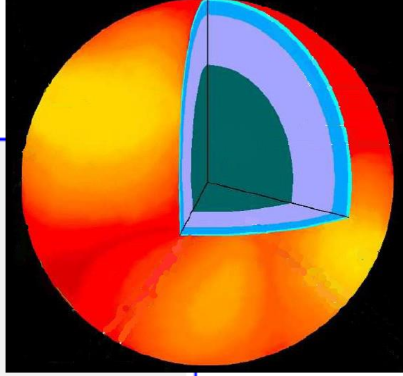
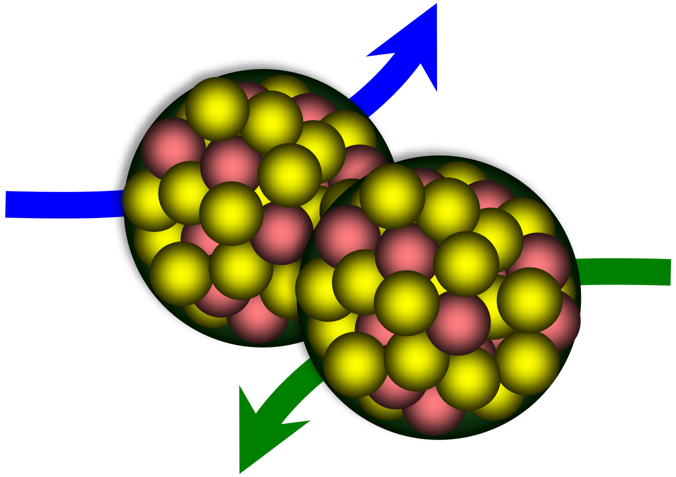


High-density nuclear matter probed by nucleus-nucleus scattering

- its implication to neutron star mass problem -



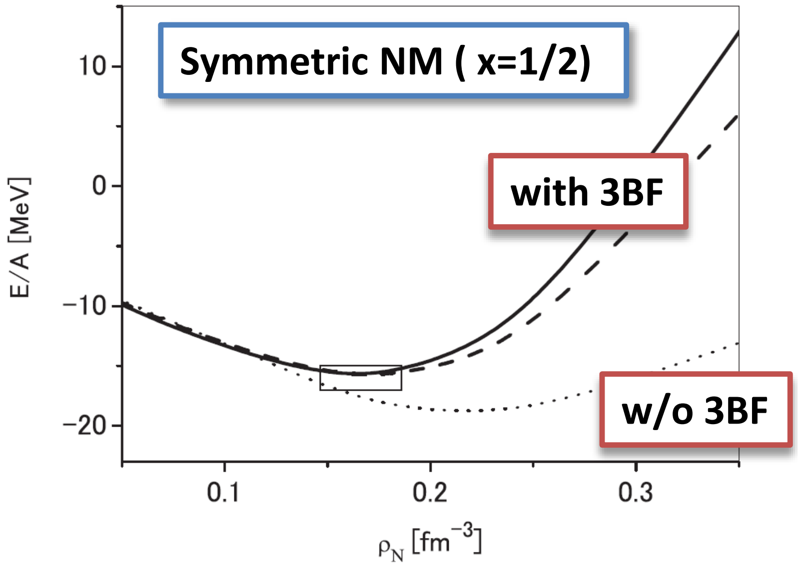
Y. Sakuragi *(Osaka City University, Japan)*

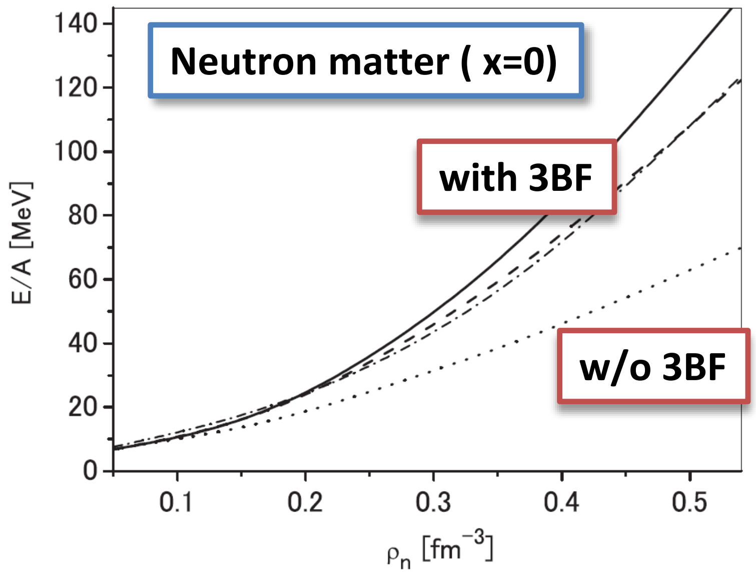
with ***T. Furumoto, Y. Yamamoto, N. Yasutake, Th. A. Rijken***

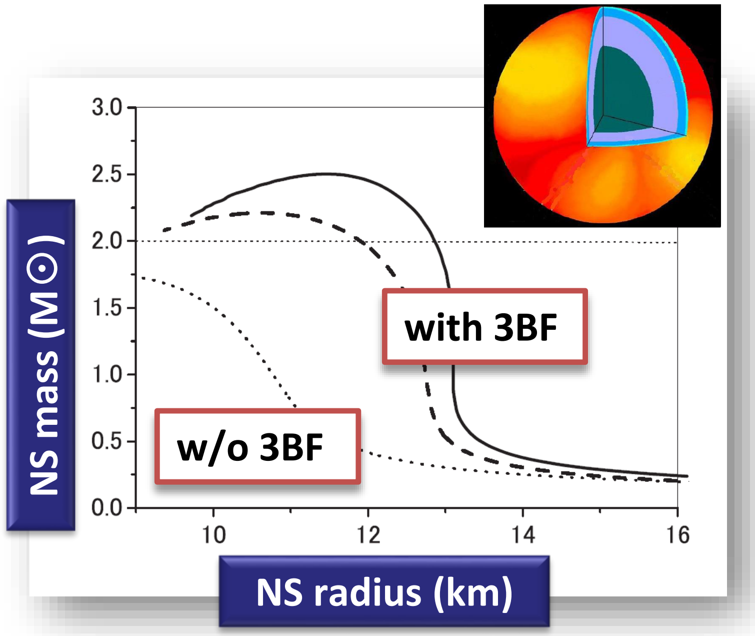
Background of the present study

- ✓ The new observation of the system J1614-2230 has brought a great impact on **the maximum-mass problem** of neutron stars. The large observed value of neutronstar mass, **1.97xM⊙**, **sets a severe condition for the stiffness of the equation of state (EOS) of neutron-star matter**

- ✓ The **repulsive 3NF force** contribution in **high-density neutron matter** should play an essential role for **stiffening the EOS** of neutron-star matter, assuring the observed **maximum mass of neutron stars** $(2M_{\odot})$

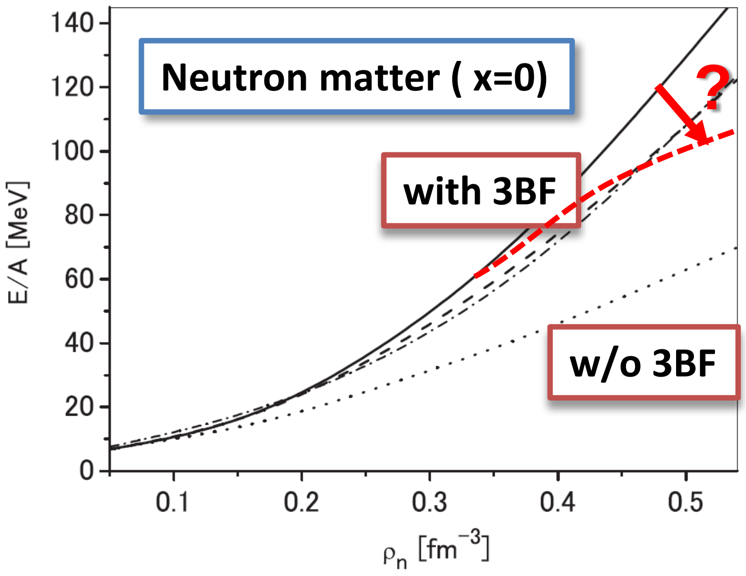


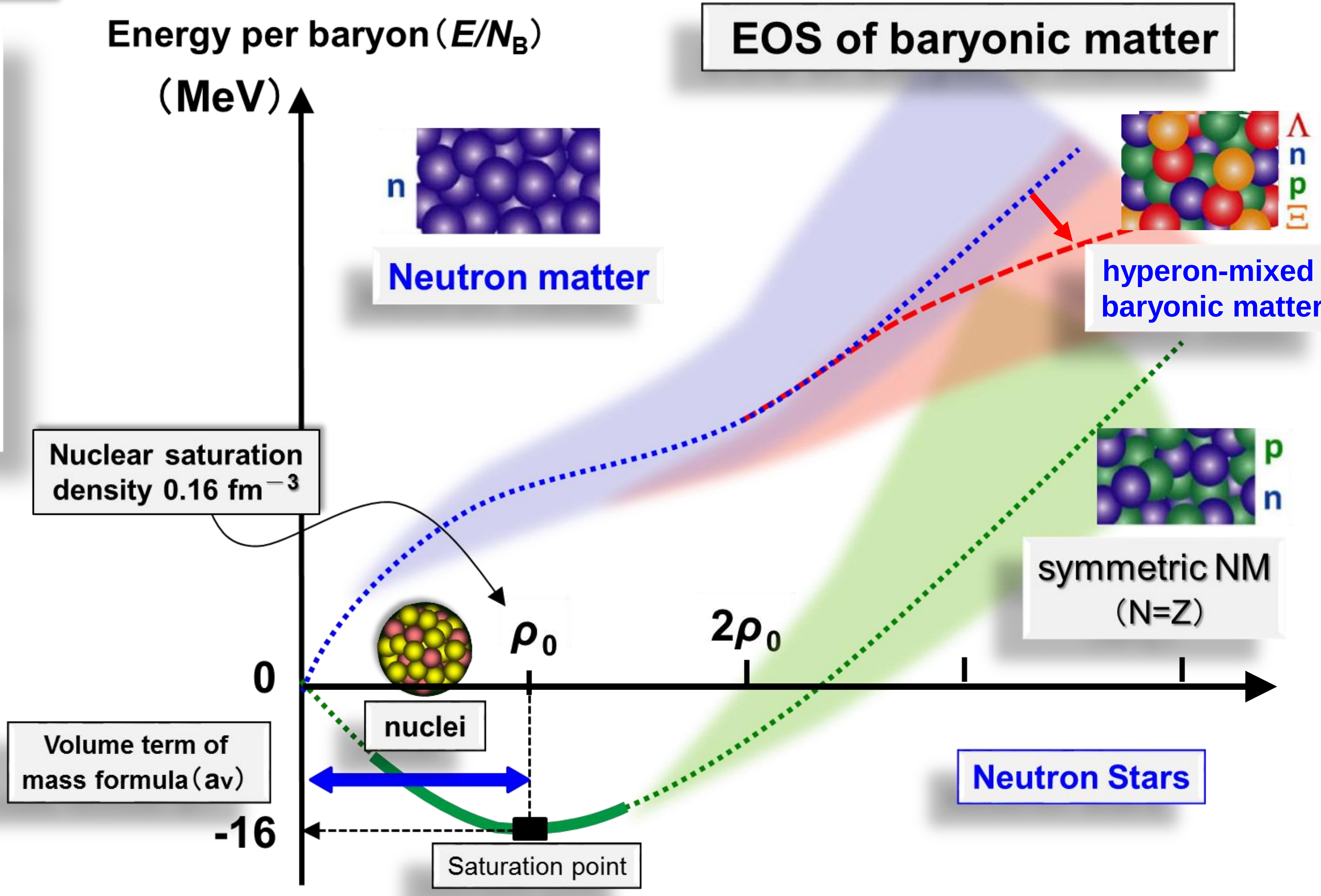




Background of the present study

✓ However, **hyperon (Y) mixing** in neutron-star matter brings about **a remarkable softening** of the EOS at high-ρ region ($\rho > (2\sim3) \times \rho_{\odot}$), which cancels the repulsive 3NF effect for the maximum mass.





Background of the present study

- ✓ In order to avoid this serious problem, we have proposed **a multi-Pomeron exchange potential (MPP)** that **works universally** not only in ***NNN*** states but also in ***YNN***, ***YYN***, and ***YYY*** states.

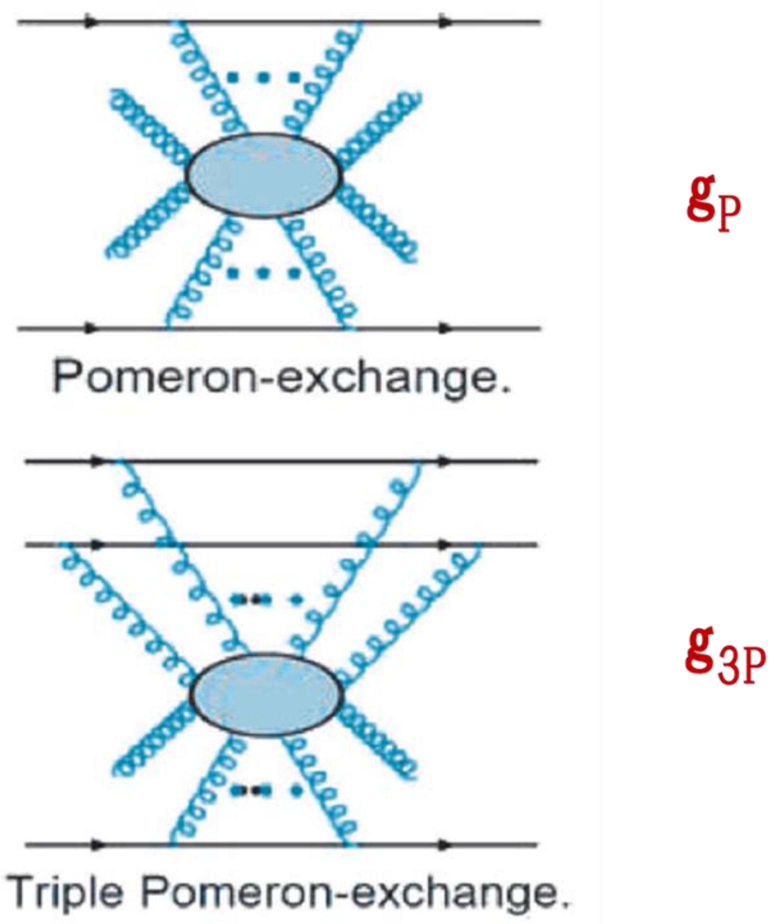
- ✓ Our basic concern is the existence of universal repulsions among three baryons (BBB), called here **3-baryon repulsion (BBB repulsion).**

- ✓ The role of the repulsive BBB for stiffening the EOS can be recovered clearly by invoking this assumption.

What is pomeron?

Why pomeron?

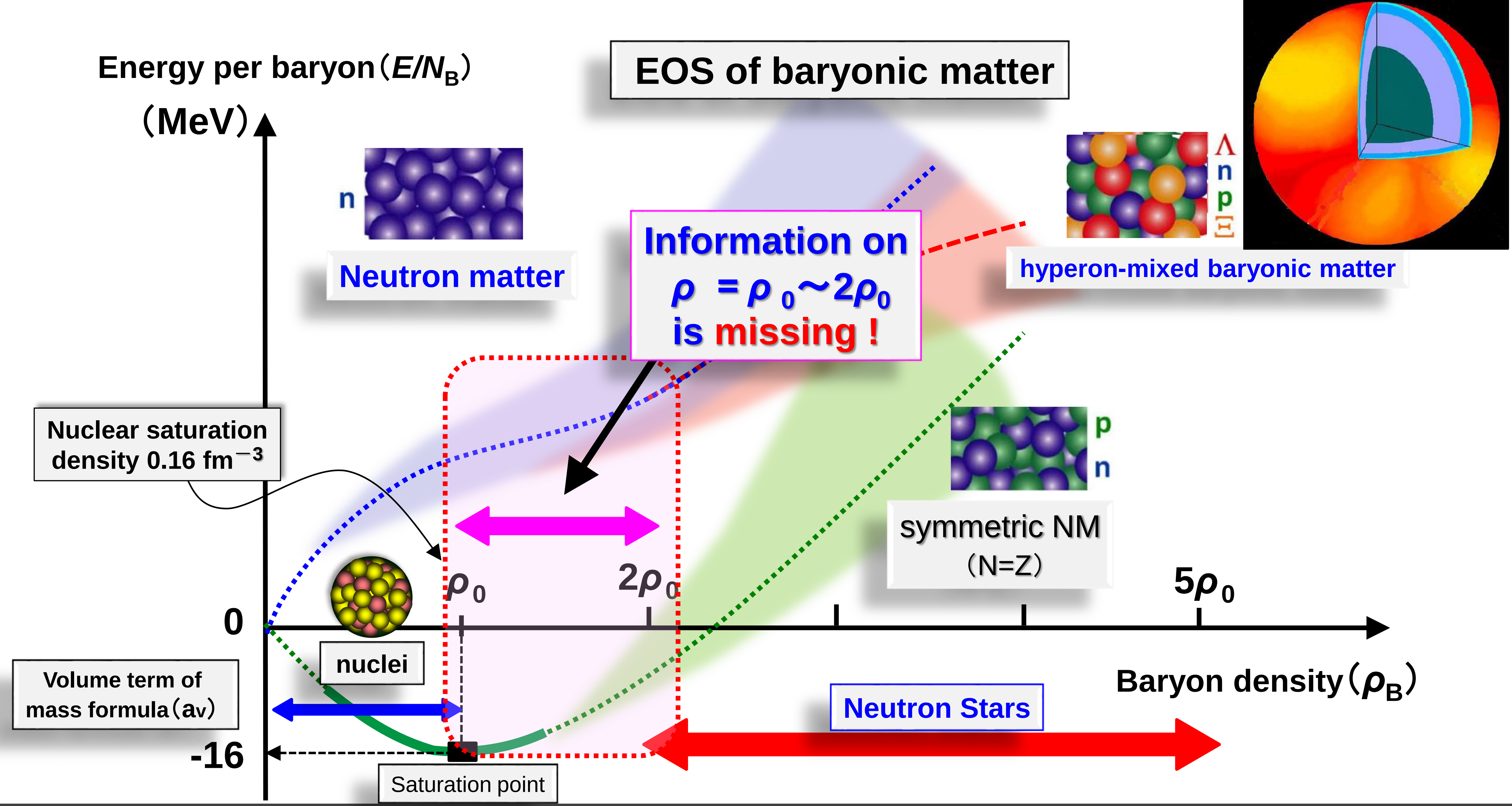
SU3 scalar

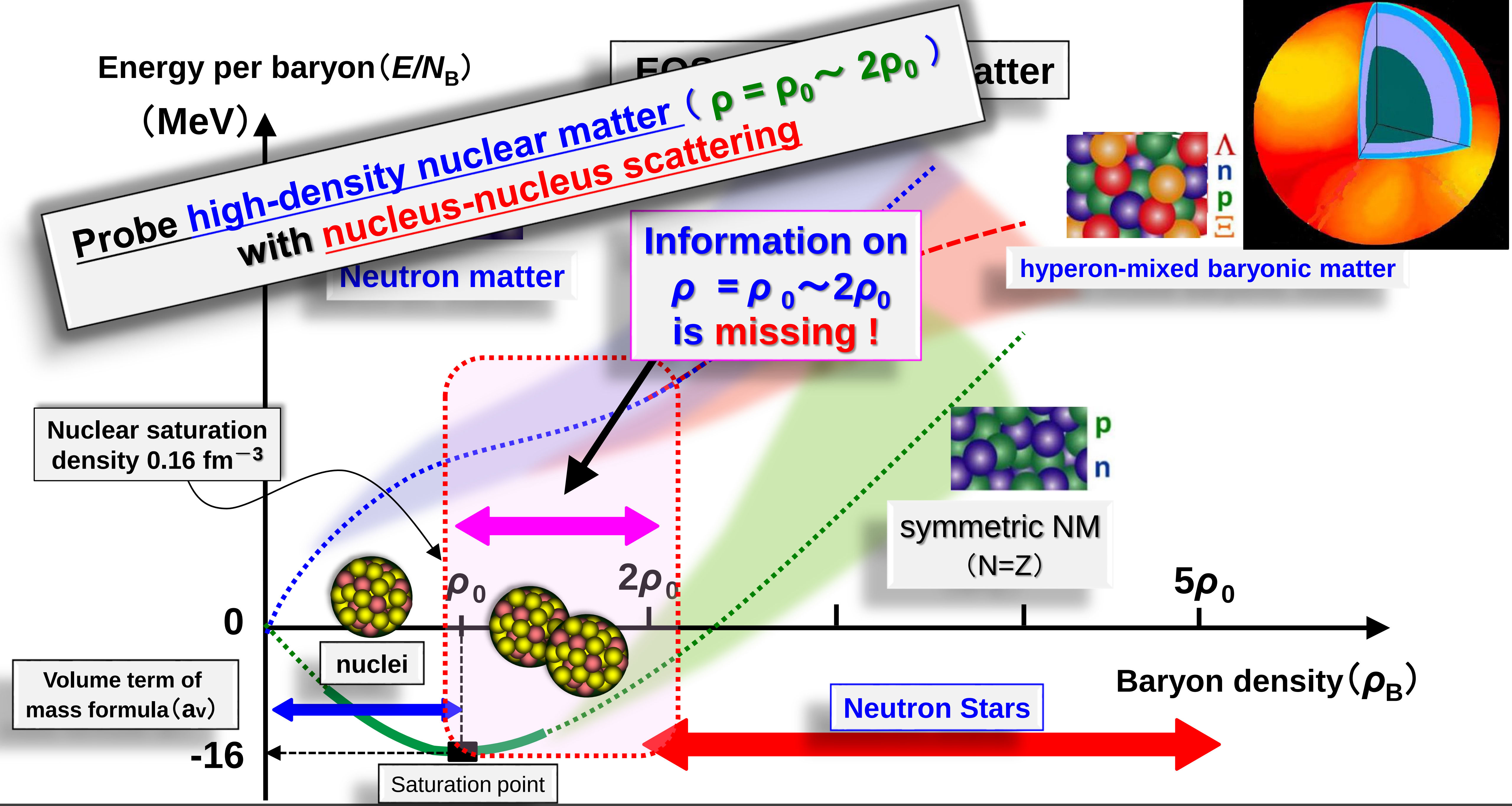


Pomeron is a model for multi-gluon exchange

Our strategy

- ✓ The 3BF is very sensitive to **nucleus-nucleus (A-A) elastic scattering**
- ✓ We determine the strength of univeral **3,4-baryon repulsion** by analyses of A-A elastic scattering with the *G*-matrix folding model (→explained soon)
- ✓ Then, construct the EOS of neutron-star matter,
- ✓ Examine if it results in a stiff EOS, enough to give the observed neutron-star mass $(M_{NS} \approx 2M_{\odot})$ with hyperon mixing.


EOS of baryonic matter
Energy per baryon（E/N_B）
（MeV）
n
Neutron matter
Information on
ρ ＝ρ 0～2ρ0
is missing !
Λ
n
p
Ξ
hyperon-mixed baryonic matter
Nuclear saturation
density 0.16 fm⁻³
p
n
symmetric NM
（N=Z）
ρ 0
2ρ 0
5ρ 0
0
-16
nuclei
Volume term of
mass formula（av）
Baryon density（ρB）
Neutron Stars
Saturation point


Probe high-density nuclear matter (ρ = ρ₀~ 2ρ₀)
with nucleus-nucleus scattering
EOS ... atter
Energy per baryon (E/N_B)
(MeV)
Neutron matter
Information on
ρ = ρ₀~2ρ₀
is missing !
Λ
n
p
Ξ
hyperon-mixed baryonic matter
Nuclear saturation density 0.16 fm⁻³
p
n
symmetric NM
(N=Z)
ρ₀
2ρ₀
5ρ₀
0
nuclei
Volume term of mass formula (av)
-16
Saturation point
Baryon density (ρ_B)
Neutron Stars

Purpose

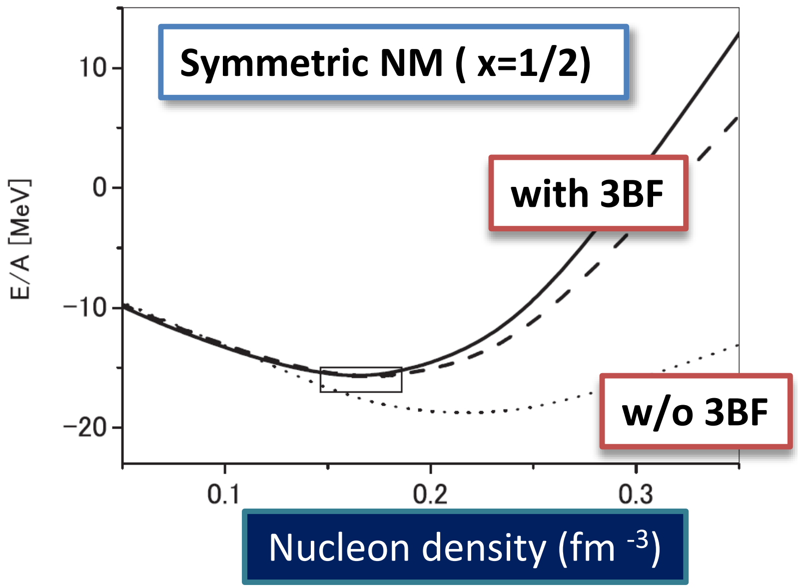
High-density nuclear matter probed by nucleus-nucleus scattering
- its implication to neutron star mass problem -

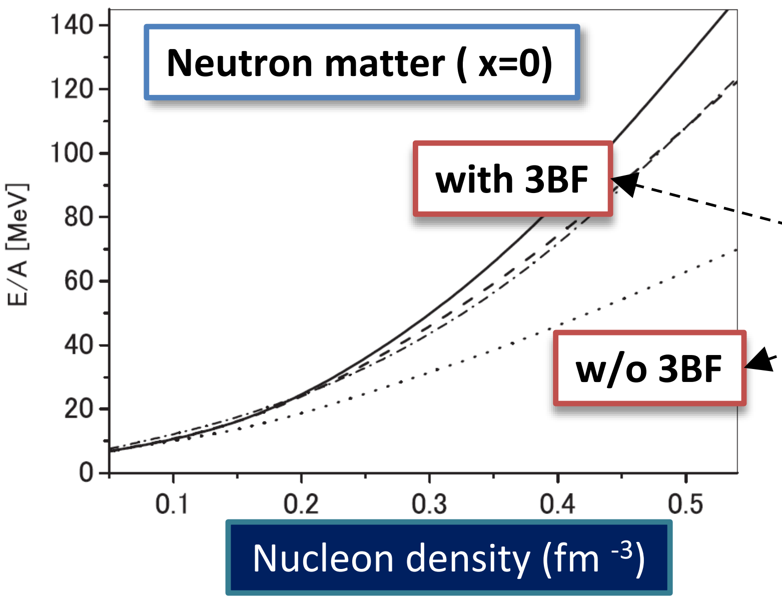
- ✓ To probe the property of **high-density nuclear matter ($\rho = \rho_0 \sim 2\rho_0$)** from the analyses of **nucleus-nucleus scattering** using **Microscopic interaction model** between finite nuclei on the basis of **Brueckner G-matrix** theory including the effects of **3-body & 4-body forces** in the **Multi-Pomeron exchange Potential** (MPP) model.

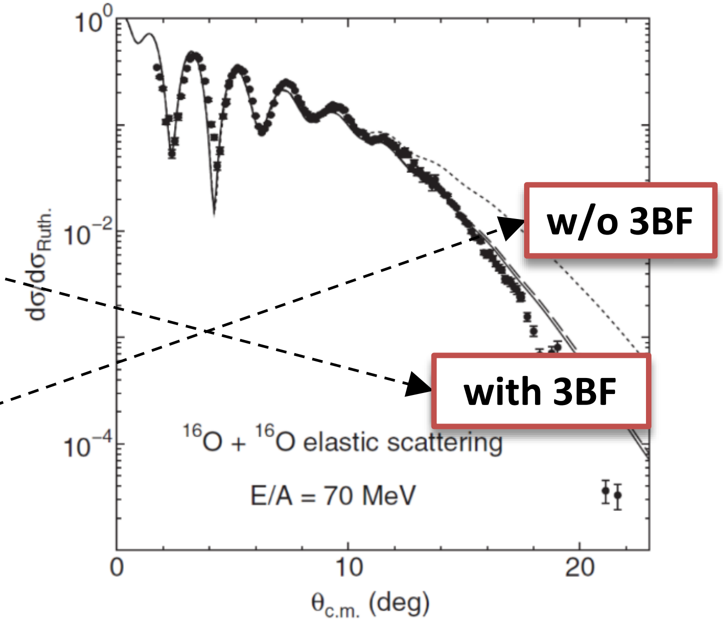
⇩

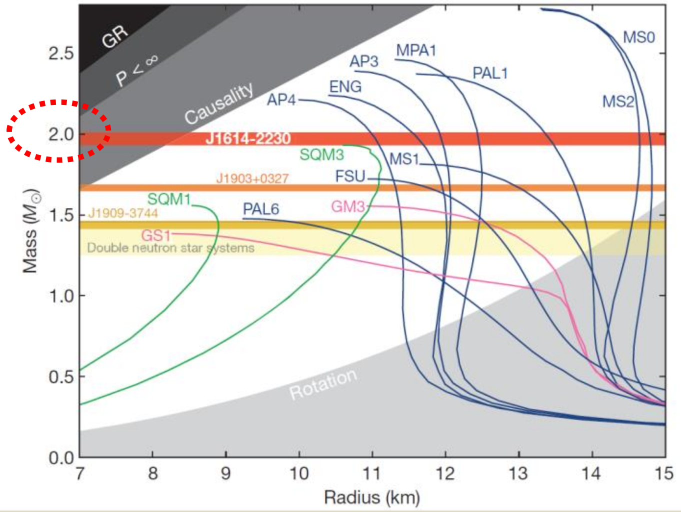
- ✓ **To fix the uncertain strength** of **3-body & 4-body forces** that are essential to determine the **stiffness of baryonic matter at high-ρ** and to see whether it is consistent with $M_{NS}^{(\max)} \cong 2 \times M_{\odot}$.

MULTI-POMERON REPULSION AND THE NEUTRON-STAR MASS

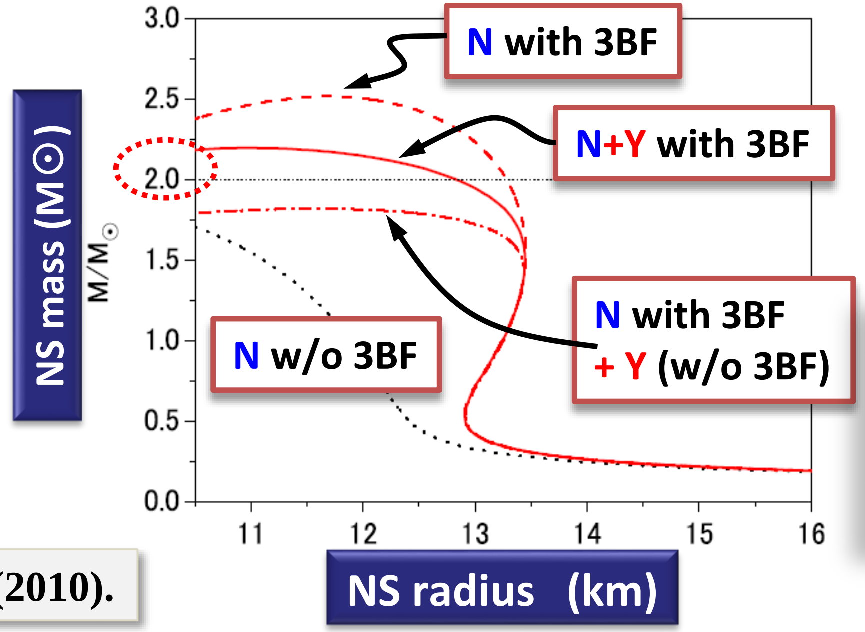








P.B. Demorest et al., Nature 467, 1081 (2010).



Complex G-matrix

> ESC+MPP model

- *Y. Yamamoto, T. Furumoto, N. Yasutake, Th. A. Rijken, PRC 88, 022802(R) (2013)*
- *Y. Yamamoto, T. Furumoto, N. Yasutake, Th. A. Rijken, PRC 90, 045805 (2014)*

● Y. Yamamoto et al., Phys.Rev.C 88, 045805 (2014)

Brueckner G-matrix generated by **SU(3)-based BB interaction model (ESC08c):**

● Th. A. Rijkenet al.,, Prog. Theor. Phys. Suppl. **185**, 14 (2010)

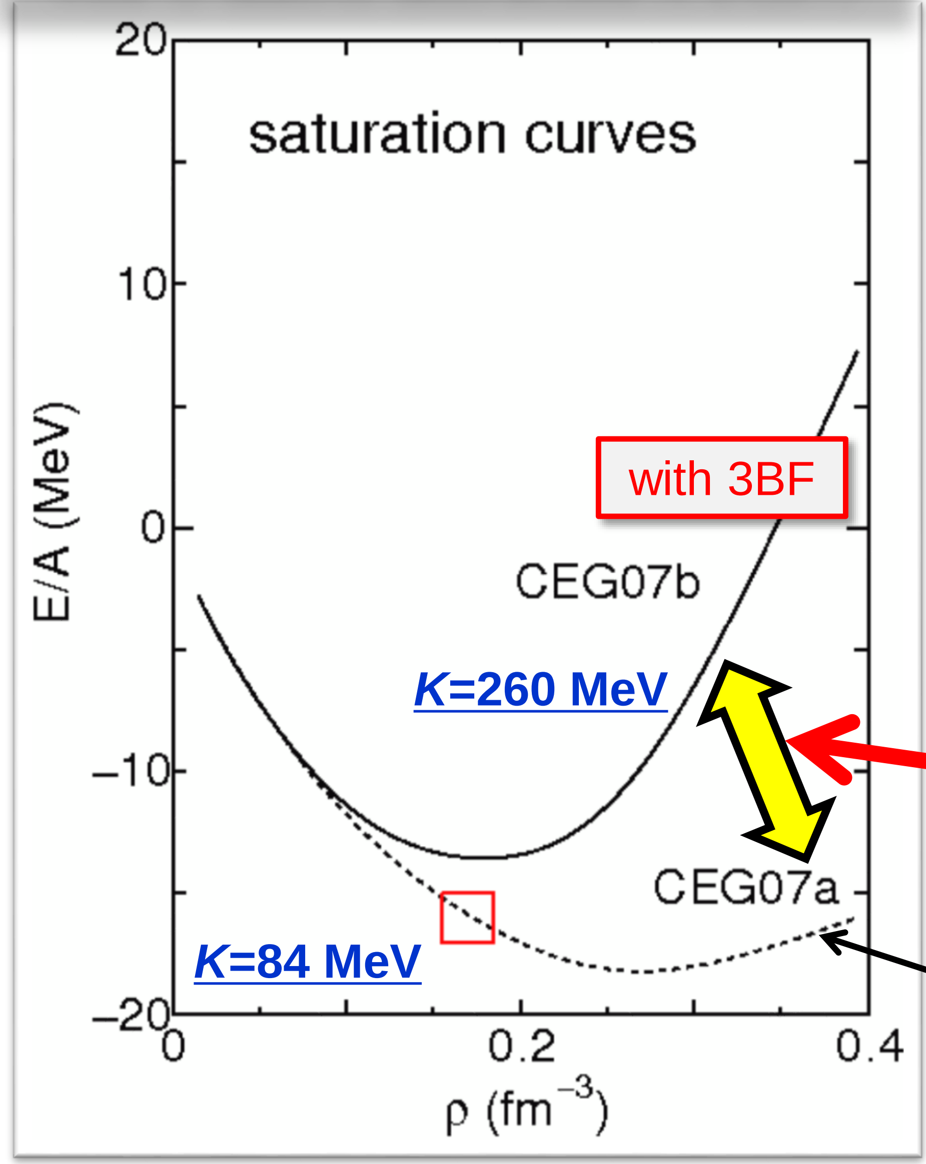
1) **NN, NY, YY** interactions are treated **on the same footing**: **SU(3)**

2) Effects of the **3-body force (3BF)** and **4-body force (4BF)** are introduced based on the **Multi-Pomeron-Exchange Potential** (MPP) model, **consistently with the ESC08 modeling** for two-baryon system.

3) **Universal repulsion** among three baryons (**NNN, YNN, YYN, YYY**)

→ the strength of **the universal 3BF can be determined** through the **sensitivity** of **3BF (NNN)** effects on the **nucleus-nucleus scattering experiments.**

Saturation cruves of Symmetric NM with G-matrix interaction（CEG07）

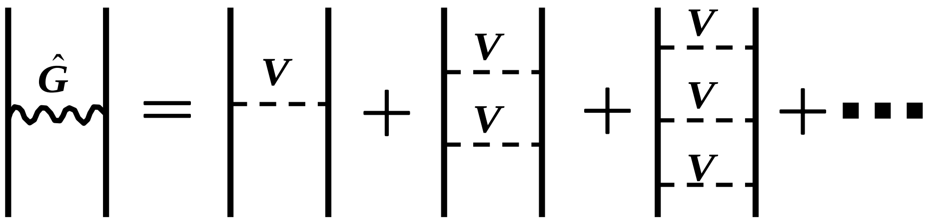


Importance of 3BF effect

w/o 3BF

Bruckner Theory (G-matrix)

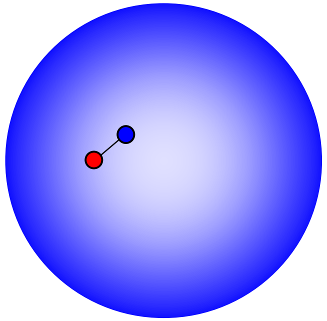
- **Effective interaction in infinite nuclear matter (NM)**
- Solve the **Bethe-Goldstone equation** in NM with a constant desity ρ
- Summing-up of the **ladder diagram**
  with Medium effects（Pauli effects, Binding effect etc.）

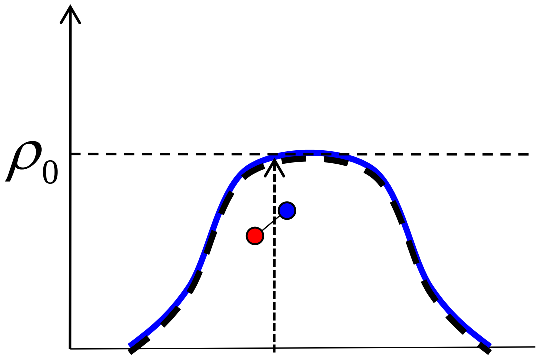


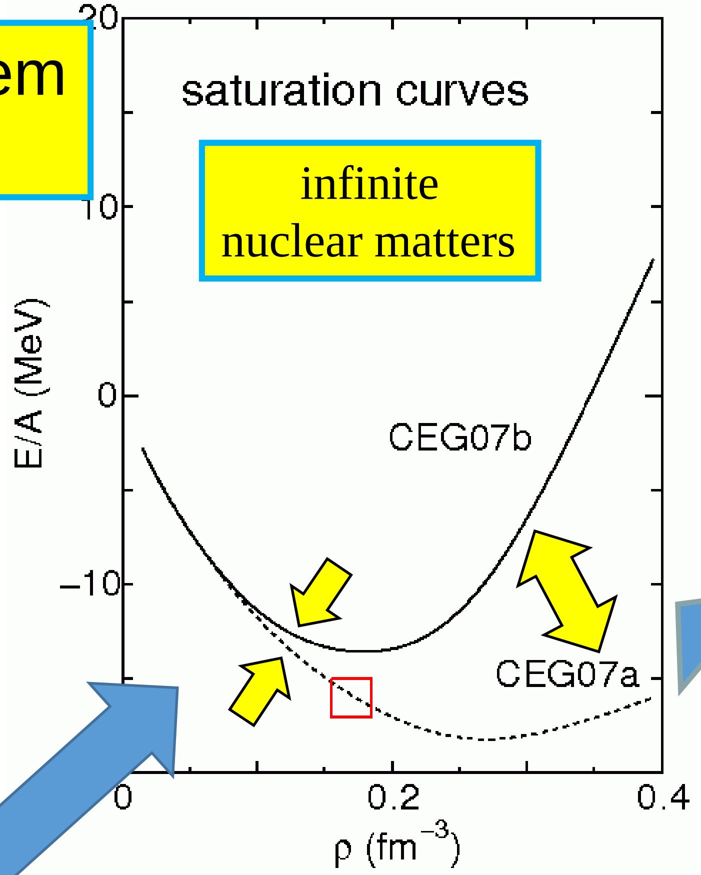
T.Furumoto, Y. Sakuragi , Y. Yamamoto, PRC 79, 011601(R) (2009)

Effective interaction in infinite NM → applied to finite system in local-density approx.(LDA)

nucleon-nucleus (NA) system
(one nuclear matter)

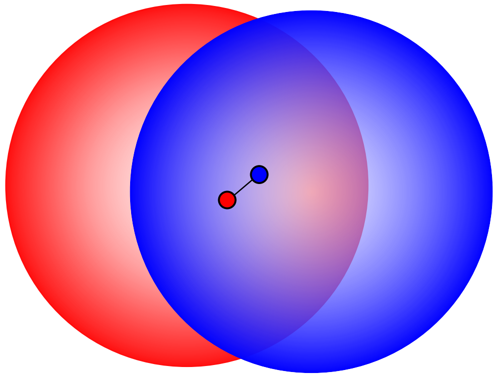


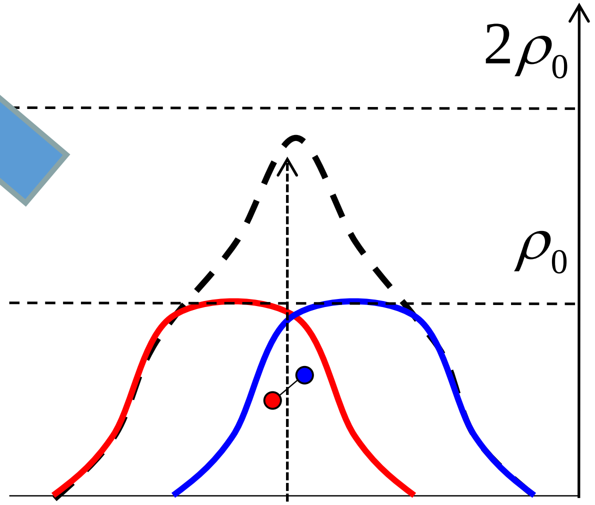




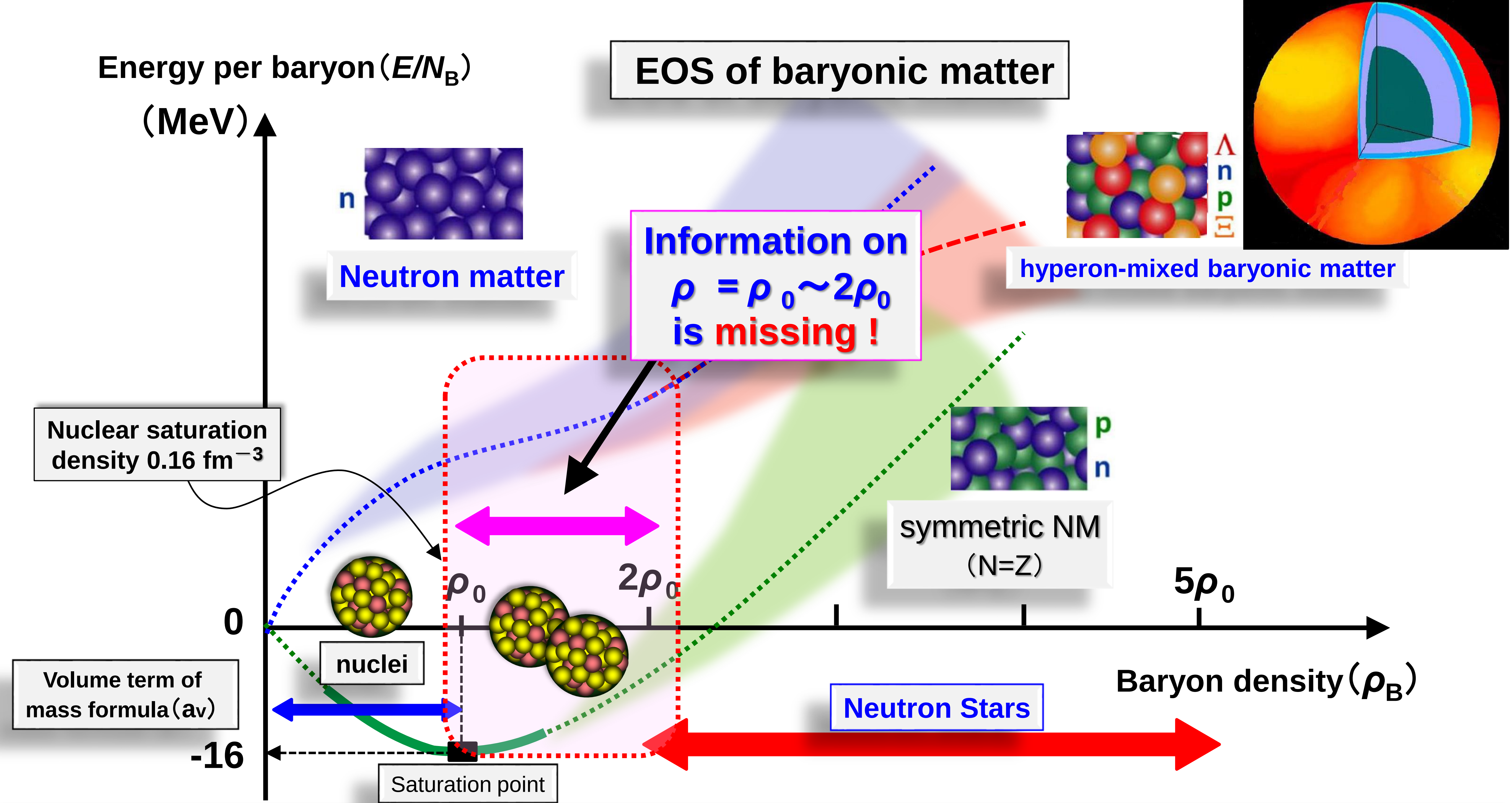
low-ρ ⇔ high-ρ

nucleus-nucleus (A-A) system
(overlapped nuclear matters)

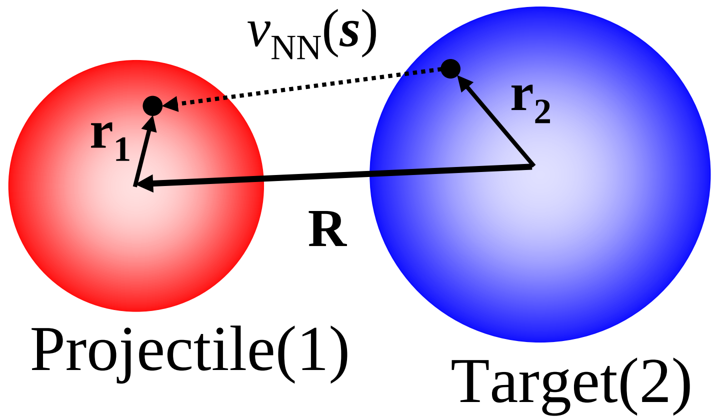




EOS of baryonic matter



Double-Folding model Potential (DFM Potential)



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

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

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

Frozen-density approx. (FDA)

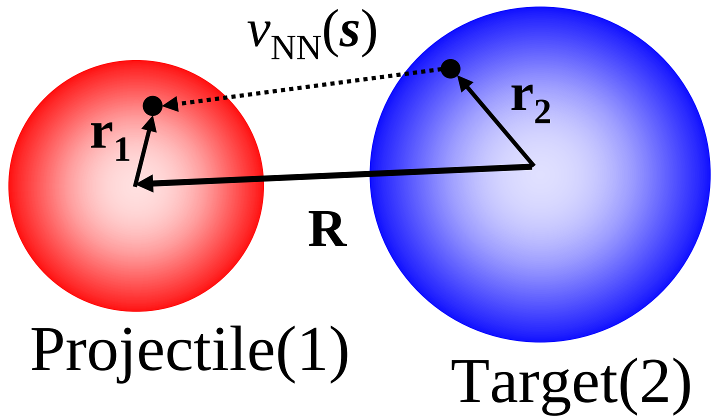
$$\rho = \rho_1 + \rho_2$$

Complex G-matrix interaction (CEG07/MP)

$$\boxed{v_{D,EX} = v_{D,EX}^{(real)} + i v_{D,EX}^{(imag)}}$$

1) T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC 78, 044610 (2008); PRC 80, 044614 (2009)
2) Y. Yamamoto, T. Furumoto, N. Yasutake, and Th. A. Rijken, PRC 88; 045805 (2014)

Double-Folding model Potential (DFM Potential)



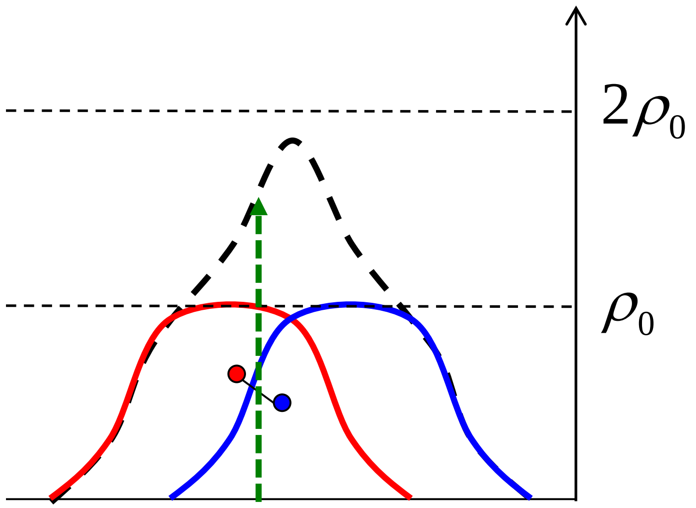
$$U(\mathbf{R}) = \int \rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2)\, \boxed{v_D(\mathbf{s};\rho,E)}\, d\mathbf{r}_1 d\mathbf{r}_2$$

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

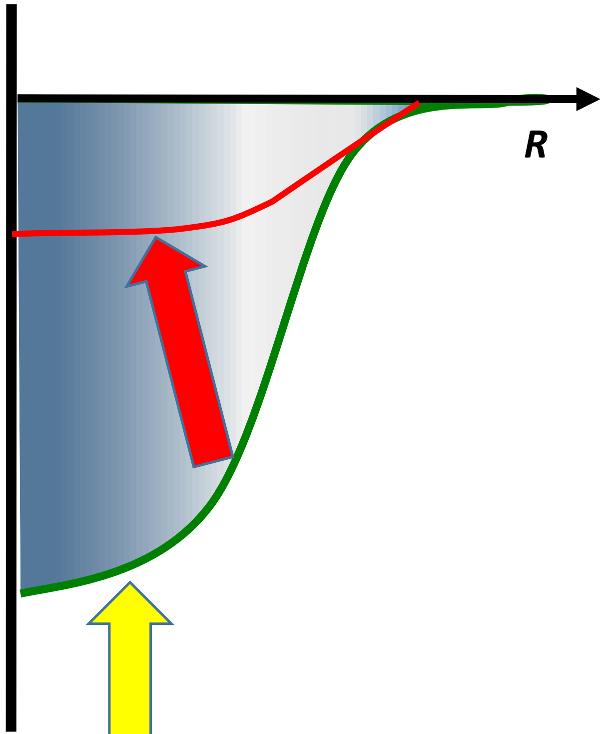
$$= V_{DFM}(\mathbf{R}) + iW_{DFM}(\mathbf{R})$$

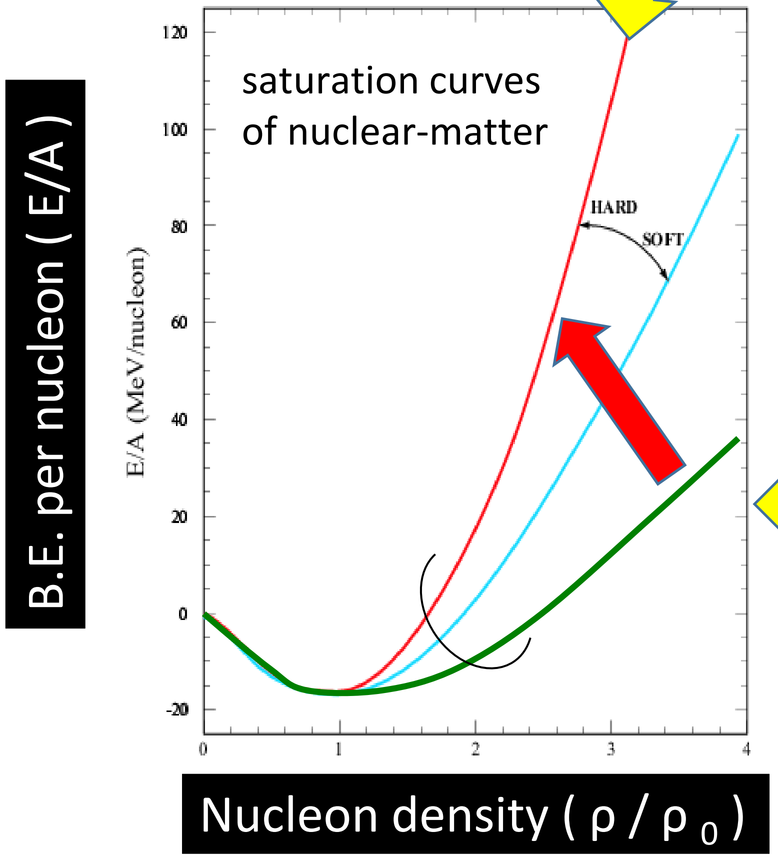
Frozen-density approx. (FDA)

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



- *If the nuclear matter is* ***hard****, the central depth of the potential become* ***shallow****.*





- *If the nuclear matter is* ***soft****, the central depth of the potential may become* ***deep****.*

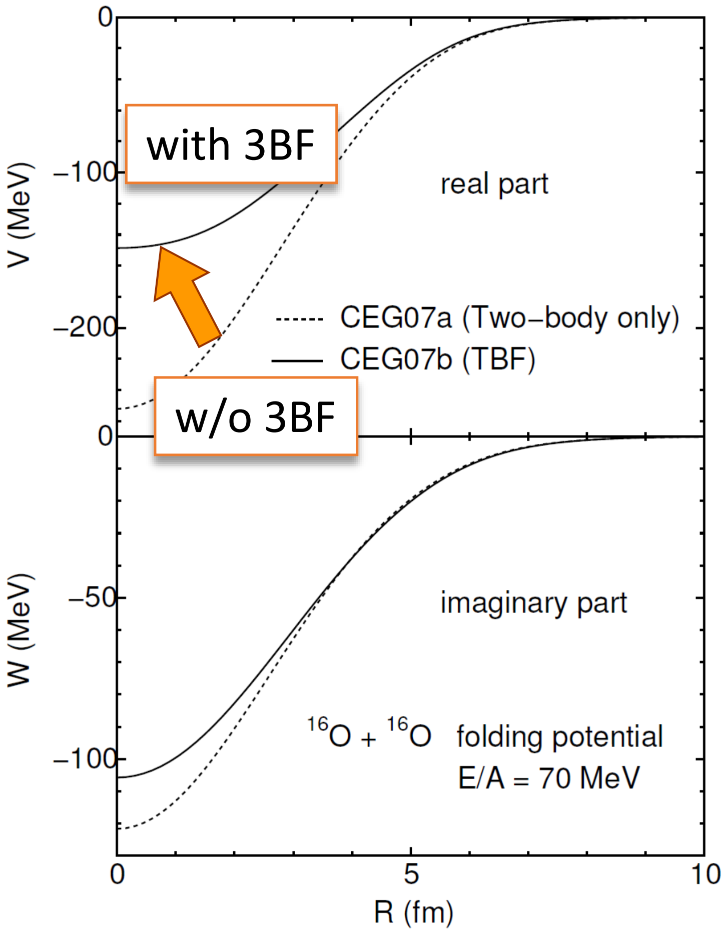
$^{16}O+^{16}O$: bench-mark system to test DFM

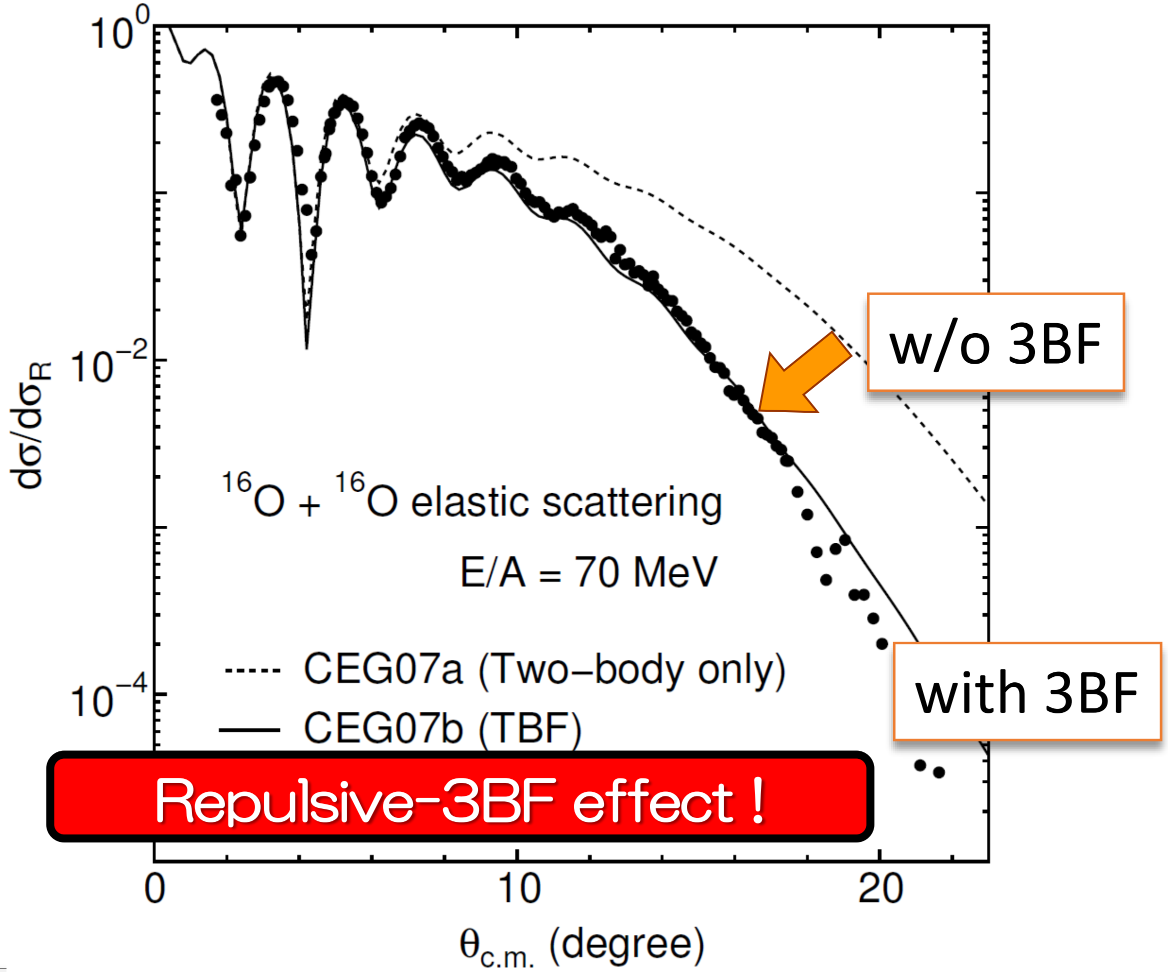
Frozen-density approx. (FDA)

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

$^{16}O+^{16}O$ Elastic Scattering at *E/A* = 70 MeV : DFM with CEG07

⇒ decisive effect of Three-body force (mainly TBR) is clearly observed !





T.Furumoto, Y. Sakuragi , Y. Yamamoto, PRC 79, 011601(R) (2009)

Exp.: F. Nuoffer et al., Nuovo Cimento A 111, 971 (1998).

Multi-Pomeron Potential (MPP) :

▪ *Y. Yamamoto, T. Furumoto, N. Yasutake, and Th. A. Rijken, PRC 88, 022802(R) (2013); PRC 88, 045805 (2014)*

✓ **For *N*− tupole Pomeron vertex, we tale the Lagrangian :**

$$\mathcal{L}_N = g_P^{(N)} \mathcal{M}^{4-N} \sigma_P^N(x)/N!$$

⇒ ***N*-body local potential by Pomeron exchange is written as** →

$$V(\mathbf{x}'_1, \ldots, \mathbf{x}'_N; \mathbf{x}_1, \ldots, \mathbf{x}_N) \equiv V(\mathbf{x}_1, \ldots, \mathbf{x}_N)\, \Pi_{i=1}^N \delta(\mathbf{x}'_i - \mathbf{x}_i),$$

$$V(\mathbf{x}_1, \ldots, \mathbf{x}_N) = g_P^{(N)} g_P^N \left\{ \int \frac{d^3k_i}{(2\pi)^3} e^{-i\mathbf{k}_i\cdot\mathbf{x}_i} \right\} \times (2\pi)^3 \delta\left(\sum_{i=1}^N \mathbf{k}_i\right) \times \Pi_{i=1}^N [\exp(-\mathbf{k}_i^2)] \mathcal{M}^{4-3N},$$

⇒ **Effective two-body potential in baryonic medium (*ρ*–dependent)** →

$$V_{eff}^{(N)}(\mathbf{x}_1, \mathbf{x}_2) = \rho_{NM}^{N-2} \int d^3x_3 \ldots \int d^3x_N\, V(\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N)$$

$$= g_P^{(N)} g_P^N \frac{\rho_{NM}^{N-2}}{\mathcal{M}^{3N-4}} \frac{1}{\pi\sqrt{\pi}} \left(\frac{m_P}{\sqrt{2}}\right)^3 \times \exp\left(-\frac{1}{2} m_P^2 r_{12}^2\right), \quad (3)$$

Multi-Pomeron Potential (MPP) :

- Y. Yamamoto, T. Furumoto, N. Yasutake, and Th. A. Rijken, PRC 88, 022802(R) (2013); PRC 88, 045805 (2014)

✓ N=3 (effective 3BF) →

$$V_{\rm eff}^{(3)}(r) = g_P^{(3)}(g_P)^3 \frac{\rho}{\mathcal{M}^5} F(r),$$

✓ N=4 (effective 4BF) →

$$V_{\rm eff}^{(4)}(r) = g_P^{(4)}(g_P)^4 \frac{\rho^2}{\mathcal{M}^8} F(r),$$

$$F(r) = \frac{1}{4\pi}\frac{4}{\sqrt{\pi}}\left(\frac{m_P}{\sqrt{2}}\right)^3 \exp\left(-\frac{1}{2}m_P^2 r^2\right)$$

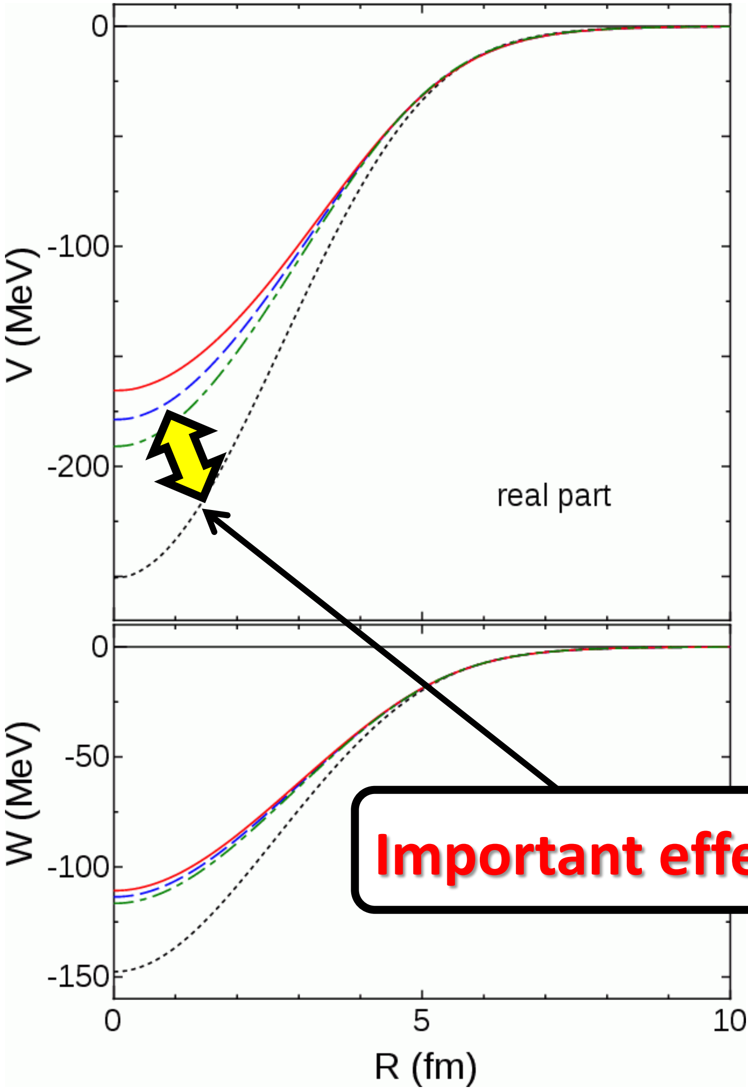
N=3 & N=4

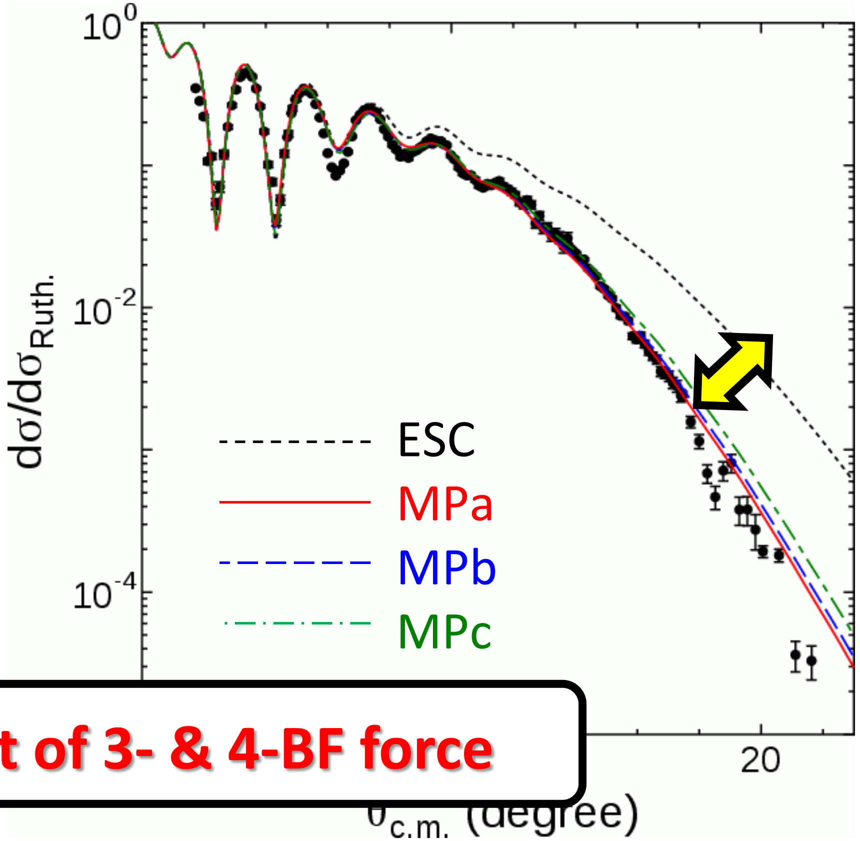
⇒ **Effective two-body potential** in baryonic medium (ρ–dependent) →

$$V_{eff}^{(N)}(\mathbf{x}_1,\mathbf{x}_2) = \rho_{NM}^{N-2}\int d^3x_3 \ldots \int d^3x_N\, V(\mathbf{x}_1,\mathbf{x}_2,\ldots,\mathbf{x}_N)$$

$$= g_P^{(N)} g_P^N \frac{\rho_{NM}^{N-2}}{\mathcal{M}^{3N-4}} \frac{1}{\pi\sqrt{\pi}}\left(\frac{m_P}{\sqrt{2}}\right)^3 \times \exp\left(-\frac{1}{2}m_P^2 r_{12}^2\right), \qquad (3)$$

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



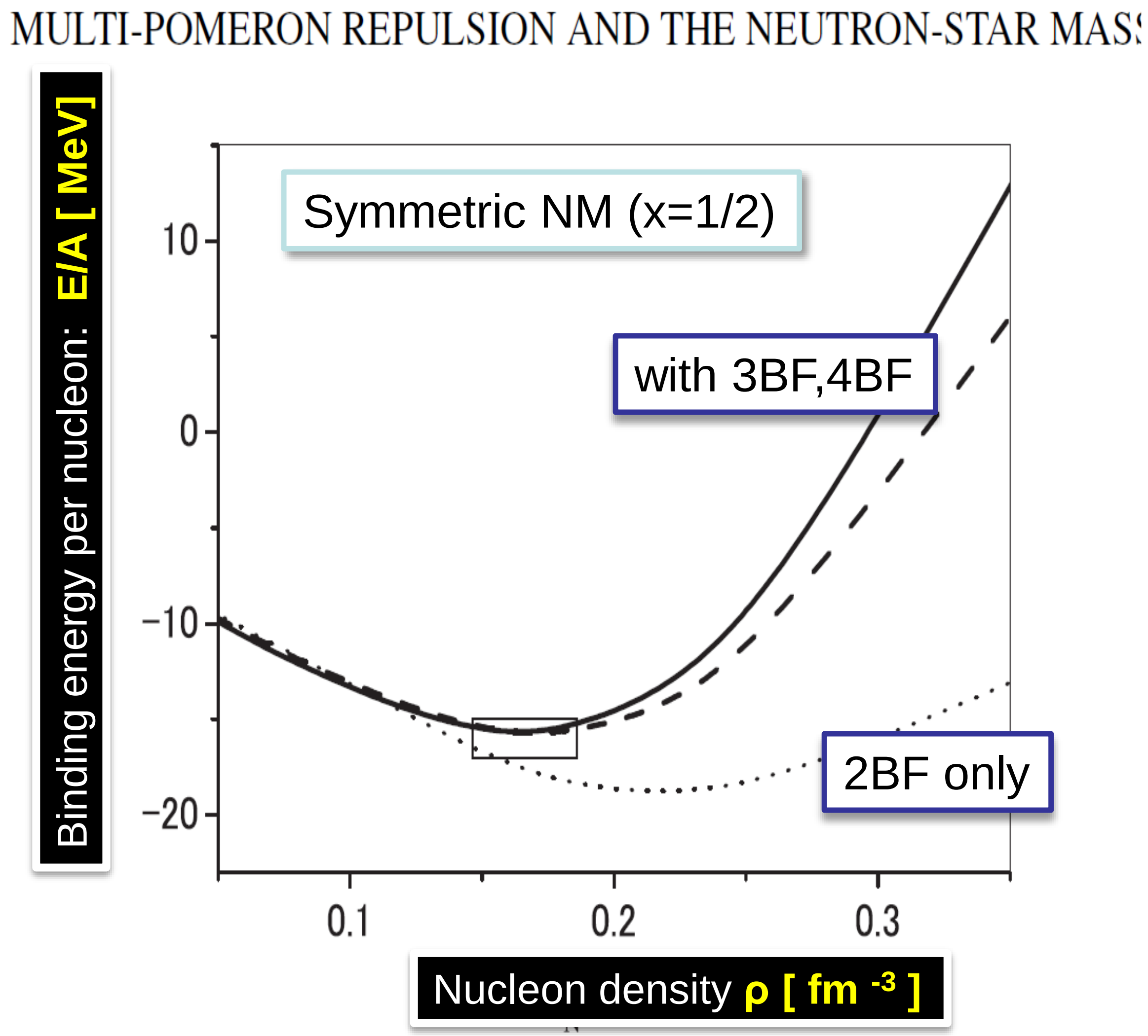


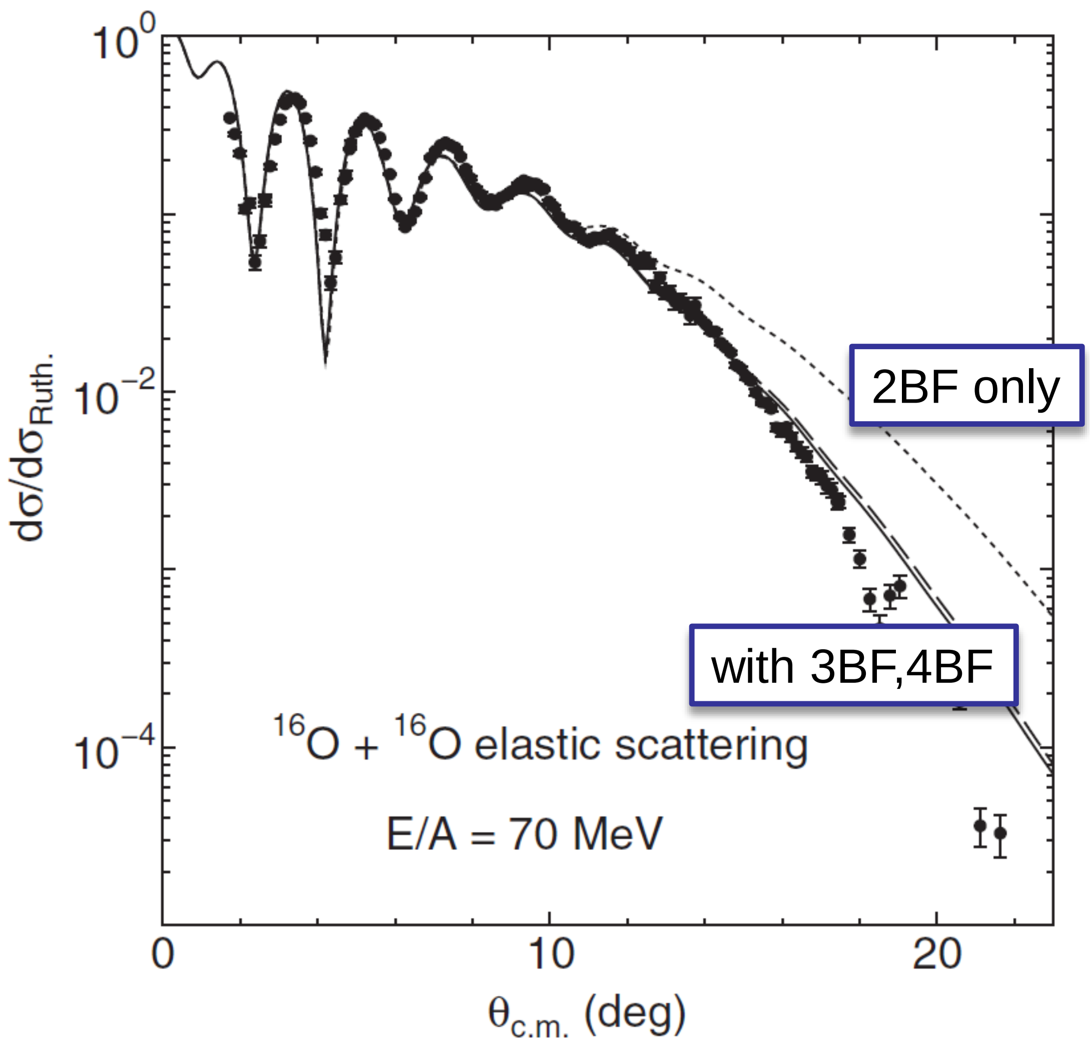
Important effect of 3- & 4-BF force

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

Effects of Three & Four-body force（with multi-Pomeron exchange model)

Y. Yamamoto, T. Furumoto, N. Yasutake, Th. A. Rijken, PRC 88, 022802(R) (2013)





Parameters for MPP model for 3BF and 4BF determined **by A-A scattering analysis** and the corresponding values (E_0, K, E_{sym}, L) for saturation curves of symmetric nuclear matter at $\rho = \rho_0$

at $\rho = \rho_0$	MPa	MPb	MPc	ESC (NN only)	Exp. [1]
$g_P^{(3)}$	2.34	2.94	2.34	0	-
$g_P^{(4)}$	30.0	0	0	0	-
E_0 (MeV)	-15.8	-15.8	-15.6	-	-16
K (MeV)	310	280	260	84	
E_{sym} (MeV)	33.1	33.1	32.7	-	32.5 ± 0.5 [1]
L (MeV)	70	69	67	-	70 ± 15 [1]

$$V_{\rm eff}^{(3)}(r) = g_P^{(3)}(g_P)^3 \frac{\rho}{\mathcal{M}^5} F(r),$$

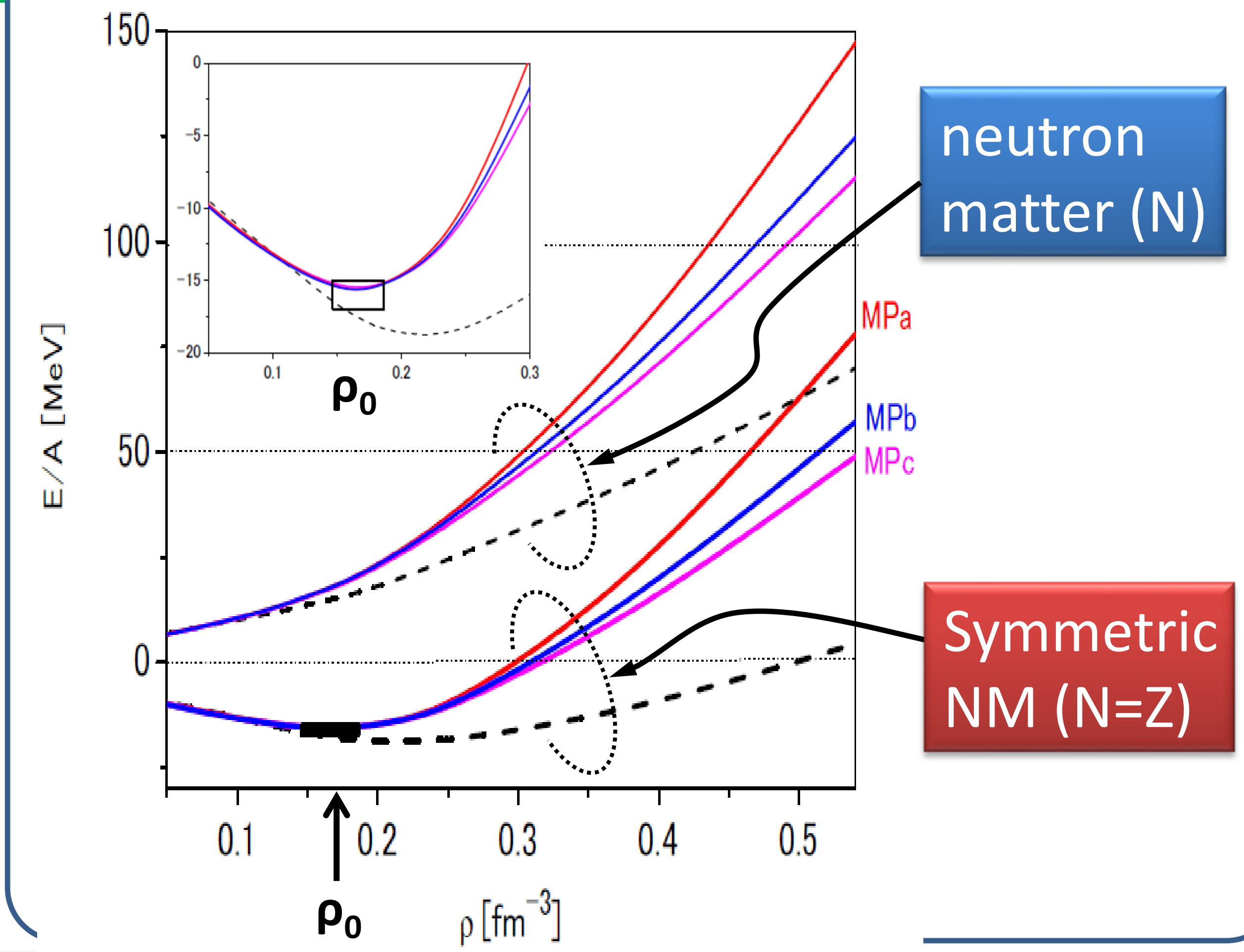
$$V_{\rm eff}^{(4)}(r) = g_P^{(4)}(g_P)^4 \frac{\rho^2}{\mathcal{M}^8} F(r),$$

$$F(r) = \frac{1}{4\pi}\frac{4}{\sqrt{\pi}}\left(\frac{m_P}{\sqrt{2}}\right)^3 \exp\left(-\frac{1}{2}m_P^2 r^2\right)$$

Y. Yamamoto, T. Furumoto, N. Yasutake, Th. A. Rijken, PRC90, 045805 (2014)

1) P. Möller, et al., PRL**108**, 052501 (2012).

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 of the ***repulsive*** and attractive parts

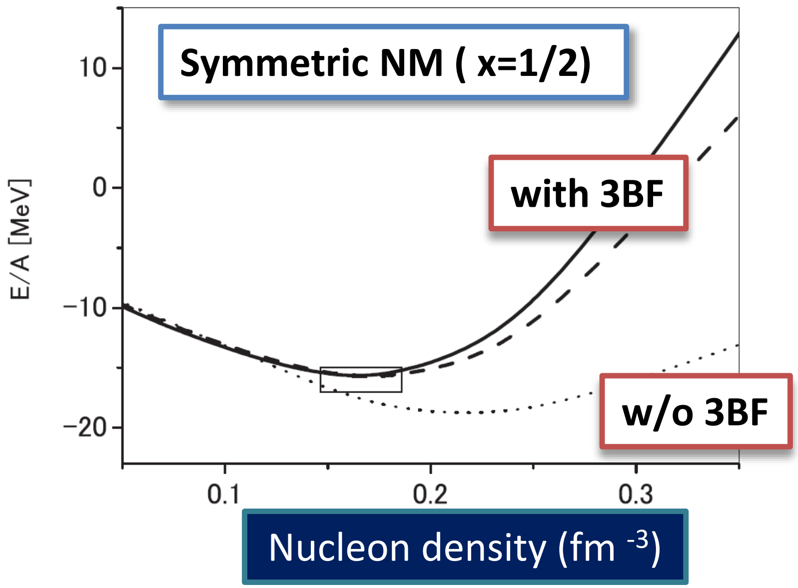


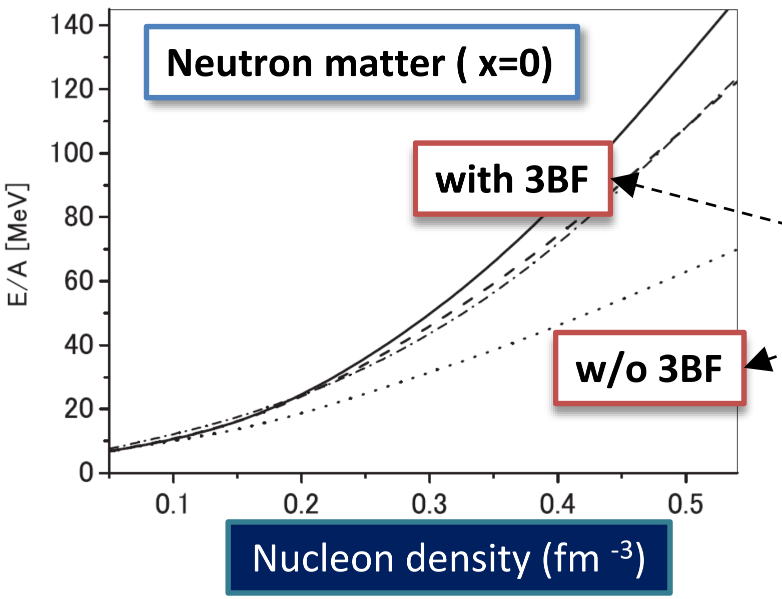
Y. Yamamoto, T. Furumoto, N. Yasutake, and Th. A. Rijken, Phys.Rev.C 90, 045805 (2014)

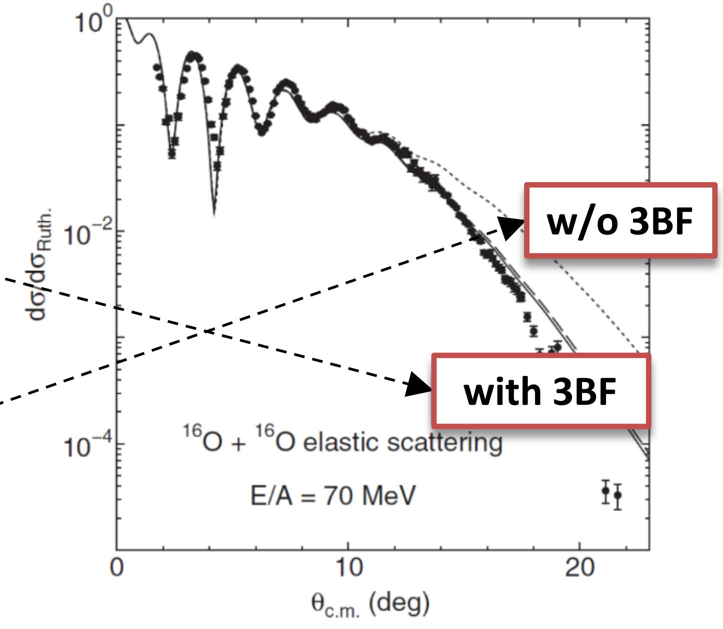
MP-model (MPa, MPb, MPc)
(multi-pomelon exchange model)

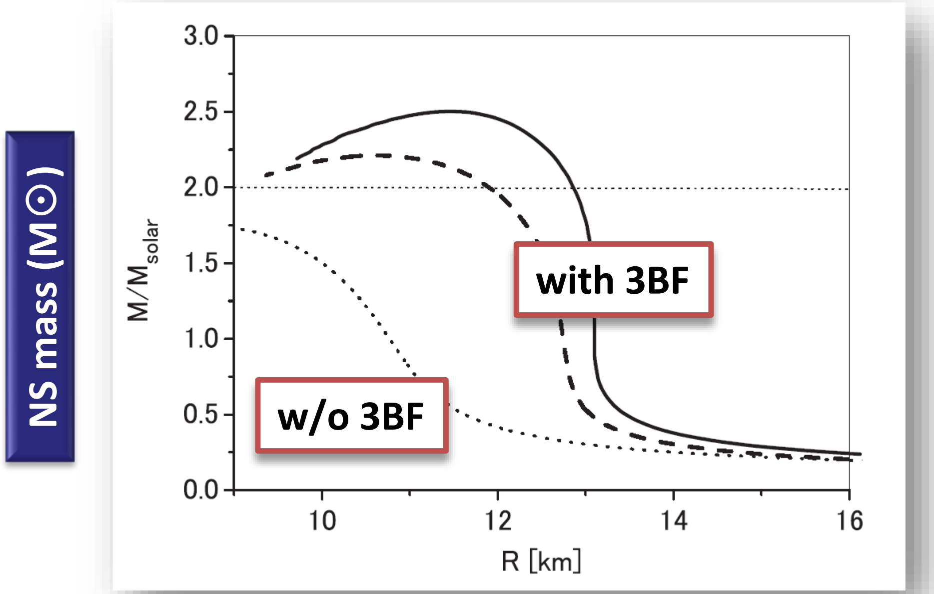
ESC : ***two-body*** only
MPa : with ***three- & four-body*** forces
MPb : with ***three-body*** forces
MPc : with ***three-body*** forces

MULTI-POMERON REPULSION AND THE NEUTRON-STAR MASS









Complex G-matrix

> ESC+MPP model

- *Y. Yamamoto, T. Furumoto, N. Yasutake, Th. A. Rijken, Phys.Rev.C 88, 022802(R) (2013)*
- *Y. Yamamoto, T. Furumoto, N. Yasutake, Th. A. Rijken, Phys.Rev.C 90, 045805 (2014)*

Hyperon mixing ratio as a function of baryon density

MPa (with 3&4BF)

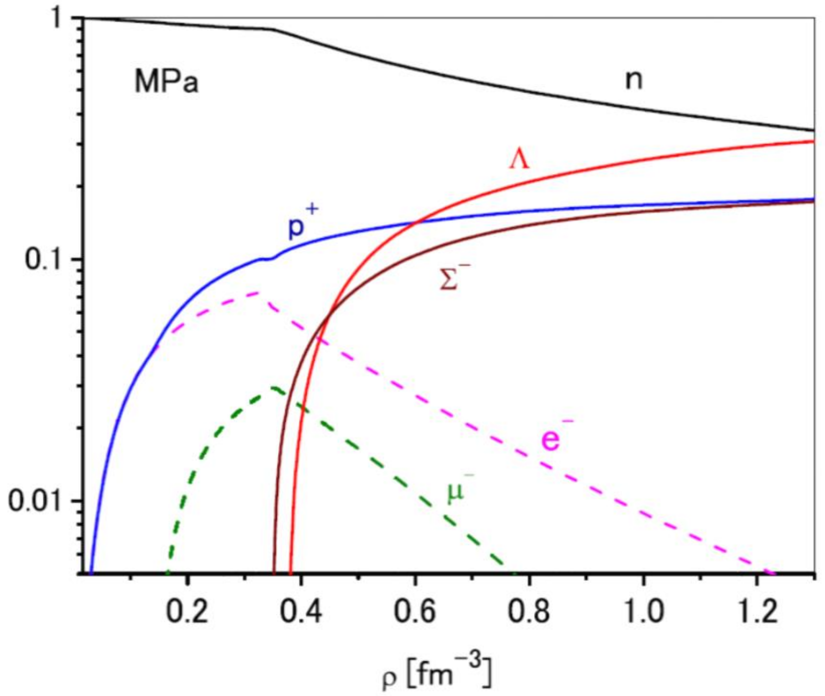


FIG. 8. (Color online) Composition of hyperonic neutron-star matter in the case of MPa.

ESC (2BF only)

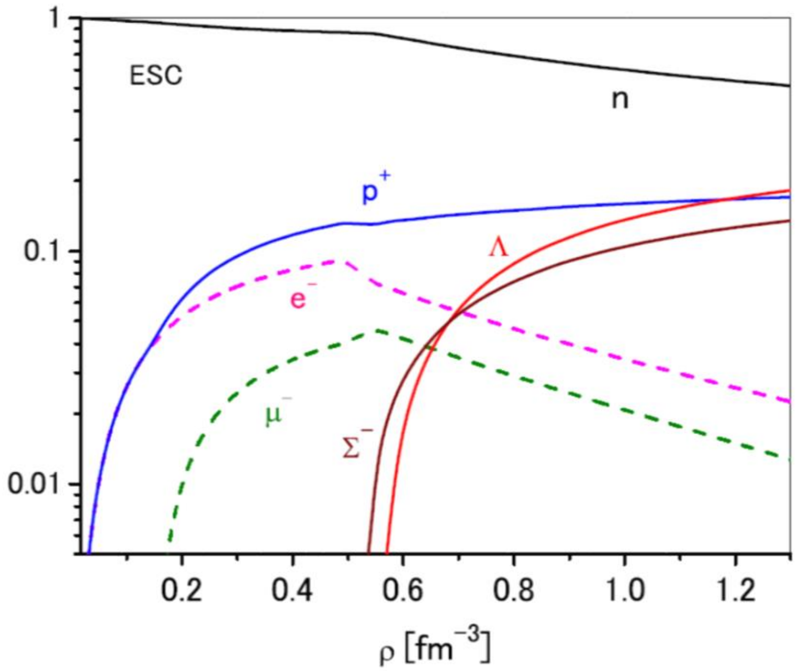
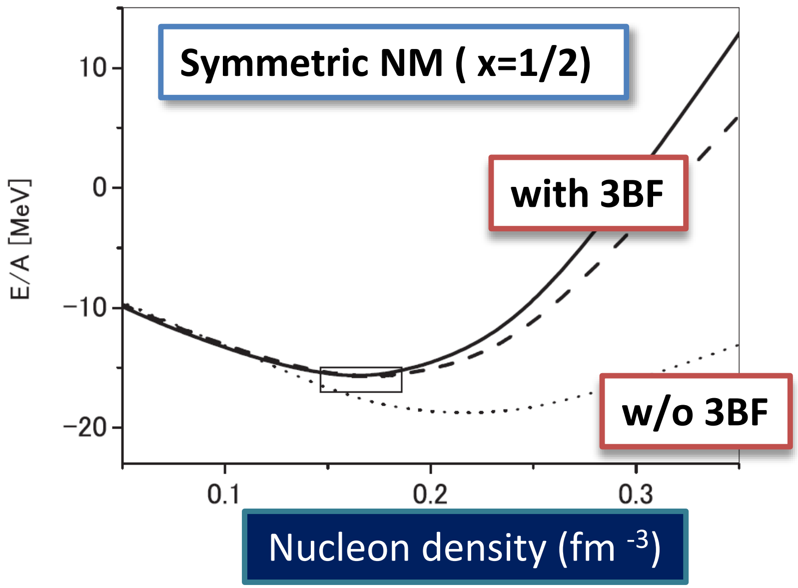
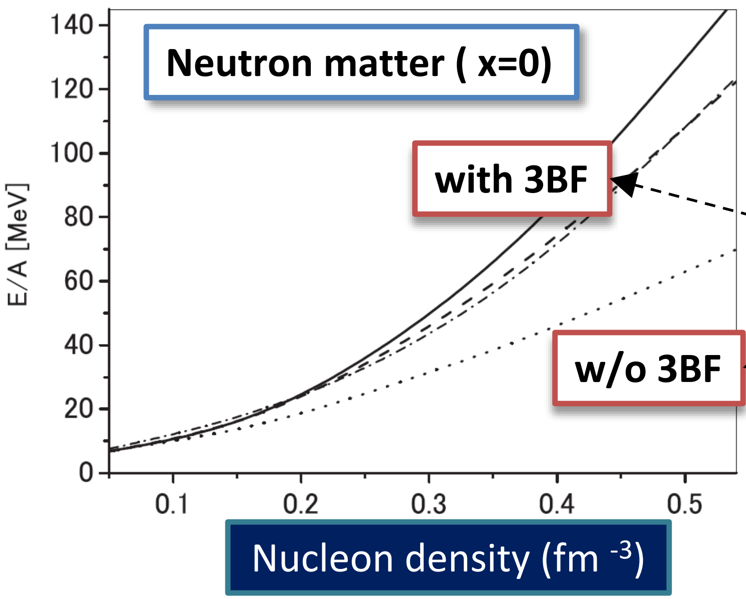


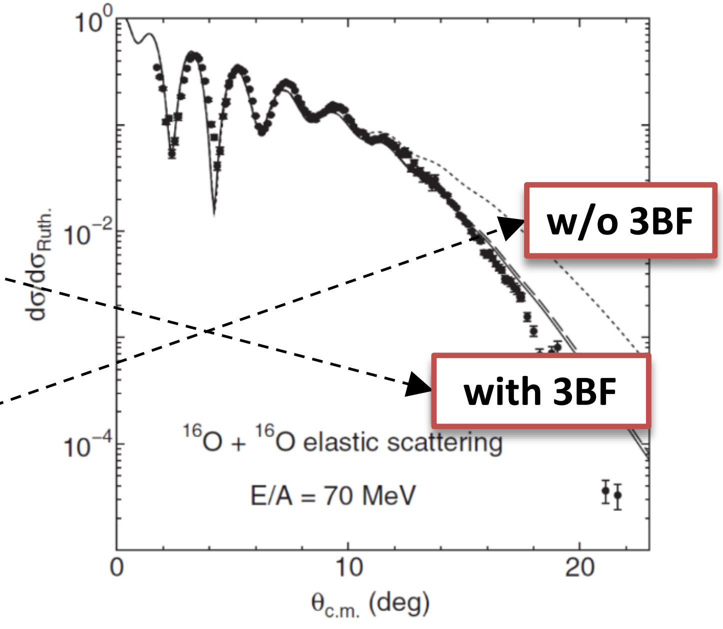
FIG. 9. (Color online) Composition of hyperonic neutron-star matter in the case of ESC.

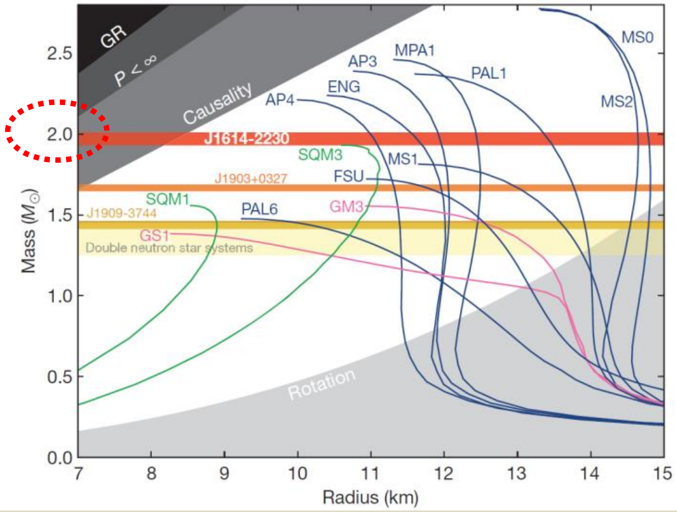
Y. Yamamoto, T. Furumoto, N. Yasutake and Th. A. Rijken, Phys. Rev. C 90, 045805 (2014)

MULTI-POMERON REPULSION AND THE NEUTRON-STAR MASS



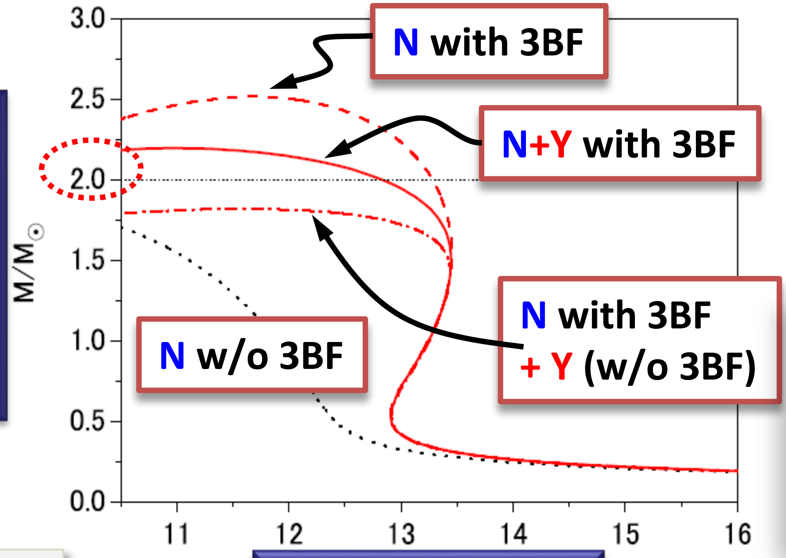






P.B. Demorest et al., Nature 467, 1081 (2010).

NS mass (M⊙)



NS radius (km)

Complex G-matrix

> ESC+MPP model

- *Y. Yamamoto, T. Furumoto, N. Yasutake, Th. A. Rijken, PRC 88, 022802(R) (2013)*
- *Y. Yamamoto, T. Furumoto, N. Yasutake, Th. A. Rijken, PRC 90, 045805 (2014)*

Conclusion: ← Our strategy

- ✓ The 3BF is very sensitive to **nucleus-nucleus (A-A) elastic scattering.**
- ✓ We determine the strength of univeral **3,4-baryon repulsion** by the analyses of A-A elastic scattering with the *G*-matrix folding model.
- ✓ Then, construct the EOS of neutron-star matter,
- ✓ That leads to a stiff EOS, enough to give the observed neutron-star mass ($M_{NS} \approx 2M_{\odot}$) even if we take account of the **hyperon mixing.**