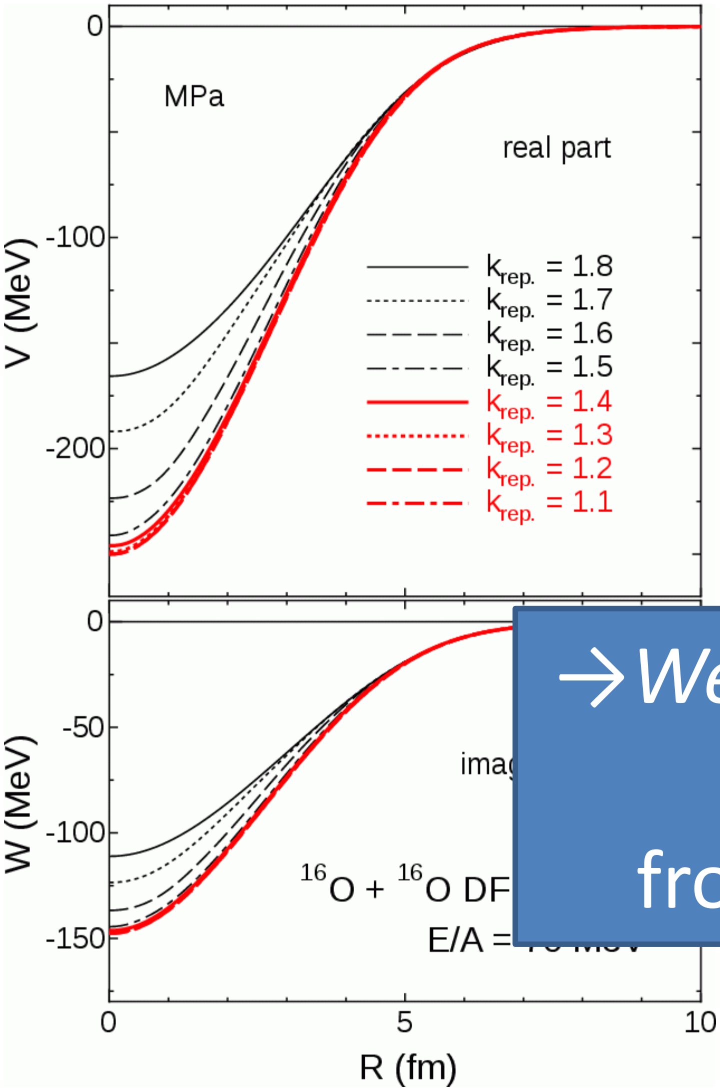


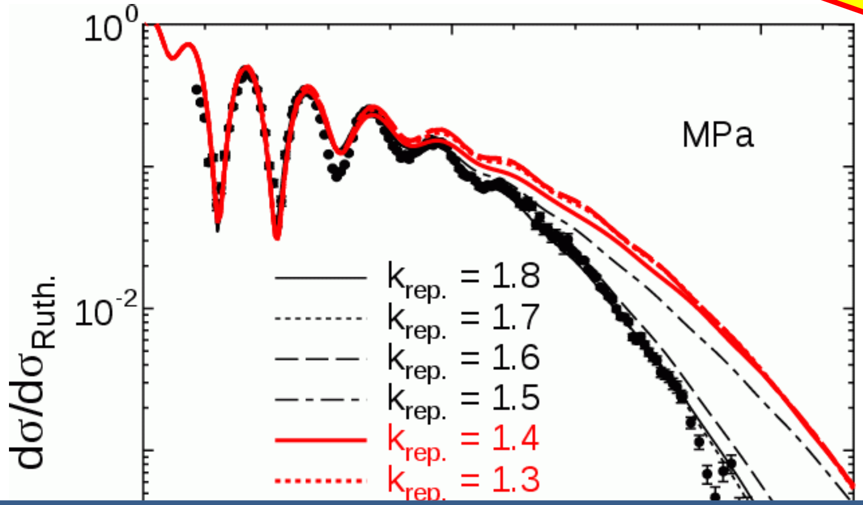
Method 2 (replacement)

<u>T. Furumoto</u>, Y. Sakuragi and Y. Yamamoto, Phys. Rev. C90, 041601(R) (2014)

^{16}O + ^{16}O elastic scattering cross section at E/A = 70 MeV

MPa



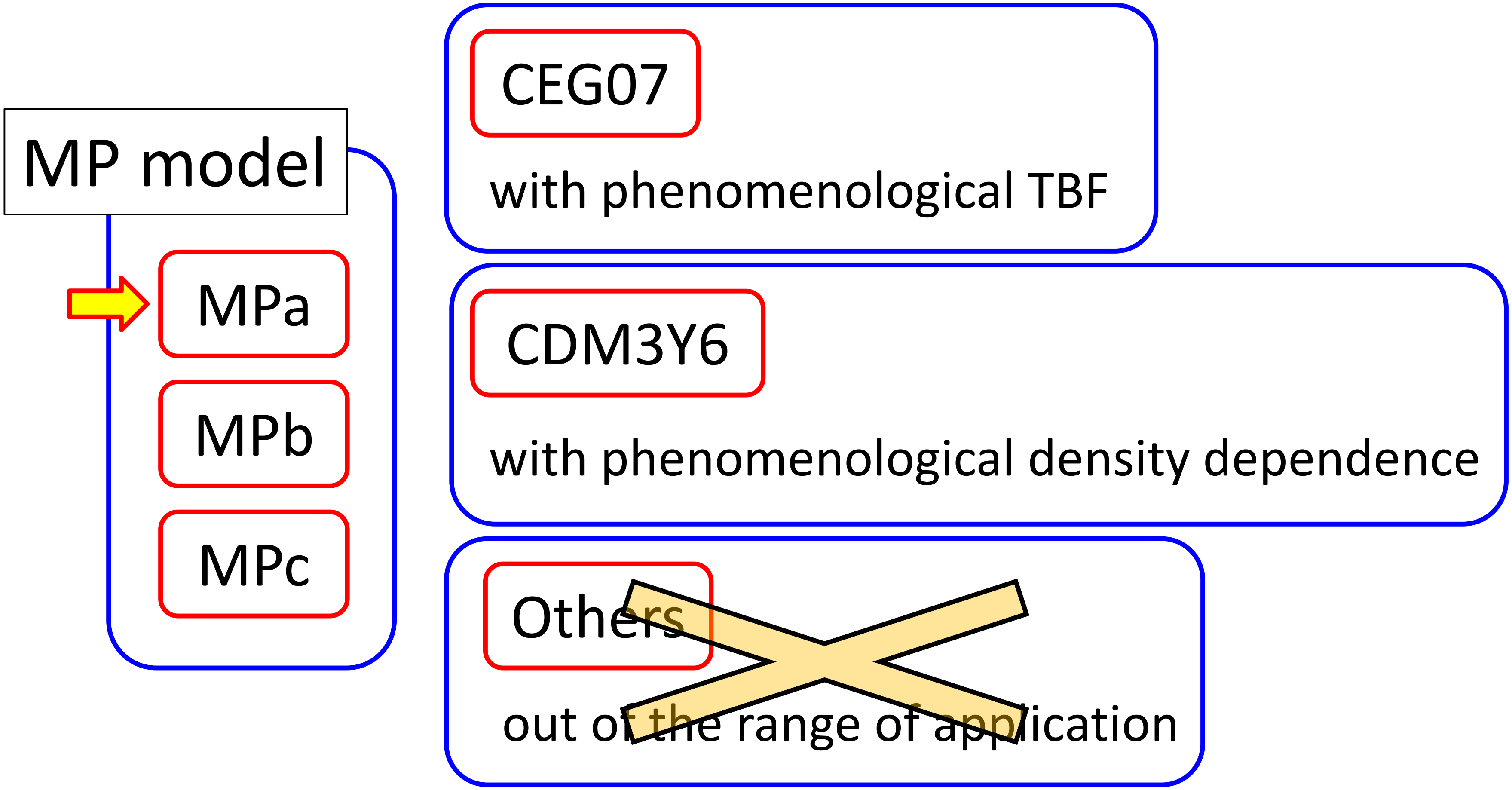


→*We can see the medium effect up to* k_F = 1.6-1.7 fm^{-1} from the experimental data

<u>T. Furumoto</u>, Y. Sakuragi and Y. Yamamoto, Phys. Rev. C90, 041601(R) (2014)

Interaction dependence

2. If the interaction is changed, can we give the same conclusion?



MP model

MPa

MPb

MPc

CEG07

with phenomenological TBF

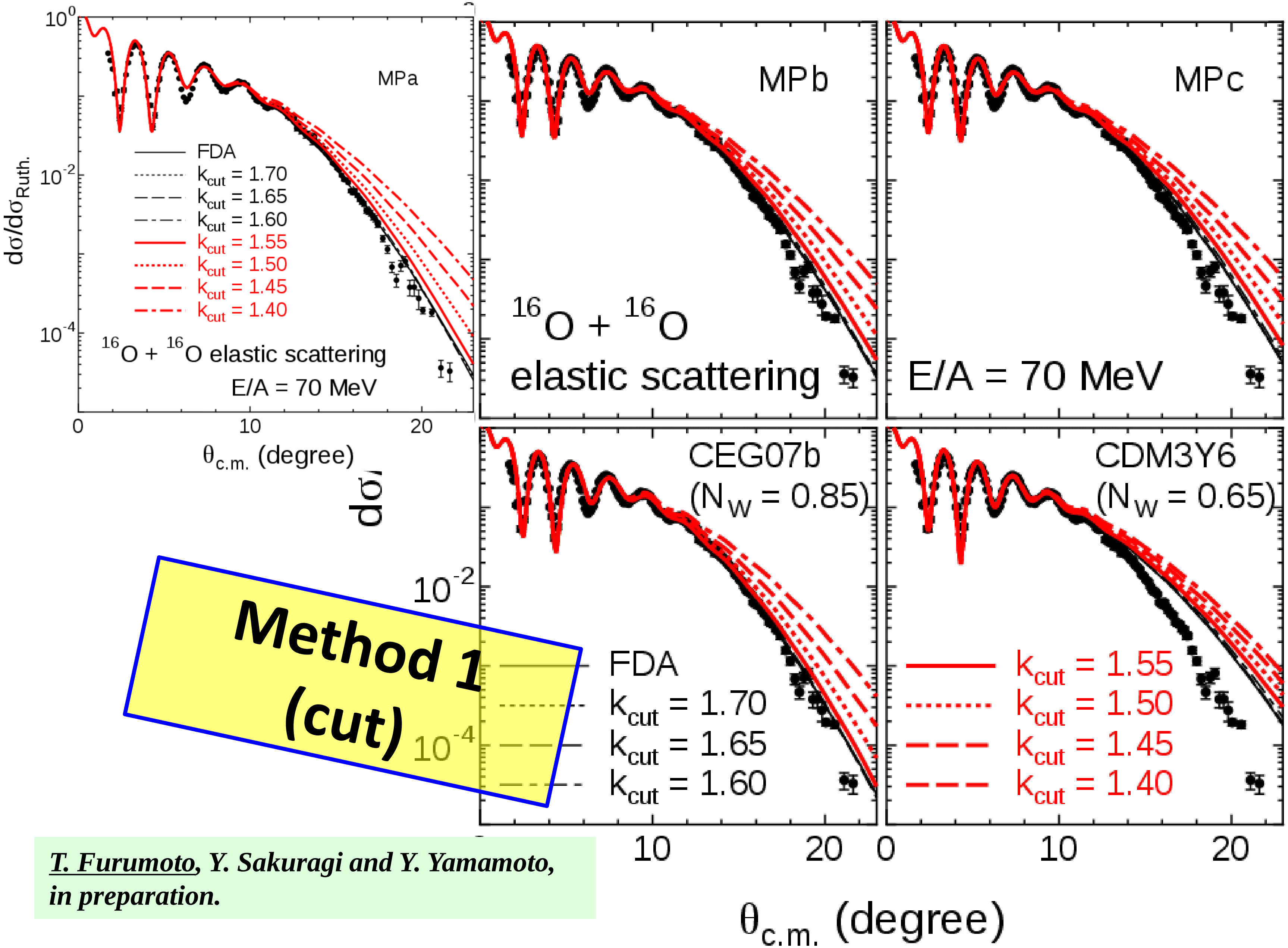
CDM3Y6

with phenomenological density dependence

Others

out of the range of application

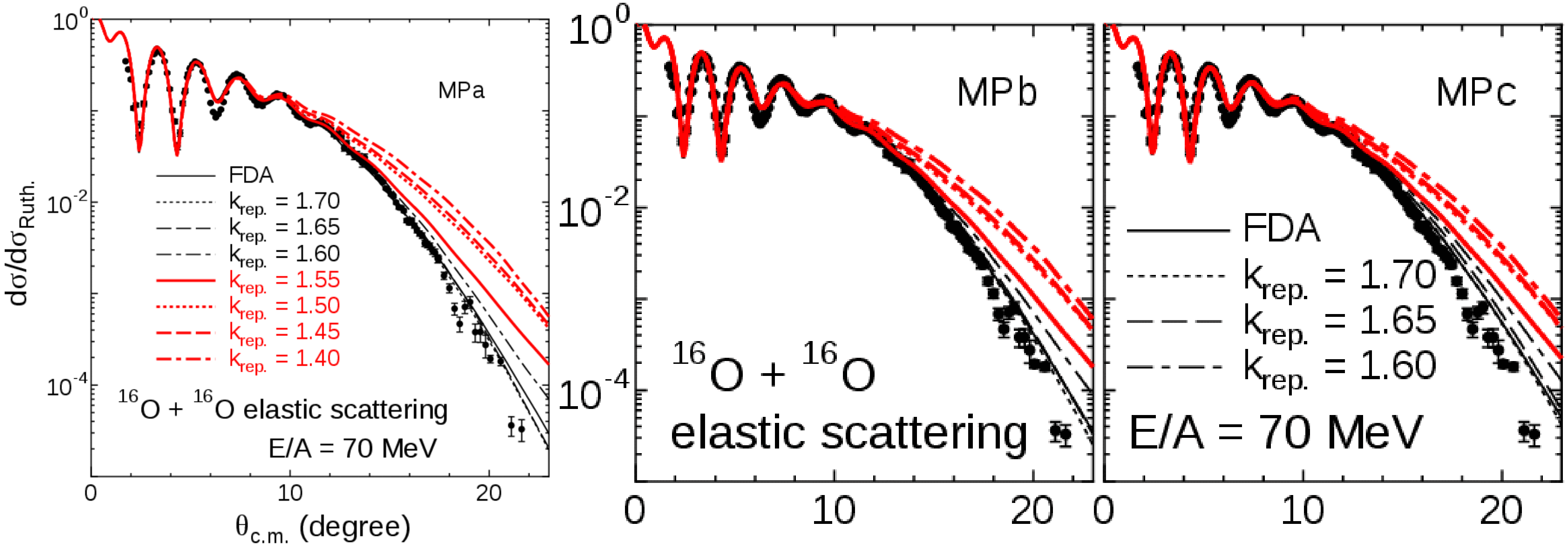
^{16}O + ^{16}O elastic scattering cross section at E/A = 70 MeV

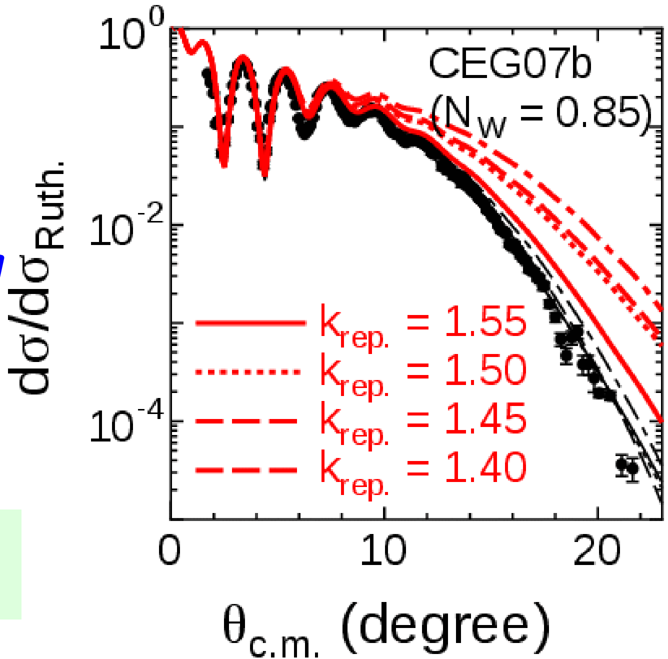


Method 1
(cut)

T. Furumoto, Y. Sakuragi and Y. Yamamoto, in preparation.

^{16}O + ^{16}O elastic scattering cross section at E/A = 70 MeV





Method 2
(replacement)

T. Furumoto*, *Y. Sakuragi and Y. Yamamoto,
in preparation.

Incident energy and target mass dependence

3. What system is the most suitable to investigate the medium effect in the high density region?

Potential

The medium effect is clearly seen with all interactions

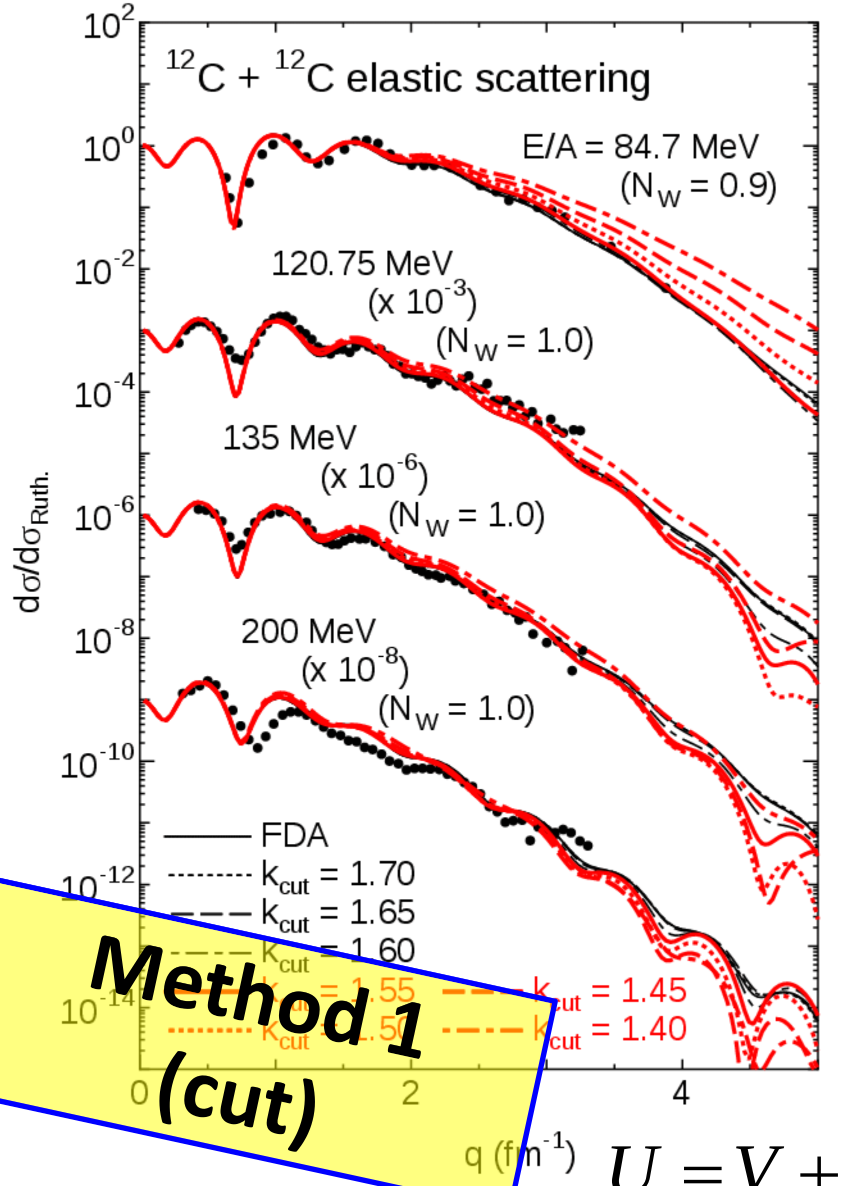
Elastic cross section

It is difficult to see the medium effect

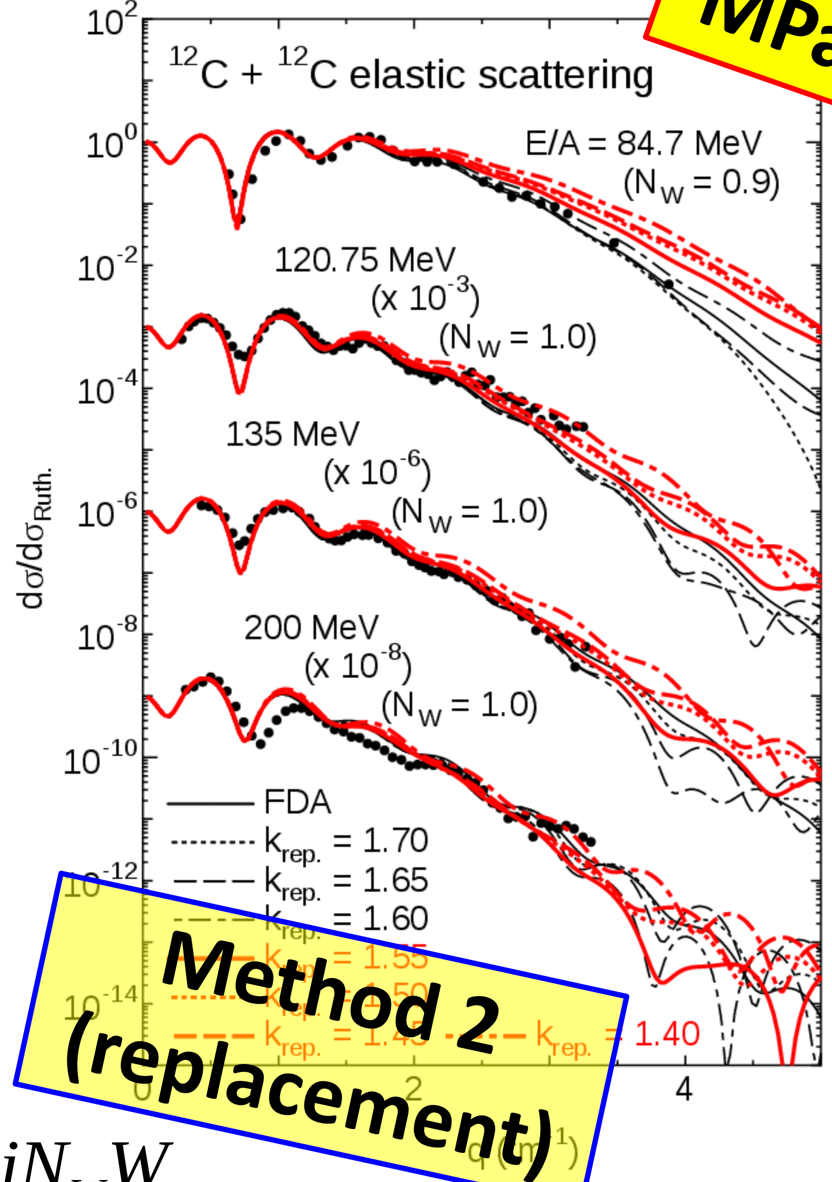
up to twice normal density

$^{12}C + {}^{12}C$ elastic scattering cross sections

MPa



Method 1 (cut)

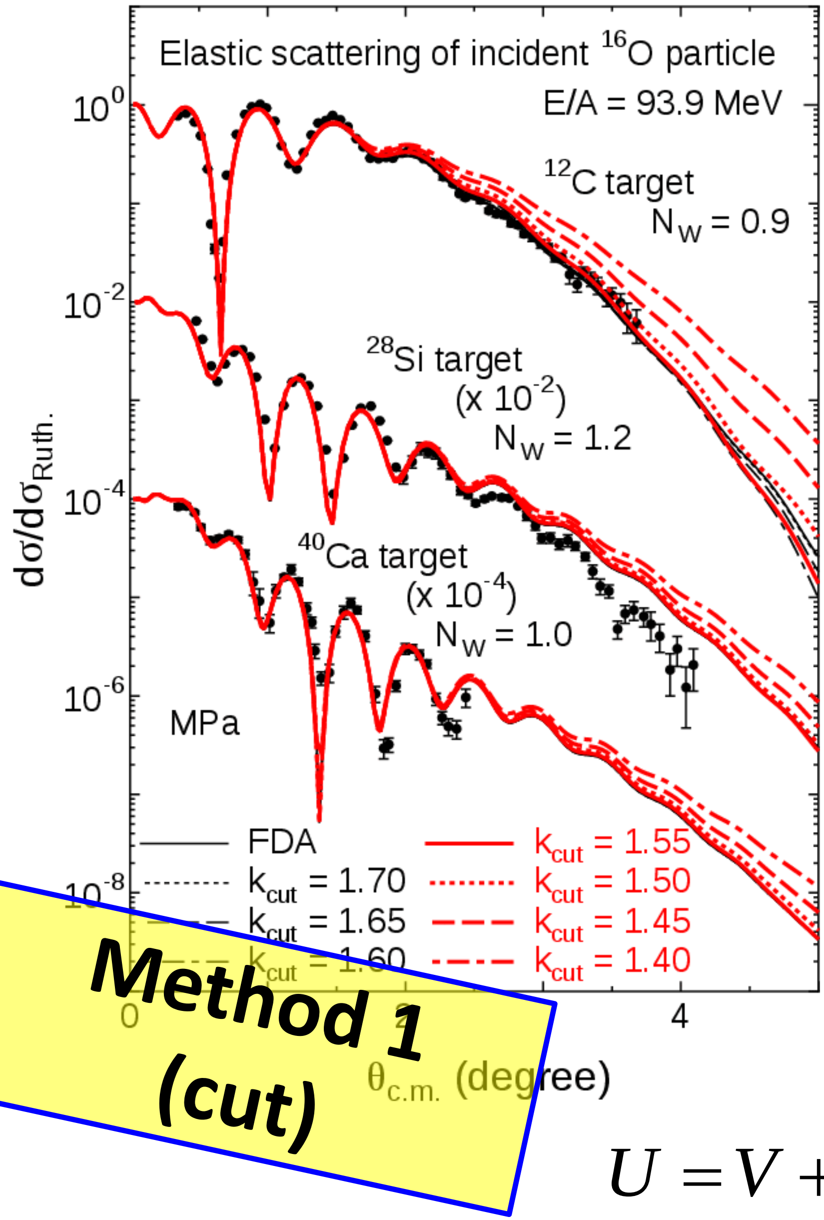


Method 2 (replacement)

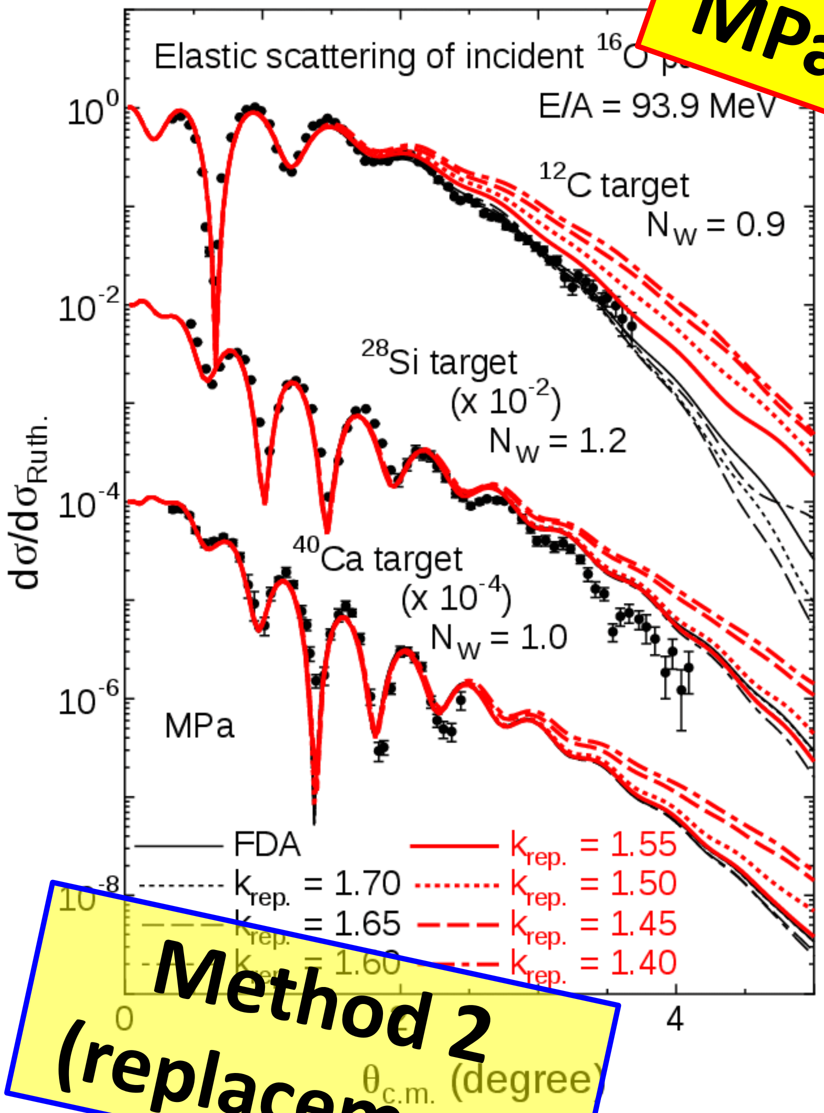
$$U = V + iN_W W$$

^{16}O + ^{12}C, ^{28}Si, ^{40}Ca, elastic scattering cross sections

MPa



Method 1 (cut)



Method 2 (replacement)

$$U = V + iN_W W$$

Summary

- **Multi-pomeron (MP) potential (TBF effect)**
  - **successful for <u>nucleus-nucleus elastic scattering</u>**

- Medium effect including TBF effect **<u>in high density region</u>**
  - needs up to <u>$\boldsymbol{k_F = 1.6\text{-}1.7\ \mathrm{fm}^{-1}}$</u> for heavy-ion elastic scattering

- Interaction dependence (MPa/b/c, CEG07b & CDM3Y6)
  - slightly different but the conclusion is not changed ($k_F = 1.6\text{-}1.7\ \mathrm{fm}^{-1}$)

- Incident energy and target mass dependences
  - The high energy and large nucleus <u>*not*</u> seems to be suitable to investigate the medium effect by present methods.