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Nuclear Symmetry Energy and its Effect on Neutron Stars

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CONTENTS

1. Introduction

- The nuclear symmetry energy a_{sym} plays an important role to determine the composition of nuclear matter（NM).

$$E(N,Z)/A = a_{vol} + a_{sym}(N-Z)^2/A^2$$
$$+ a_{surf}A^{-1/3} + a_{Coul}Z^2/A^{4/3} + \cdots$$

a_{vol} : negative

a_{sym}, a_{surf}, a_{Coul} : positive

1) $a_{sym} = 0$

$Z = 0$ i.e. pure neutron matter

2) a_{sym} = finite, neglecting a_{Coul}

$Z = N$ i.e. symmetric nuclear matter

3) composition of neutron stars（nucleons, hyperons, leptons）

equation of state (EOS)

→ properties of neutron stars

2. Nuclear Symmetry Energy a_{sym}

- a_{sym} depends on two-nucleon potentials

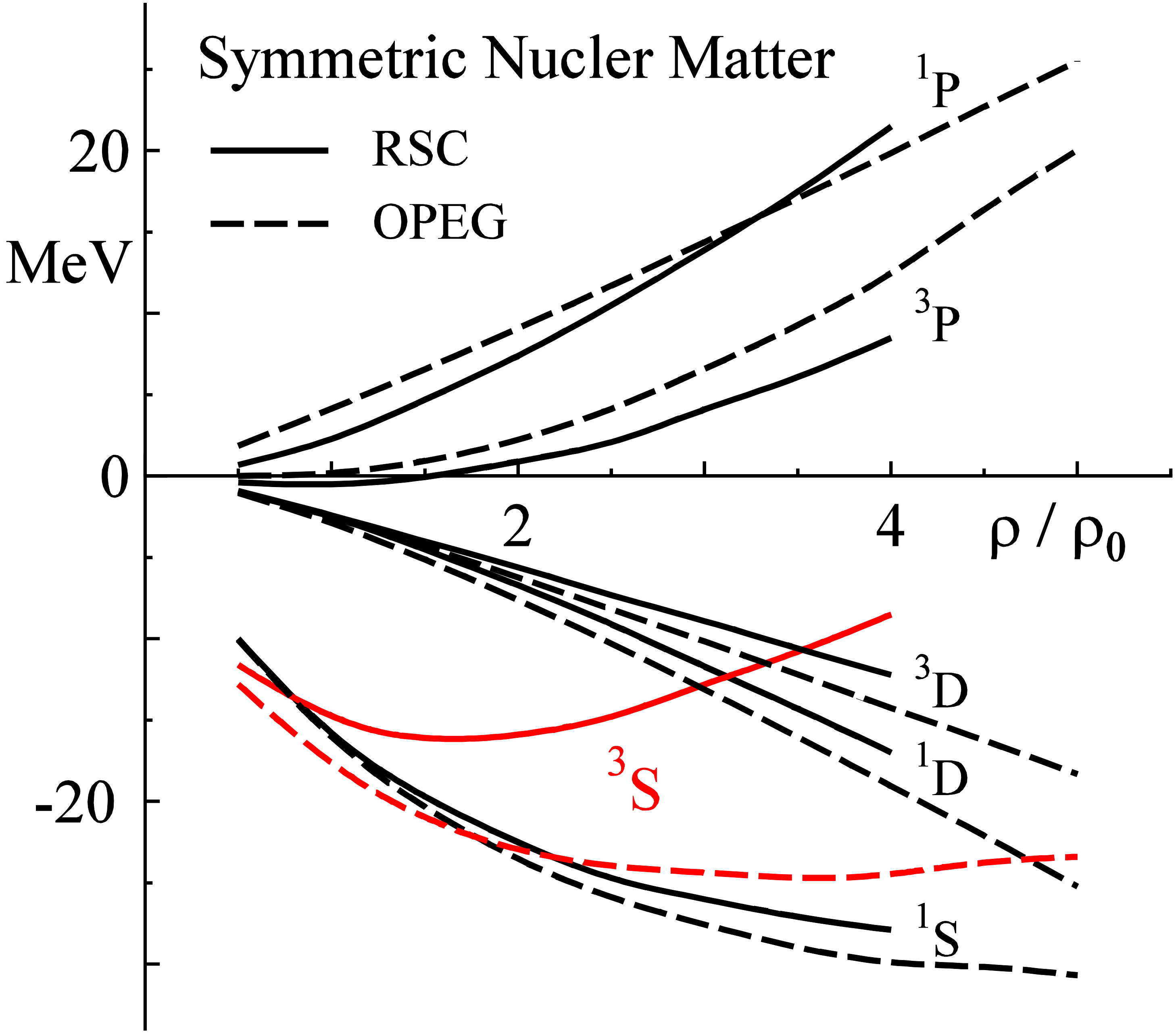
  G-matrix calculation with

  RSC : R.V.Reid, Ann. of Phys. 50(1968), 411.

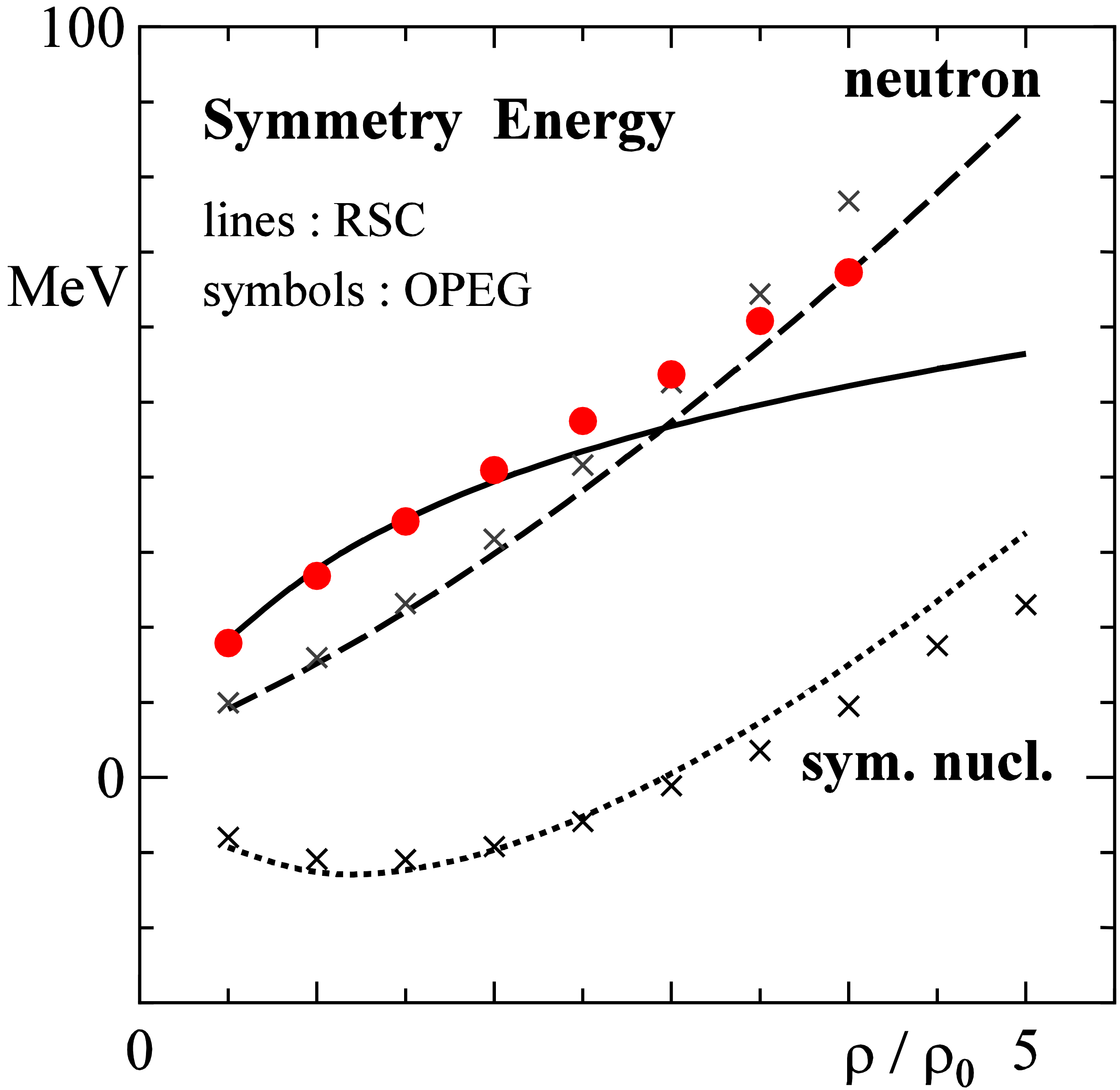
  OPEG : R.Tamagaki, Prog. Theor. Phys. 39(1968), 91.

- In case of stronger tensor force (RSC),

  the attractive contribution of ^3S ($-^3D$) is reduced at higher density compared with the case of weaker tensor force (OPEG).

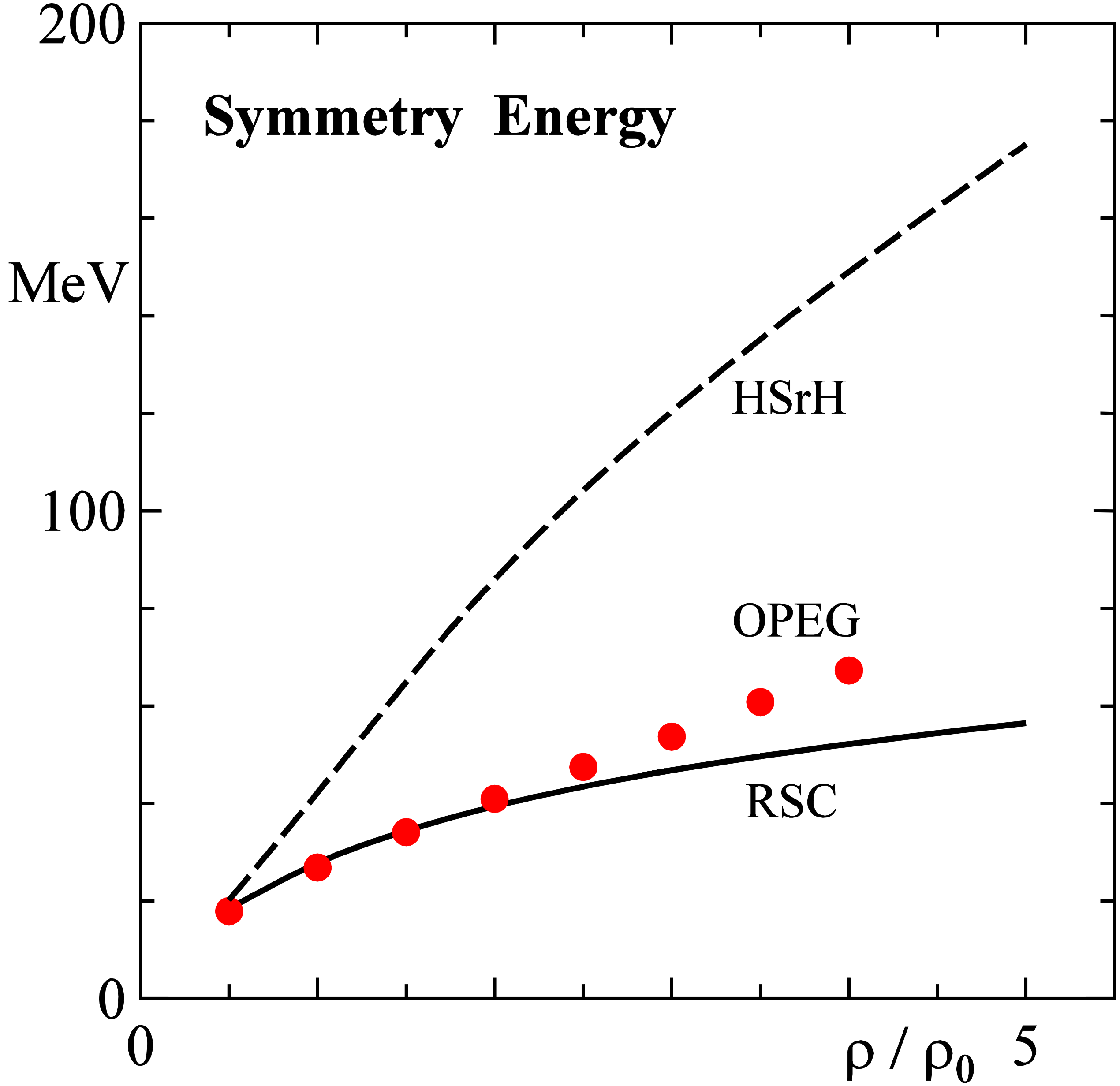


Symmetric Nucler Matter
RSC
OPEG
MeV
20
0
-20
2
4
ρ / ρ_0
^1P
^3P
^3D
^1D
^3S
^1S


100
neutron
Symmetry Energy
lines : RSC
MeV
symbols : OPEG
0
sym. nucl.
0
ρ / ρ0
5

Relativistic Nuclear Model

- C.J.Horowitz and B.D.Serot, Nucl. Phys. A368(1981), 503.
  - relativistic Hartree model with σ, ω, ρ mesons(HSrH)
- a_{sym} is larger than those from G-matrix and steeply depends on the density.
  - kinetic energy term with the density-dependent m*
  - ρ meson contribution linearly depending on the density



Symmetry Energy
MeV
200
100
0
0
ρ / ρ0
5
HSrH
OPEG
RSC

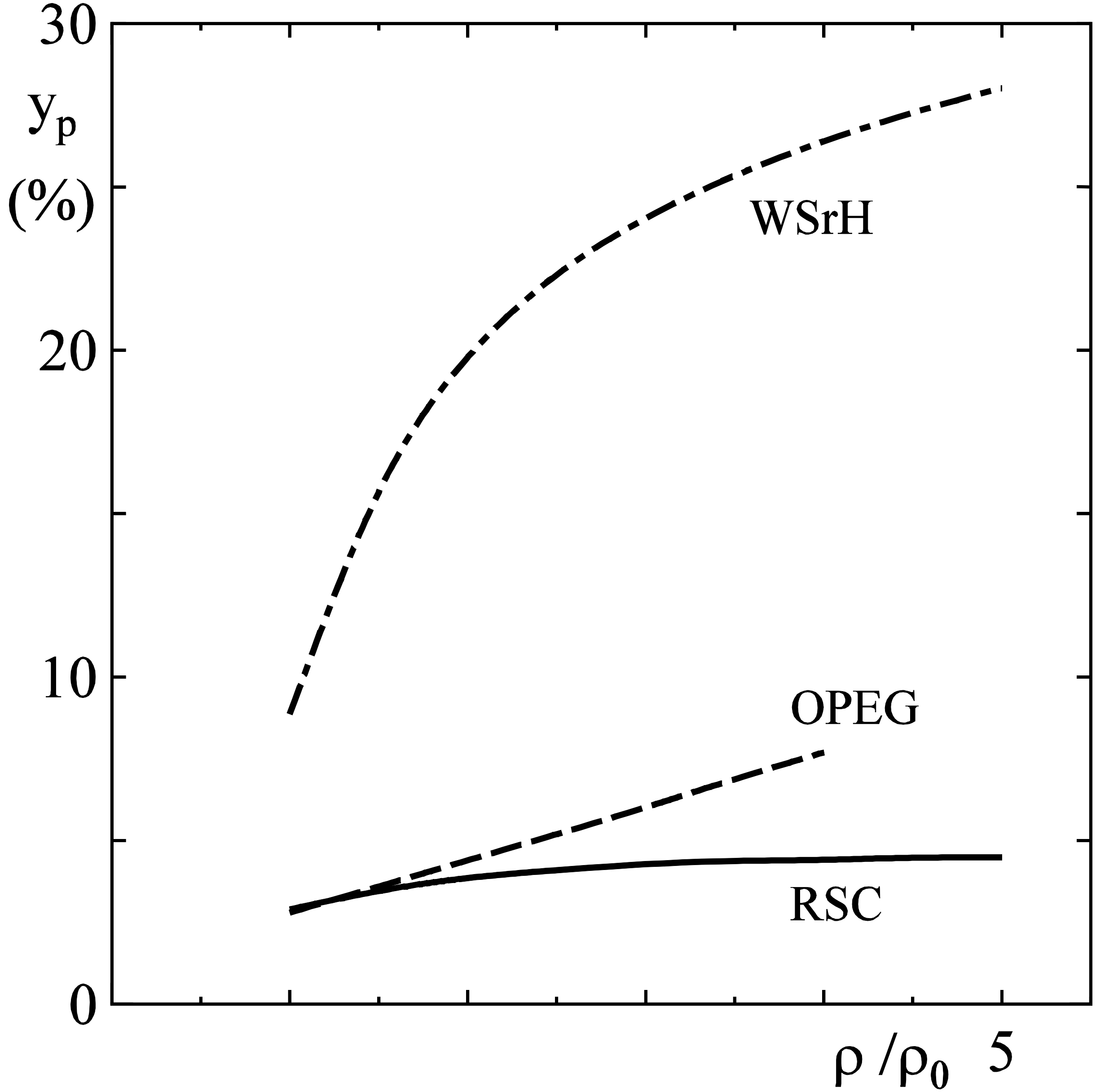
Proton Mixing in Neutron Star Matter

- neutrons, protons, electrons, muons
  - chemical equilibrium
  - charge neutrality
- Simple approximation for energy per nucleon

$$E(\rho,\alpha) = E_0(\rho) + E_2(\rho)\alpha^2$$

$$E_0(\rho) = E(\rho,0), \quad E_2(\rho) = E(\rho,1) - E(\rho,0) = a_{sym}$$

$$\alpha = (\rho_n - \rho_p)/\rho, \quad \rho = \rho_n + \rho_p$$



30
20
10
0
y_p
(%)
WSrH
OPEG
RSC
ρ/ρ_0
5

3. Hyperons in Neutron Stars

3.1 Effective interaction approach

1) Effective interactions are derived from G-matrix calculation with realistic NN, YN, YY interactions.

NN from RSC : ρ- and α-dependent

S.Nishizaki et al., Prog. Theor. Phys. 86(1991), 853.

YN and YY from Nijmegen-D(NHC-D) :

ρ- and y_Y-dependent

S.Nishizaki et al., Prog. Theor. Phys. **105** (1991), 607; **108**(2002), 703.

M.M.Nagels et al., Phys. Rev. **D12**(1975), 744; **D15**(1977), 2547; **D20**(1979), 1633.

realistic NN,YN,YYinteraction ← scattering data, hypernuclei

↓ G-matrix･･･short range correlation

Effective interactions V

density-dependent two-body interaction

(1) NN interaction

V_{NN}(RSC), PTP 86(1991), 853.

$$V(r;\rho,\alpha;\beta,\gamma) = \sum_{i=1}^{5} c_i(r;\rho,\alpha;\beta,\gamma)\cdot e^{-(r/\lambda_i)^2}$$

$$c_i(r;\rho,\alpha;\beta,\gamma) = a_i(\alpha;\beta,\gamma) + b_i(\alpha;\beta,\gamma)(k_F)^{1/2}$$

$$\alpha = (\rho_n - \rho_p)/\rho,\ \beta = {}^1E, {}^3O, {}^3E, {}^1O,\ \gamma = nn, pp, np$$

D.W.L.Sprung and P.K.Banerjee, NP A168(1971), 273.

(2) ΛN, ΛΛ interaction ← G-matrix in (n,Λ)-matter

NHC-D, NHC-F, NHC-Dm

$V_{\Lambda n}$: $\rho = \rho_n + \rho_\Lambda$, $y_\Lambda = \rho_\Lambda / \rho$

$V_{\Lambda p}$: $\rho = \rho_p + \rho_\Lambda$, $y_\Lambda = \rho_\Lambda / \rho$

$V_{\Lambda\Lambda}$: $\rho = \rho_n + \rho_p + \rho_\Lambda$, $y_\Lambda = \rho_\Lambda / \rho$

PTP 105(2001), 607.

(3) Σ^-N, $\Sigma^-\Sigma^-$ interaction ← G-matrix in (n,Σ^-)-matter

NHC-D

$V_{\Sigma^- n}$: $\rho = \rho_n + \rho_{\Sigma^-}$, $y_{\Sigma^-} = \rho_{\Sigma^-} / \rho$

$V_{\Sigma^- p}$: $\rho = \rho_p + \rho_{\Sigma^-}$ (I=3/2), $y_{\Sigma^-} = \rho_{\Sigma^-} / \rho$ I=1/2?

$V_{\Sigma^- \Sigma^-}$: $\rho = \rho_n + \rho_p + \rho_{\Sigma^-}$, $y_{\Sigma^-} = \rho_{\Sigma^-} / \rho$

PTP 108(2002), 703.

2) A ρ-dependent two-body interaction is used as the three-body force to reproduce the saturation properties of symmetric NM.

TNR at higher ρ, TNA at lower ρ

I.E. Lagaris and V.R. Pandharipande, Nucl. Phys. **A359**(1981), 349.

3) EOS is derived by interacting Fermi gas model.

4) Properties of neutron stars are calculated by TOV equations.

R.C. Tolman, Phys. Rev. 55 (1939), 364.

J.R. Oppenheimer and G.M. Volkoff, Phys. Rev. 55 (1939), 374.

Prob. $\rho_s = 1.19\rho_0$, $E_s = -12.2\text{MeV/A}$

for Nuclear Matter at T = 0 MeV

3 body force, relativistic effects, etc

"unknown parts" → phenomenological approach

TNI I.E.Largaris and V.R.Pandharipande,

NP A359(1981), 349.

(1) repulsive at high density (TNR)

(2) attractive at low density (TNA)

$$V_{TNI}(r;\rho) = V_{TNR}(r;\rho) + V_{TNA}(r;\rho)$$

$$V_{TNR}(r;\rho) = V_1 e^{-(r/\lambda_r)^2} \cdot (1 - e^{-\eta_1 \rho})$$

$$V_{TNA}(r;\rho) = V_2 e^{-(r/\lambda_a)^2} \cdot \rho \cdot e^{-\eta_2 \rho} (\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)^2$$

(3) TNI for hyperons

$$V_{TNR}(r;\rho_N) \rightarrow V_{TNR}(r;\rho_B), \quad \rho_B = \rho_n + \rho_p + \rho_\Lambda + \rho_{\Sigma^-}$$

TOV equation

$$dP/dr = -\{GM(r)e(r)/r^2\} \times \{1+4\pi r^3 P(r)/M(r)\}\cdot\{1+P(r)/e(r)\}/\{1-2GM(r)/r\}$$

$$M(r) = \int^{r} 4\pi r^2 e(r)\, dr$$

$e(r)$: energy density , $P(r)$: pressure

Hyperon Mixing in Neutron Star Matter

$(n, p, \Lambda, \Sigma^-, e^-, \mu^-)$-system at zero Temperature

Baryon Number Conservation: $y_n + y_p + y_\Lambda + y_{\Sigma^-} = 1$

Charge Neutrality: $y_p = y_{e^-} + y_{\mu^-} + y_{\Sigma^-}$

Chemical Equilibrium:

$$\mu_n = \mu_p + \mu_{e^-}$$

$$\mu_{\Sigma^-} = \mu_n + \mu_{e^-}$$

$$\mu_\Lambda = \mu_n$$

$$\mu_{\mu^-} = \mu_{e^-}$$

$y_a = \rho_a/\rho$: Fractions, μ_a : Chemical Potentials

NN : RSC

ΛN : NHC-Dm

ΛΛ : NHC-D

Σ^{-}n : NHC-D

$\Sigma^{-}\Sigma^{-}$: NHC-D

Σ^{-}p : same as Λn

$\Lambda\Sigma^{-}$: neglect

TNI3u(κ=300MeV)

Threshold density

$\rho_t(\Lambda) = 4.01\rho_0$

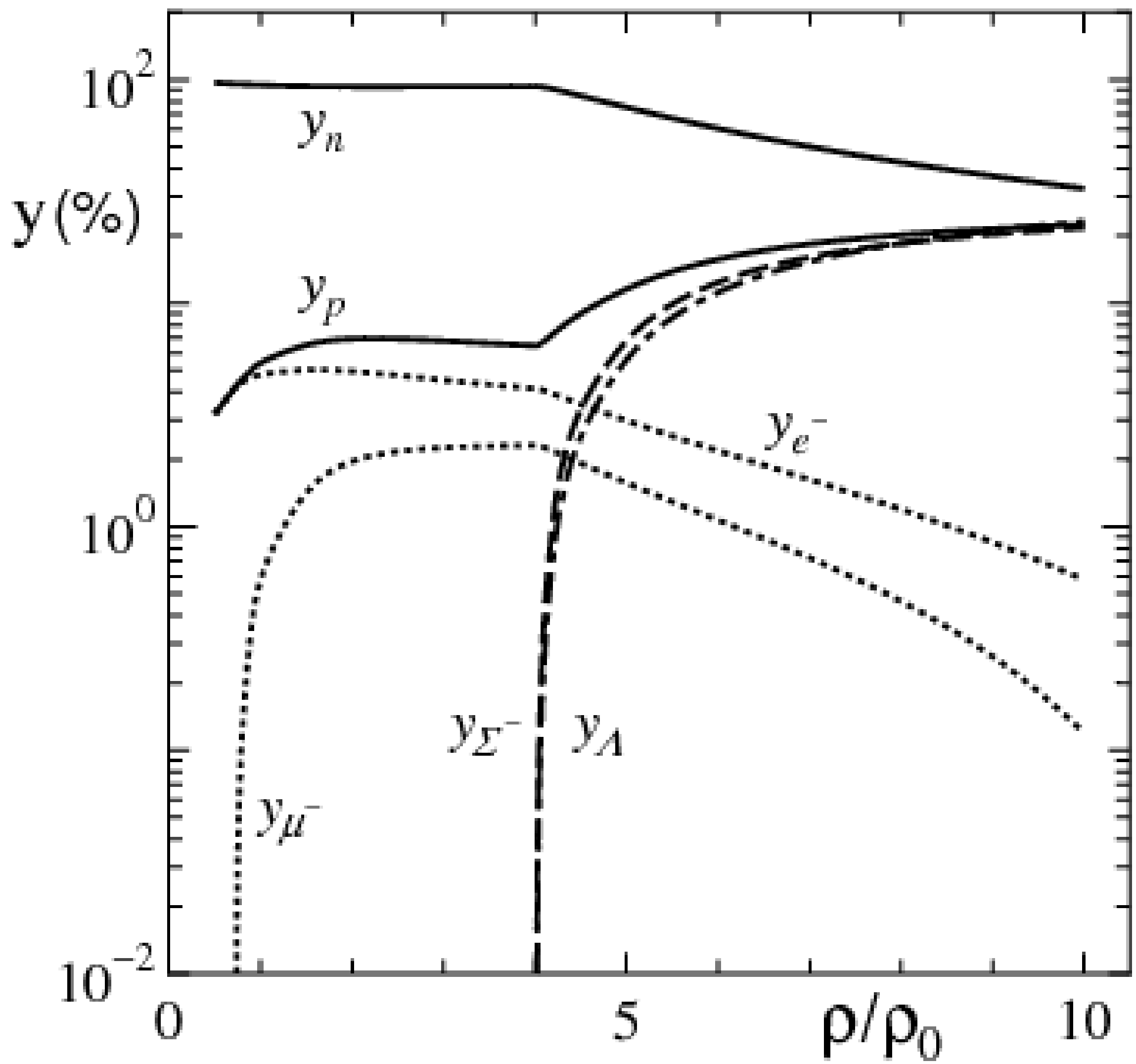
$\rho_t(\Sigma^{-}) = 4.01\rho_0$

Y-Mixing at $8\rho_0$

y_Λ, y_{Σ^-} : ∼19%

cf. y_n∼42%

y_p∼20%

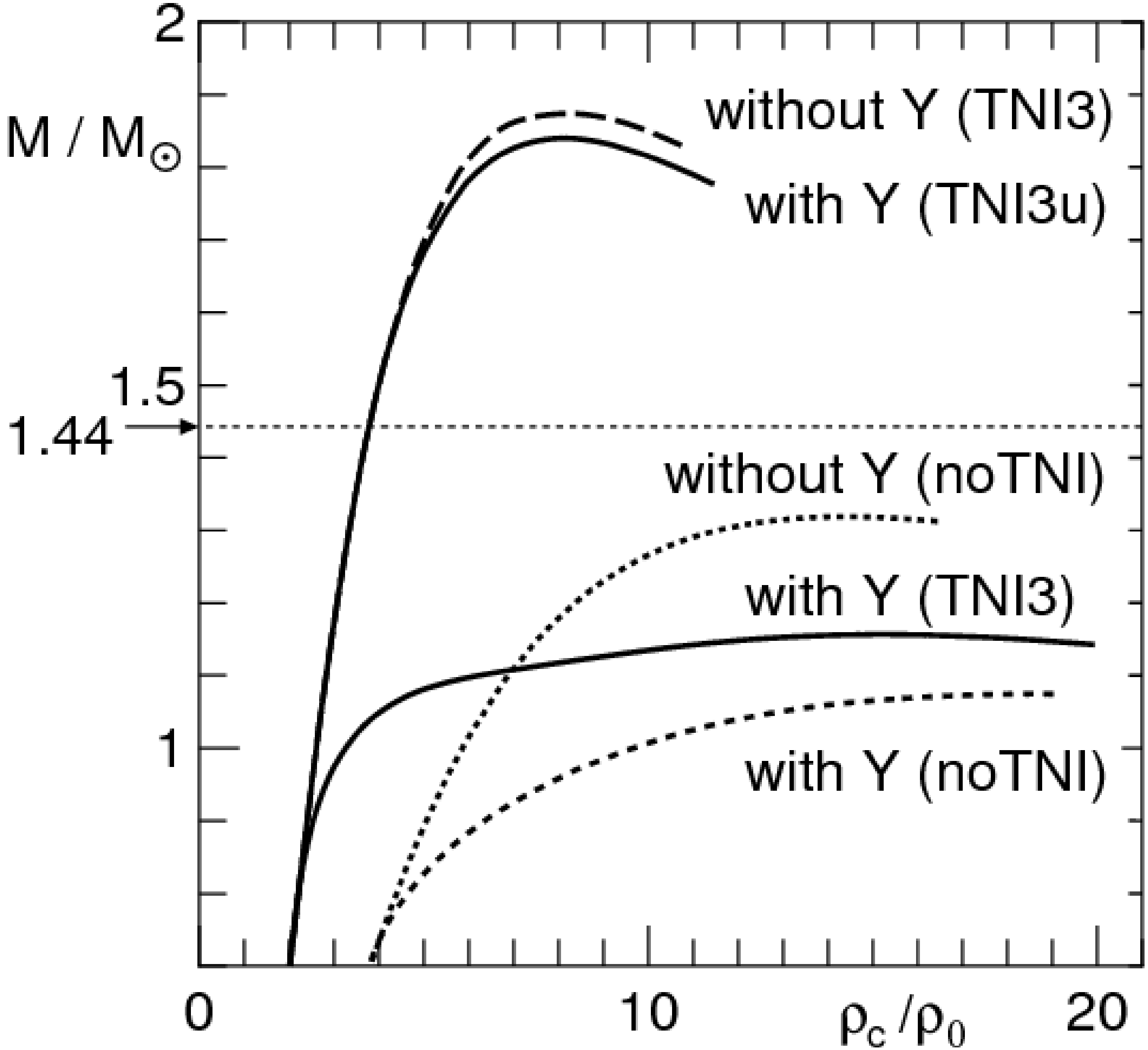


Neutron Star

M_{max}=1.83$M_{\odot}$

R = 9.55km

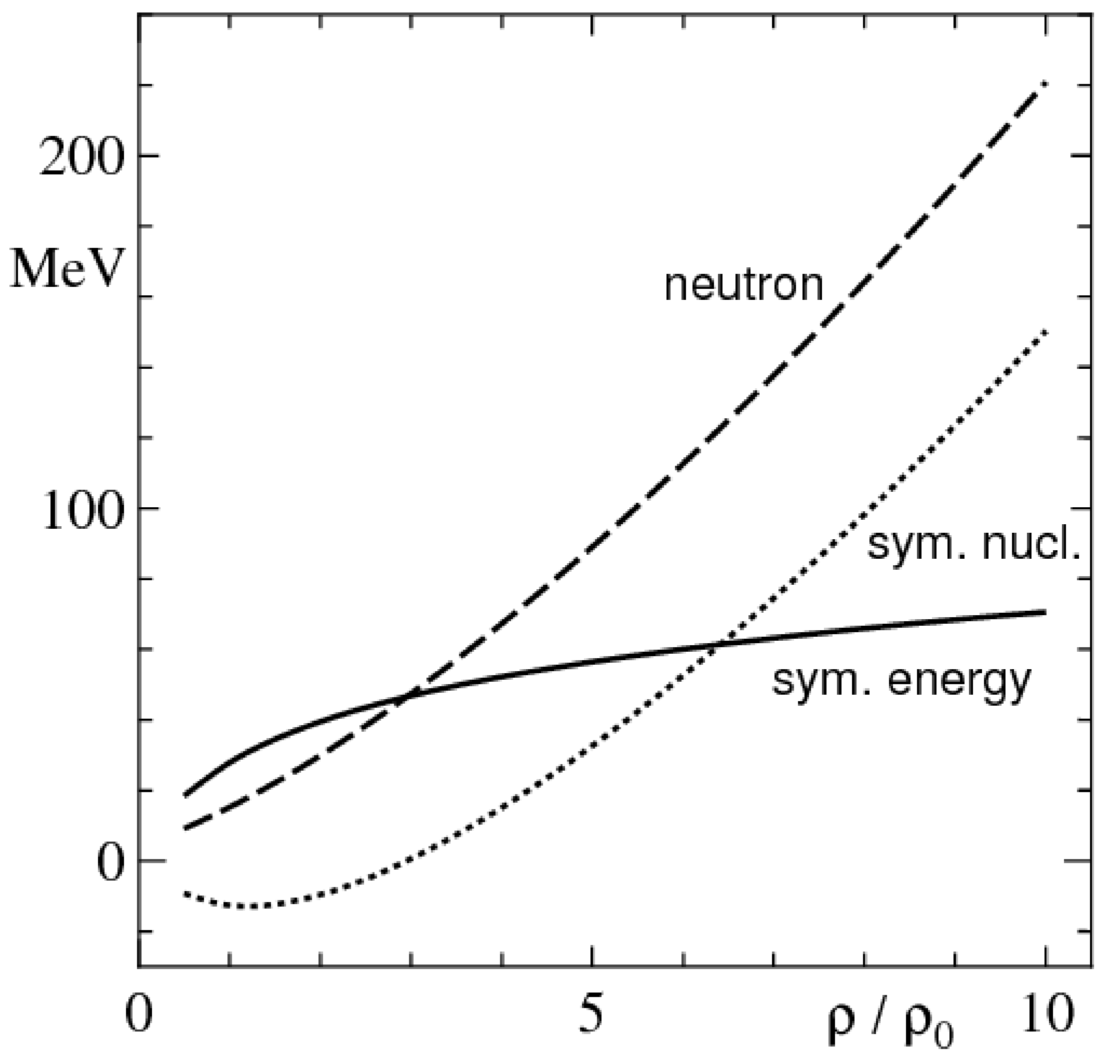
ρ_c = 8.26ρ_0



3.2 Symmetry energy effect

Present symmetry energy weakly depends on density.

How affects the ρ-dependence of a_{sym} on hyperon mixing in neutron stars?



○ NN interaction

$V_{TO} = \alpha_{TO} V_{TO}(RSC)$ ･･･ nn, pp, np

$V_{TE} = \alpha_{TE} V_{TE}(RSC)$ ･･･ np

→・a_{sym} with different density dependence

・a_{sym}=28MeV at ρ_0

Other parts of the interaction are the same.

○ α_{TO} = 2.00

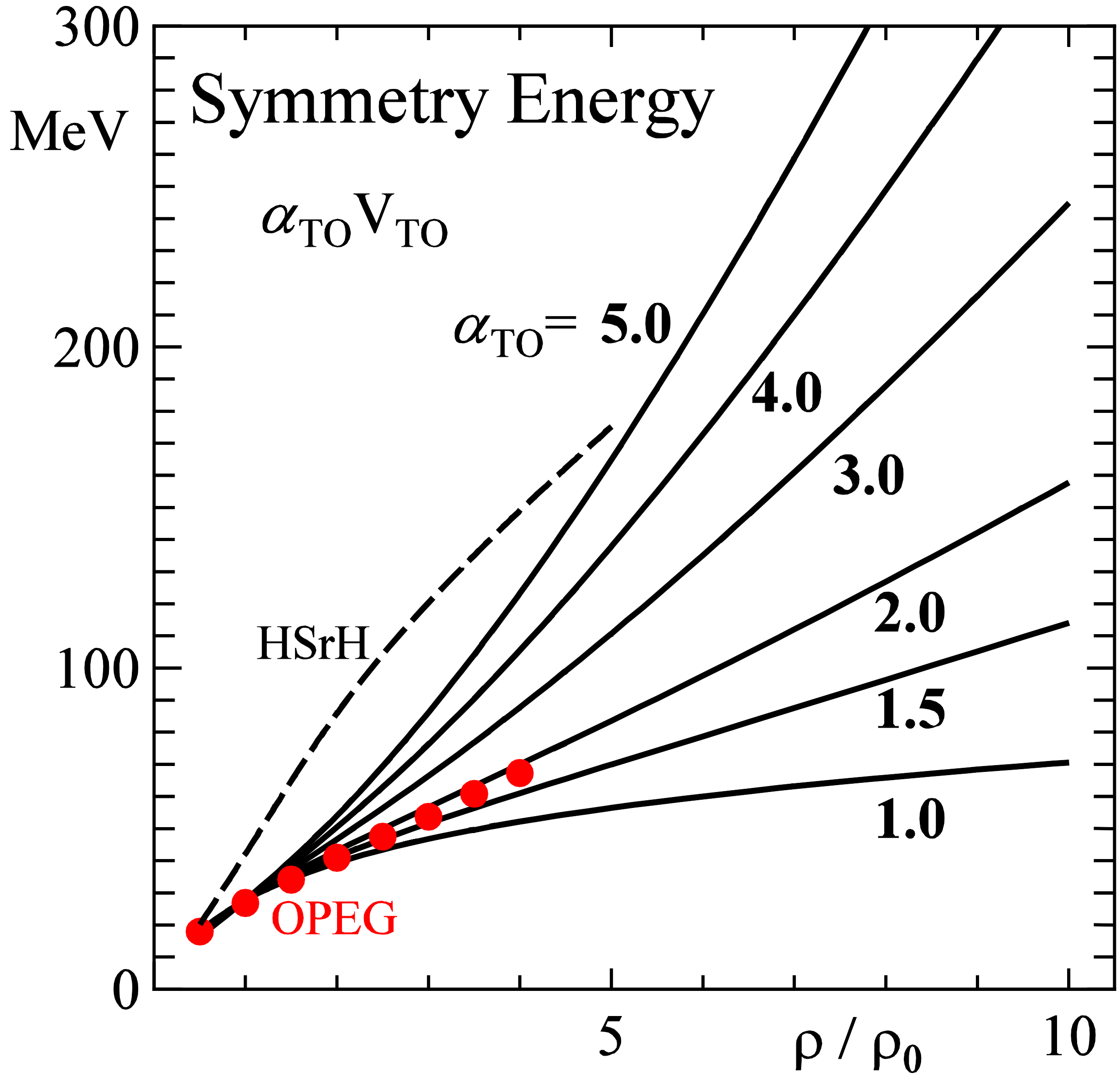
α_{TE} = 0.970

OPEG

○ α_{TO} = 5.00

α_{TE} = 0.877

HSrH



3.3 Results

(1) Threshold Densities : $\rho_t(\Lambda)$, $\rho_t(\Sigma^-)$

$$U_\Lambda(k=0) + \Delta m_\Lambda = k_{Fn}^2/2m_n + U_n(k_{Fn})$$

$$\Delta m_\Lambda = m_\Lambda - m_n \sim 176\text{MeV}$$

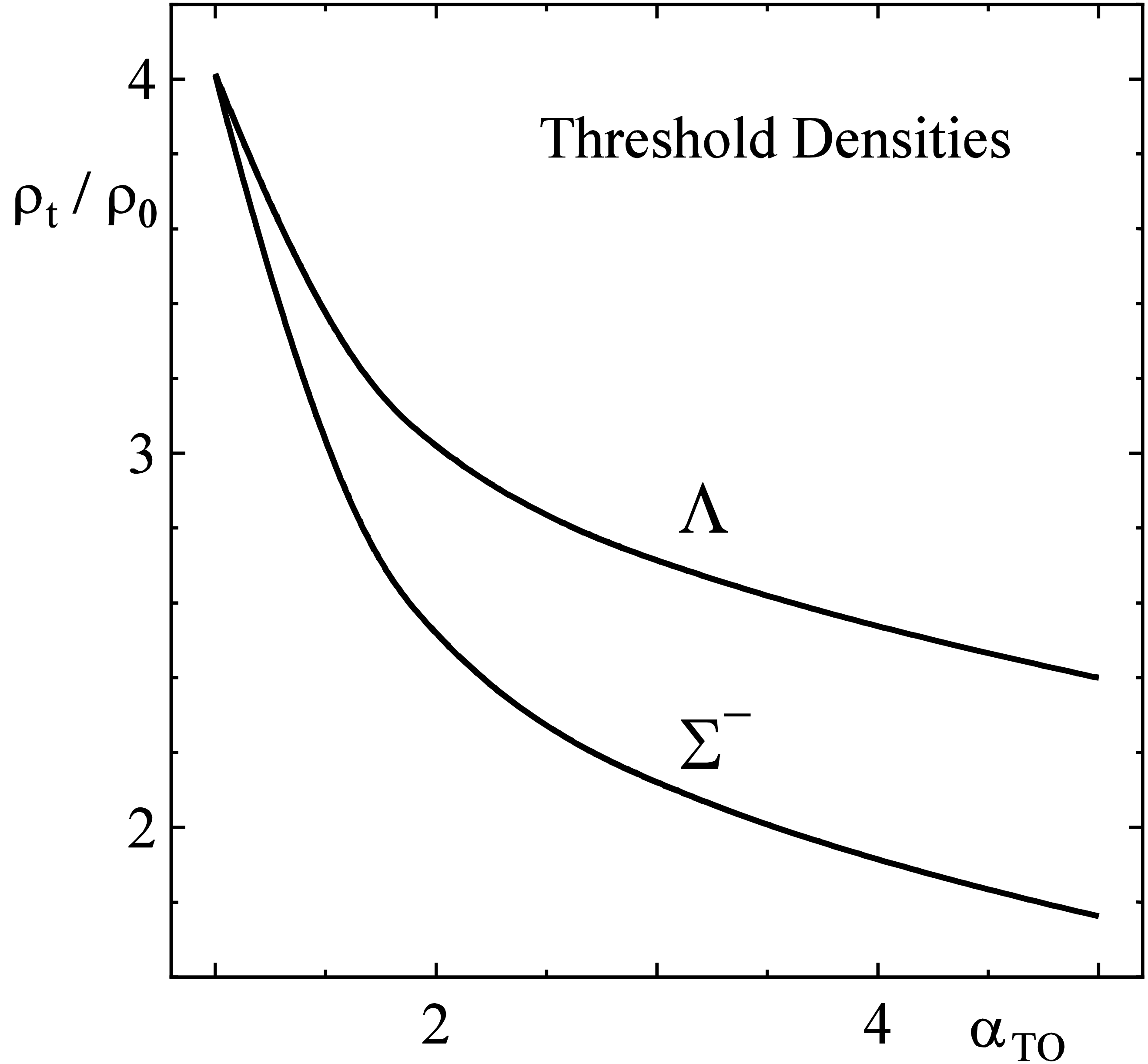
$$U_{\Sigma^-}(k=0) + \Delta m_{\Sigma^-} - \mu_{e^-}$$

$$= k_{Fn}^2/2m_n + U_n(k_{Fn})$$

$$\Delta m_{\Sigma^-} = m_{\Sigma^-} - m_n \sim 255\text{MeV}$$

$$\mu_{e^-} = 100 \sim 200\text{MeV}$$

α_{TO}	:	$\rho_t\,(\Lambda)$	$\rho_t\,(\Sigma^-)$
1.0	:	$4.01\rho_o$	$4.01\rho_o$
2.0	:	$3.00\rho_o$	$2.49\rho_o$
5.0	:	$2.40\rho_o$	$1.76\rho_o$



Threshold Densities
ρ_t / ρ_0
4
3
2
2
4
α_{TO}
Λ
Σ^-

(2) Λ, Σ^--fractions

$\underline{\alpha_{TO}=2.00}$

$y_n \sim 32\%$

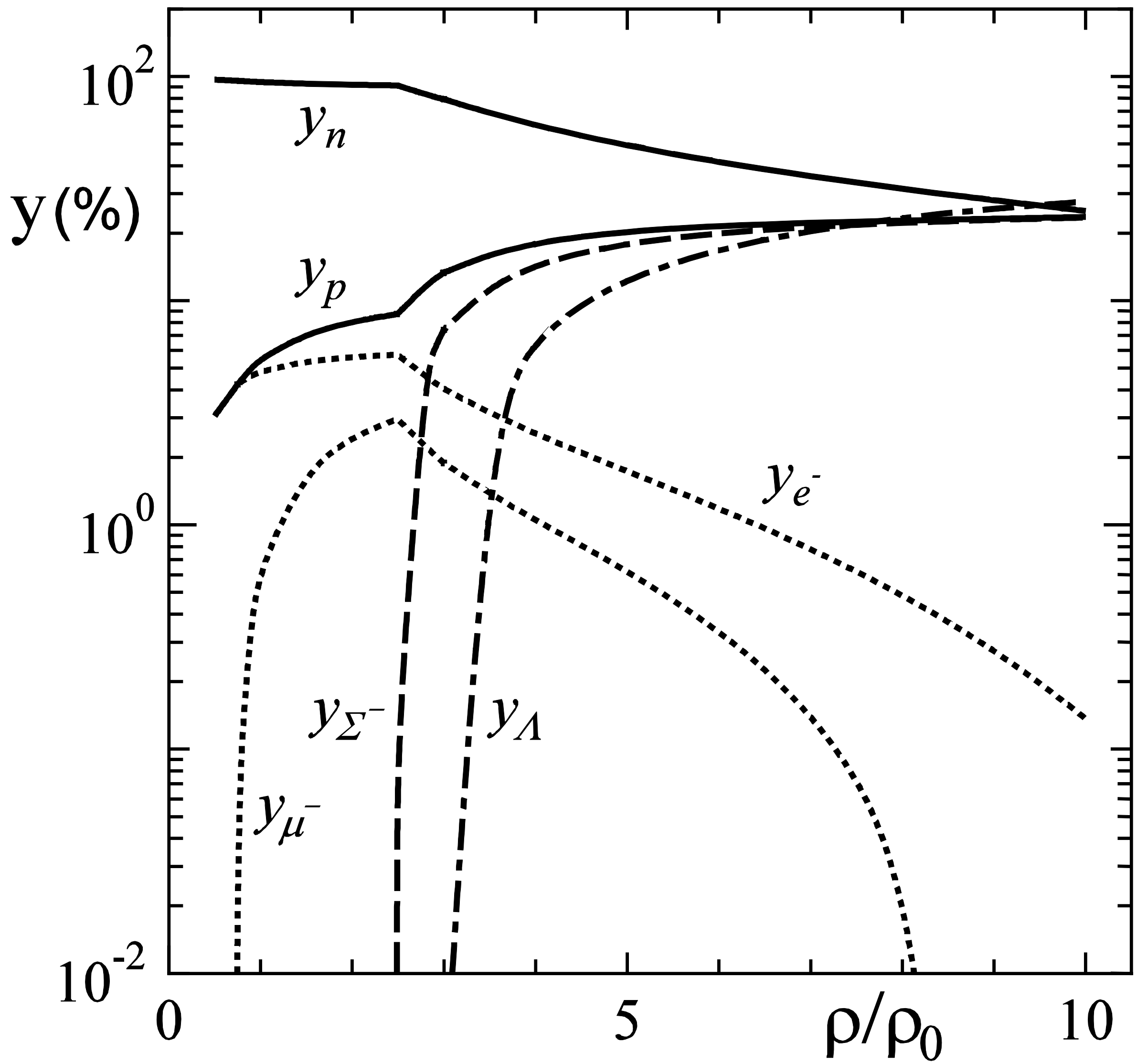
$y_p \sim 23\%$

Y-Mixing

$y_\Lambda \sim 23\%$

$y_{\Sigma^-} \sim 22\%$

at $\rho = 8\rho_0$



α_{TO} =5.00

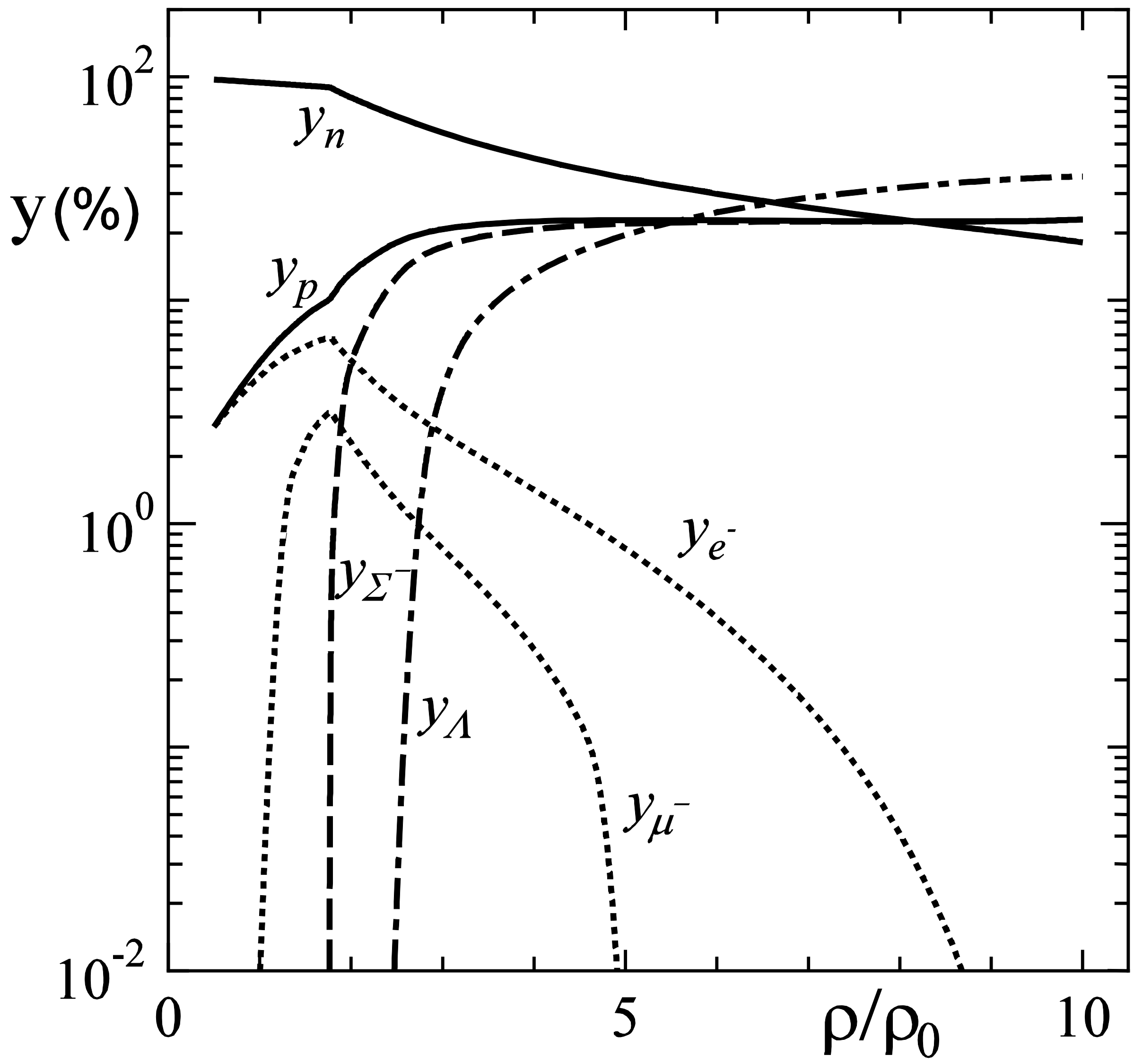
$y_n \sim 23\%$

$y_p \sim 23\%$

Y-Mixing

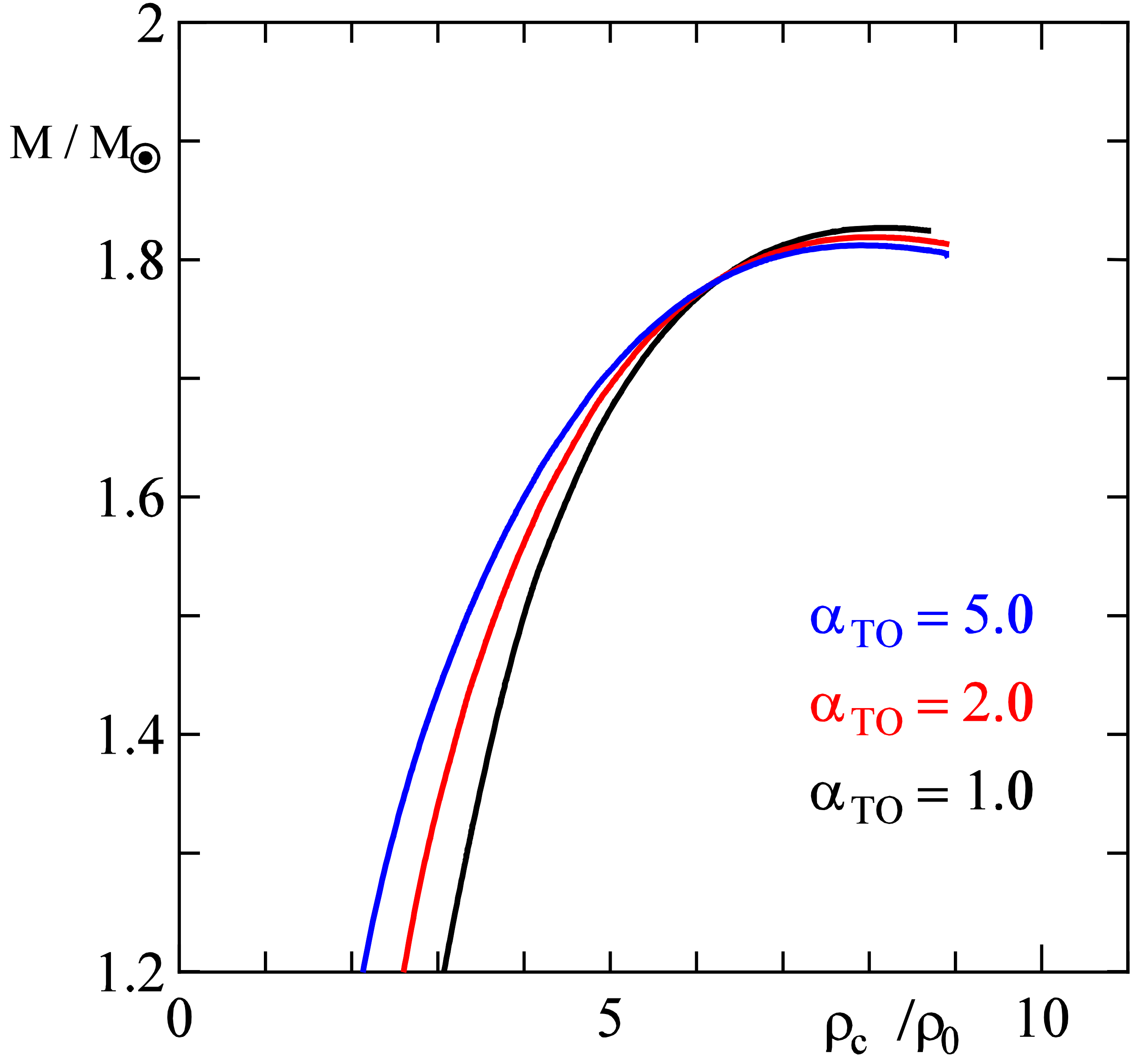
$y_\Lambda \sim 31\%$

$y_{\Sigma^-} \sim 23\%$



(3) Properties of Neutron Stars with Maximum Mass

α_{TO} :	$M/M_{\odot}$	R(km)	ρ_c / ρ_0	$N_B(10^{57})$
1.0 :	1.827	9.545	8.259	2.547
2.0 :	1.819	9.763	8.018	2.513
5.0 :	1.812	9.826	7.975	2.472



M / M☉
2
1.8
1.6
1.4
1.2
0
5
10
ρc /ρ0
αTO = 5.0
αTO = 2.0
αTO = 1.0

4．Summary

（1） We estimate how the density dependence of symmetry energy affect on hyperon mixing in neutron stars.

（2） As the density dependence is steeper, threshold densities decrease largely.

$$\rho_t(\Sigma^-) = (4.01 \rightarrow 2.49 \rightarrow 1.76)\rho_0$$

$$\rho_t(\Lambda) = (4.01 \rightarrow 3.00 \rightarrow 2.40)\rho_0$$

（3 ）In the central region of neutron star with maximum mass, fractions of baryons change as

$y_{\Sigma^-} = (19 \rightarrow 22 \rightarrow 23)\%$, $y_{\Lambda} = (19 \rightarrow 23 \rightarrow 31)\%$

$y_n = (42 \rightarrow 32 \rightarrow 23)\%$, $y_p = (20 \rightarrow 23 \rightarrow 23)\%$

（4）EOS and properties of neutron stars with maximum mass change slightly.