Baryonic matter equation of state and the baryons in baryonic matter

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OUTLINE

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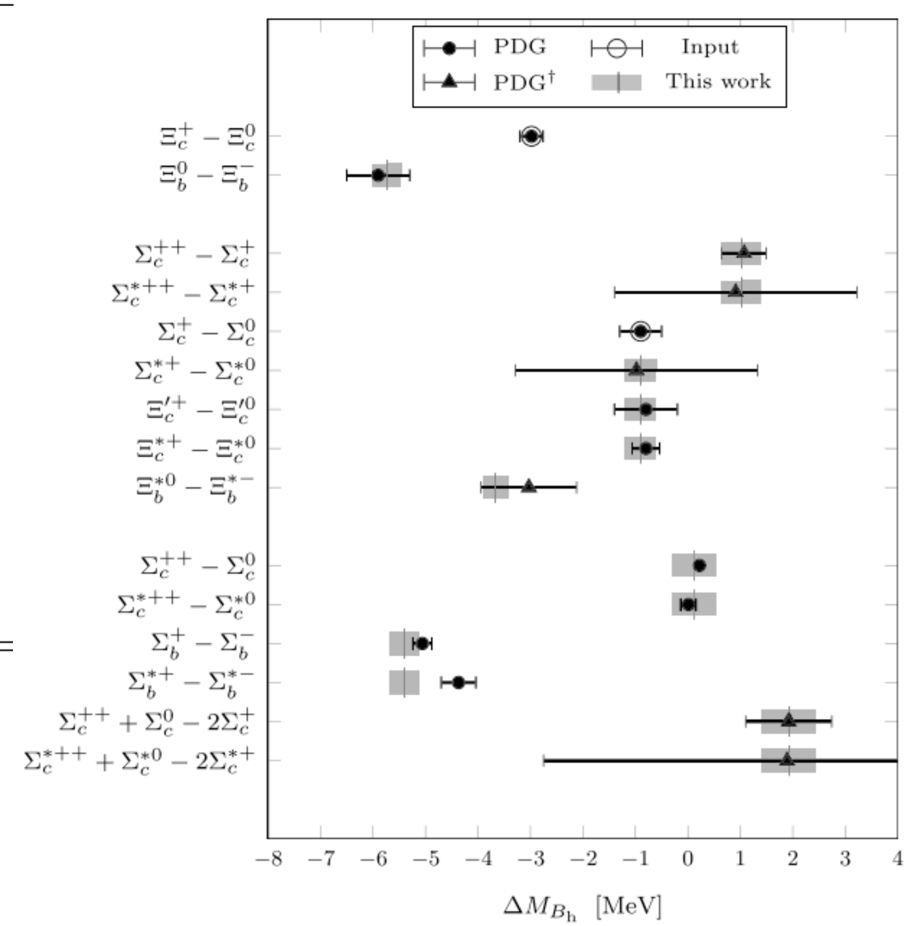
Motivation

- In the large N_c limit, the nucleon can be viewed as a state of N_c valence quarks bound by the meson field [1].

Mass [Mev]	Exp. [input]	Numerical results[2]
M_p	938.272 ± 0.00008	938.76 ± 3.65
M_n	939.565 ± 0.00008	940.27 ± 3.64
M_Λ	1115.683 ± 0.006	1109.61 ± 0.70
M_{Σ^+}	1189.37 ± 0.007	1188.75 ± 0.70
M_{Σ^0}	1192.642 ± 0.024	1190.20 ± 0.77
M_{Σ^-}	1197.449 ± 0.030	1195.48 ± 0.71
M_{Ξ^0}	1314.83 ± 0.20	1319.30 ± 3.43
M_{Ξ^-}	1321.31 ± 0.13	1324.52 ± 3.44

Mass [Mev]	Exp.	Numerical results[2]
$M_{\Delta^{++}}$	$1231 - 1233$	1248.54 ± 3.39
M_{Δ^+}	$1231 - 1233$	1249.36 ± 3.37
M_{Δ^0}	$1231 - 1233$	1251.53 ± 3.38
M_{Δ^-}	$1231 - 1233$	1255.08 ± 3.37
$M_{\Sigma^{*+}}$	1382.8 ± 0.4	1388.48 ± 0.34
$M_{\Sigma^{*0}}$	1383.7 ± 1.0	1390.66 ± 0.37
$M_{\Sigma^{*-}}$	1387.2 ± 0.5	1394.20 ± 0.34
$M_{\Xi^{*0}}$	1531.80 ± 0.32	1529.78 ± 3.38
$M_{\Xi^{*-}}$	1535.0 ± 0.6	1533.33 ± 3.37
M_{Ω^-}	1672.45 ± 0.29	Input

The mass spectrum of singly heavy baryon [3]



[1] E. Witten, Nucl. Phys. B 160, 57 (1979).
[2] G. S. Yang and H.-Ch. Kim, Prog. Their. Phys. **128**, 397 (2012)
[3] G. S. Yang, H. Ch. Kim, Phys. Lett. B. **808**, 135619 (2020).

Pion mean-field approach

- Collective Hamiltonian [2]

$$H = M_{\mathrm{cl}} + \frac{1}{2I_1}\sum_{i=1}^{3}\hat{J}_i^2 + \frac{1}{2I_2}\sum_{p=4}^{7}\hat{J}_p^2$$

$$+ (m_{\mathrm{d}} - m_{\mathrm{u}})\left(\frac{\sqrt{3}}{2}\alpha D_{38}^{(8)}(\mathcal{A}) + \beta\hat{T}_3 + \frac{1}{2}\gamma\sum_{i=1}^{3}D_{3i}^{(8)}(\mathcal{A})\hat{J}_i\right)$$

$$+ (m_{\mathrm{s}} - \bar{m})\left(\alpha D_{88}^{(8)}(\mathcal{A}) + \beta\hat{Y} + \frac{1}{\sqrt{3}}\gamma\sum_{i=1}^{3}D_{8i}^{(8)}(\mathcal{A})\hat{J}_i\right) + H_{\mathrm{em}}$$

$$\alpha = -\left(\frac{2}{3}\frac{\Sigma_{\pi N}}{m_{\mathrm{u}} + m_{\mathrm{d}}} - Y'\frac{K_2}{I_2}\right)$$

$$\beta = -\frac{K_2}{\bar{I}_2}$$

$$\gamma = 2\left(\frac{K_1}{\bar{I}_1} - \frac{K_2}{\bar{I}_2}\right)$$

[2] G. S. Yang and H.-Ch. Kim, Prog. Their. Phys. **128**, 397 (2012)

Nuclear matter

- Binding energy per baryon

$$\varepsilon = \frac{E^* - E}{A} = \frac{Z\Delta M_p + N\Delta M_n + \sum_{s=1}^{3} N_s \Delta M_s}{A}$$

$$= \Delta M_N \left(1 - \sum_{s=1}^{3} \delta_s\right) + \frac{1}{2}\delta \Delta M_{np} + \sum_{s=1}^{3} \delta_s \Delta M_s$$

$$M_{np} = M_n - M_p$$

$$\Delta M_N = M_N^* - M_N$$

$$\delta = \frac{N - Z}{A}$$

$$\delta_s = \frac{N_s}{A}$$

Nuclear matter

- The properties of symmetric nuclear matter

Volume energy: $\varepsilon(\lambda, 0, 0, 0, 0) = \varepsilon_V(\lambda) = \Delta M_N(\lambda)$

Pressure: $P(\lambda) = \rho_0 \lambda^2 \dfrac{\partial \varepsilon_V(\lambda)}{\partial \lambda}$

Compressibility: $K(\lambda) = 9\lambda^2 \dfrac{\partial^2 \varepsilon_V(\lambda)}{\partial \lambda^2}$

Values at the saturation density:

$\varepsilon_V(1) = -16\ \mathrm{MeV}$ $\quad P(1) = 0\ \mathrm{MeV fm}^{-3}$ $\quad K(1) = 240\ \mathrm{MeV}$

Nuclear matter

- The properties of asymmetric nuclear matter

The nuclear symmetry energy: $\varepsilon_{\rm sym}(\lambda) = \frac{1}{2!} \frac{\partial^2 \varepsilon(\lambda, \delta, 0, 0, 0)}{\partial \delta^2}\Big|_{\delta=0}$

Slope parameter: $L_{sym} = 3 \frac{\partial \varepsilon_{\rm sym}(\lambda)}{\partial \lambda}\Big|_{\lambda=1}$

Values at the saturation density:

$\varepsilon_{\rm sym}(1) = 32 \text{ MeV}$ $L_{sym} = 60 \text{ MeV}$

Nuclear matter

- Medium functions

$$M^*_{\rm cl} = M_{\rm cl}\left(1 + C_{\rm cl}\lambda\right)$$

$$I^*_1 = I_1\left(1 + C_1\lambda\right)$$

$$I^*_2 = I_2\left(1 + C_2\lambda\right)$$

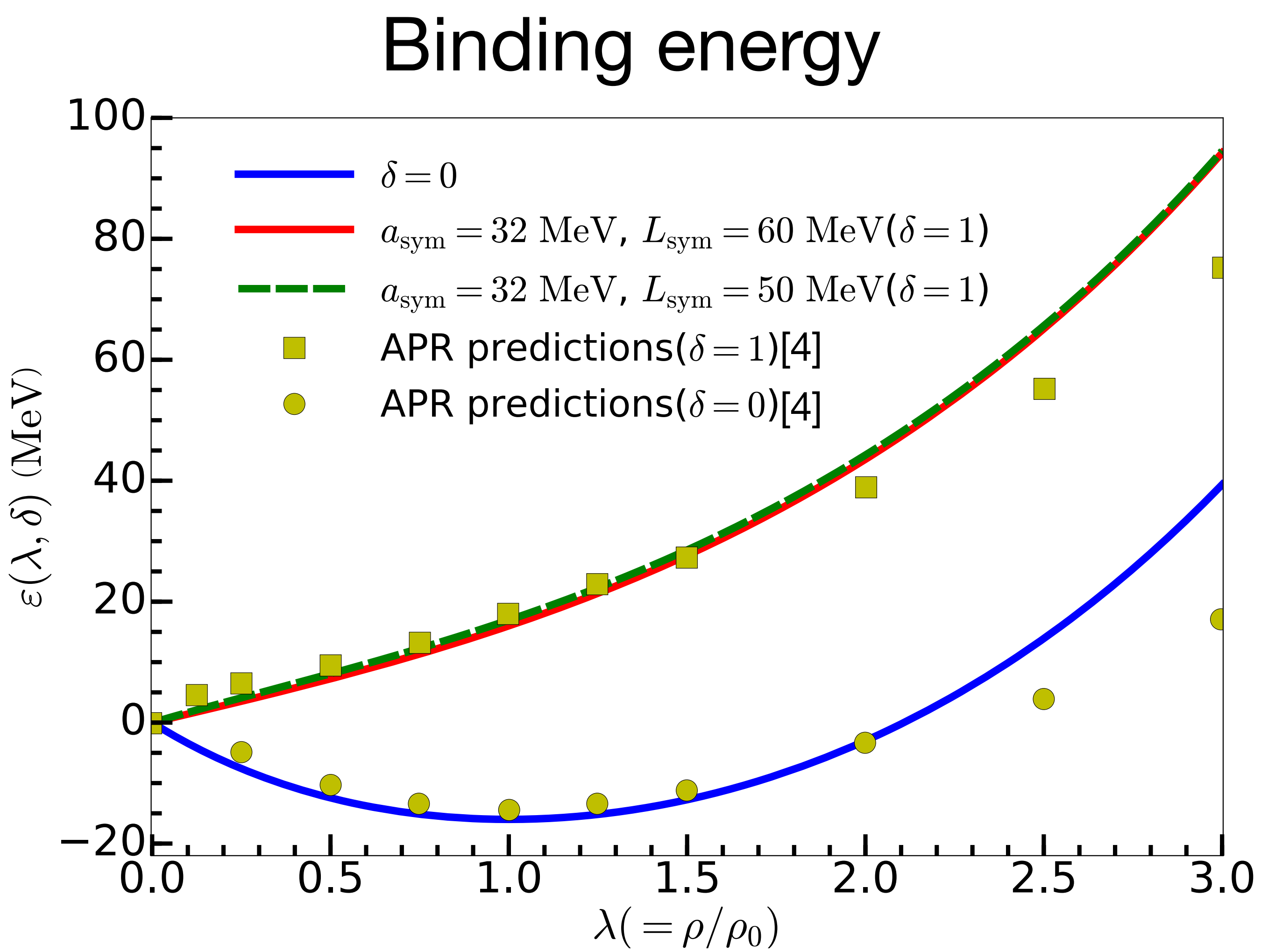
$$\frac{K^{I*}_{1,2}}{I^*_{1,2}} = \frac{K^{I}_{1,2}}{I_{1,2}}\left(1 + \frac{C_{\rm num}\lambda\delta}{1 + C_{\rm den}\lambda}\right)$$

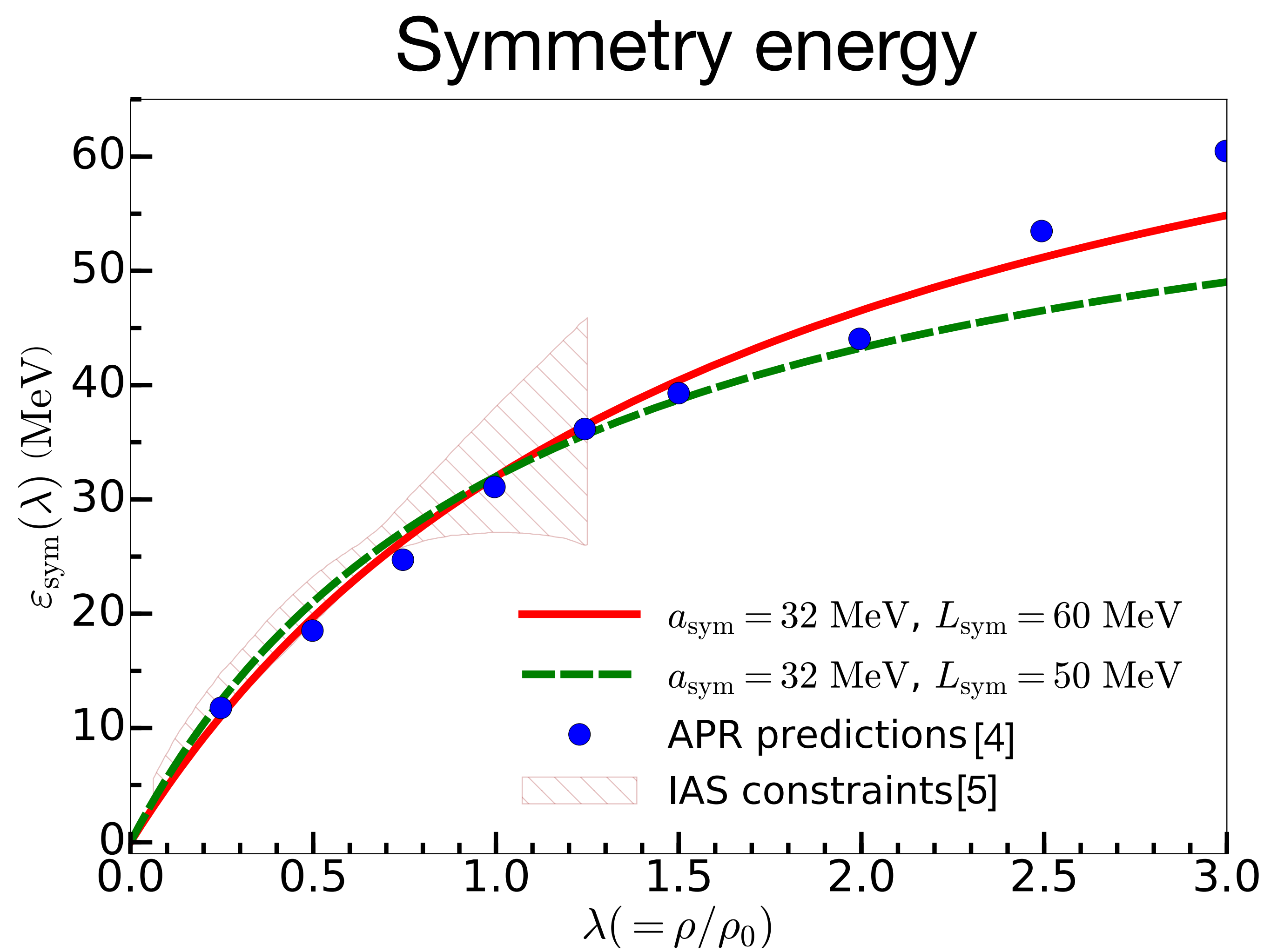
- Density-dependent parameters

	Values
$C_{\rm cl}$	-0.0561
C_1	0.6434
C_2	-0.1218
$C_{\rm num}$	65.60
$C_{\rm den}$	0.60

RESULTS

Nuclear matter



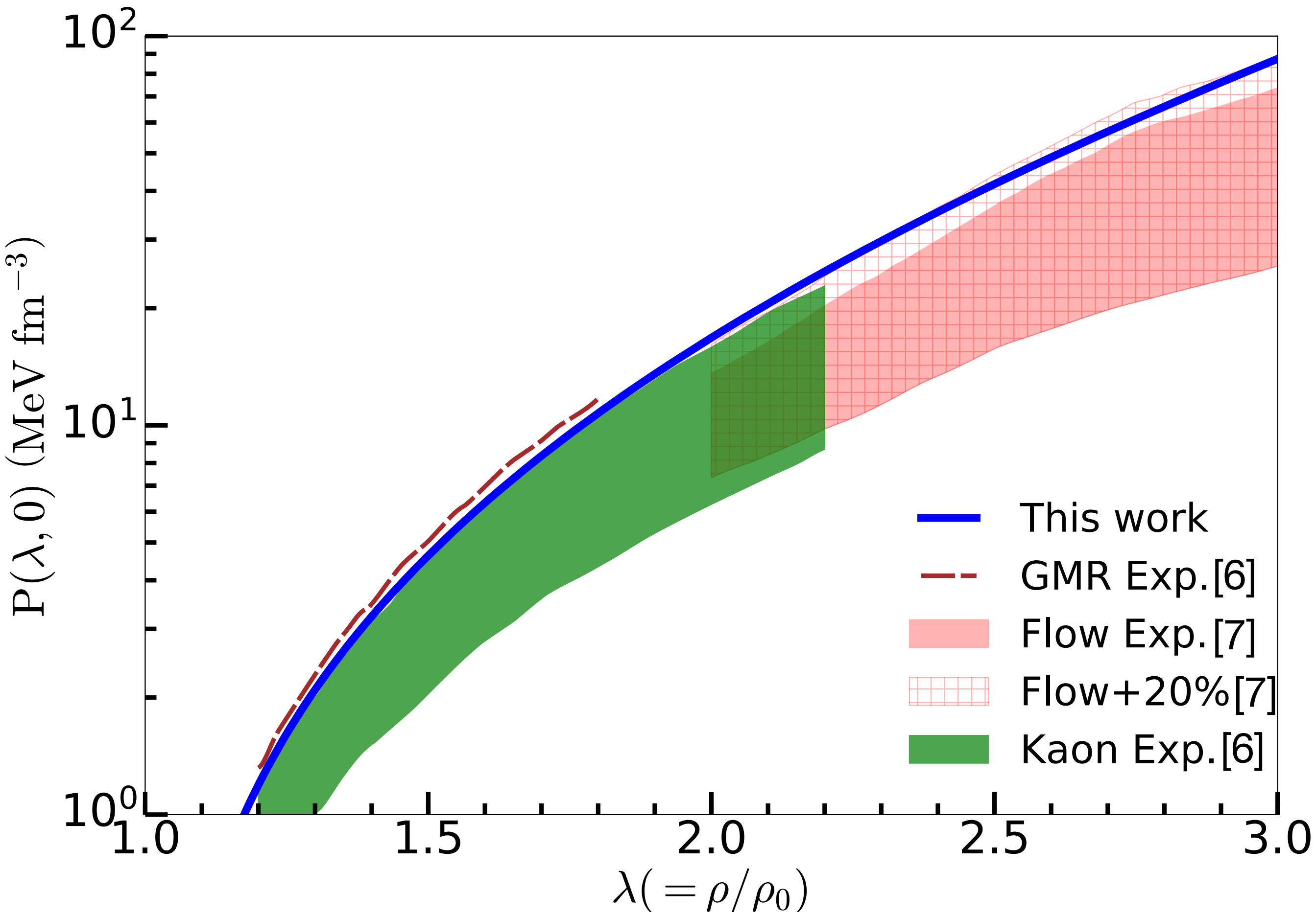


[4] A. Akmal, V. R. Pandharipande and D. G. Ravenhall, Phys. Rev. C **58**, 184 (1998)
[5] P. Danielewicz and J. Lee, Nucl. Phys. A **922**, 1 (2014)

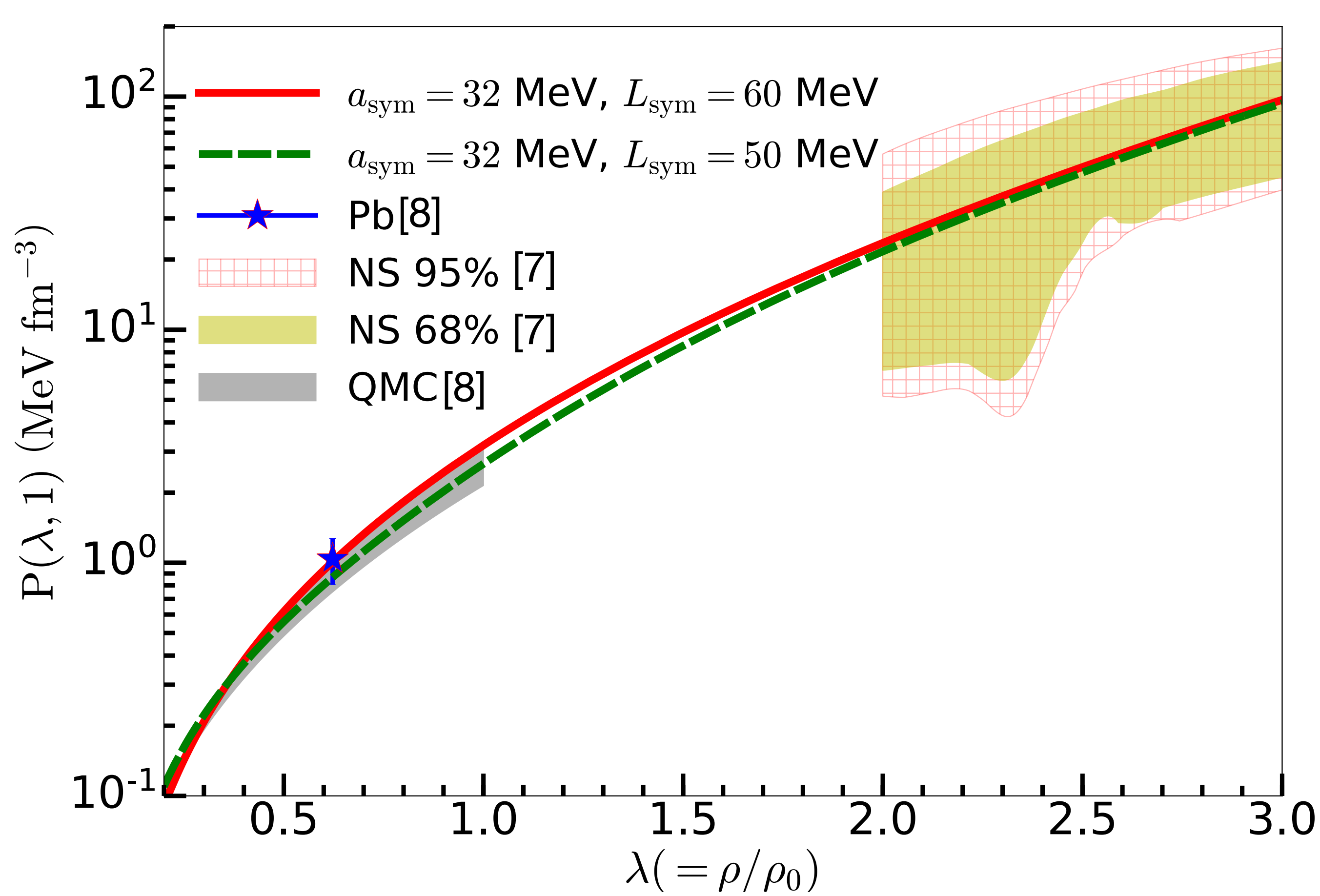
RESULTS

Nuclear matter

Pressure of symmetric matter



Pressure or pure neutron matter

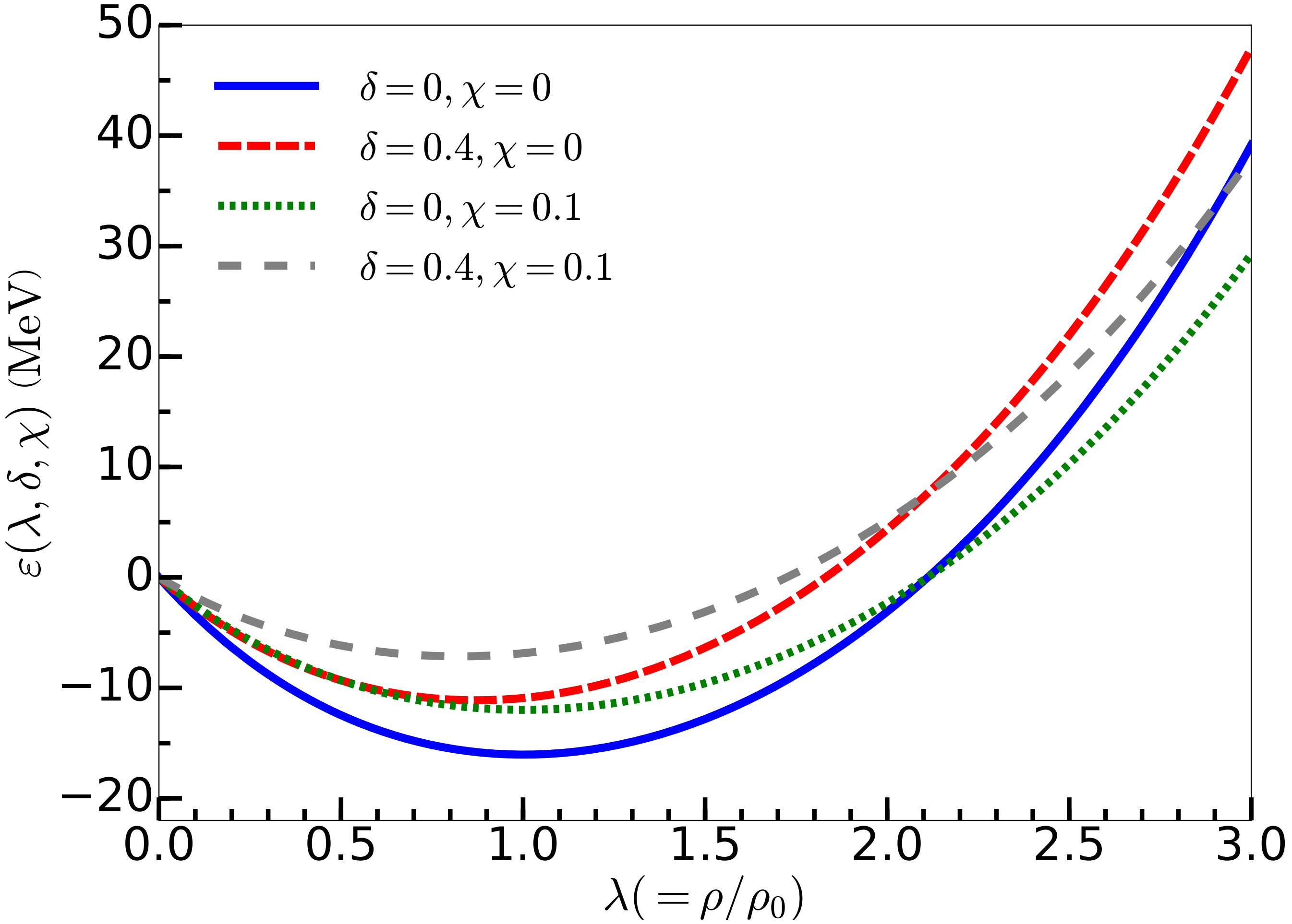


[6] W. G. Lynch, M. B. Tsang, Y. Zhang, P. Danielewicz, M. Famiano, Z. Li and A. W. Steiner, Prog. Part. Nucl. Phys. **62**, 427 (2009).
[7] A. W. Steiner, J. M. Lattimer and E. F. Brown, Astrophys. J. Lett. **765**, L5 (2013).
[8] M. B. Tsang et al., Phys. Rev. C 86, 015803 (2012).

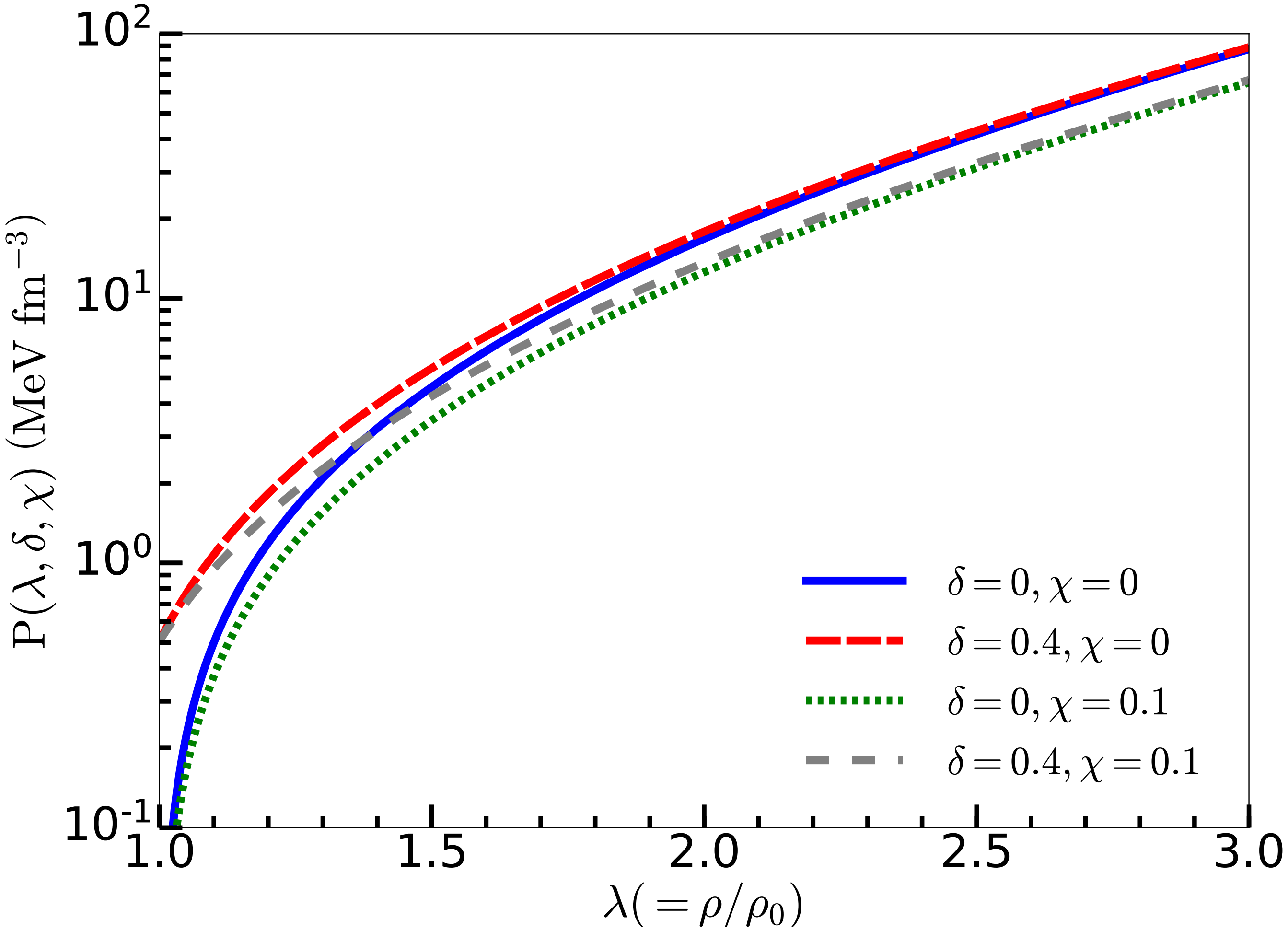
RESULTS

Baryonic matter

Binding energy($\delta_s = s\chi$)



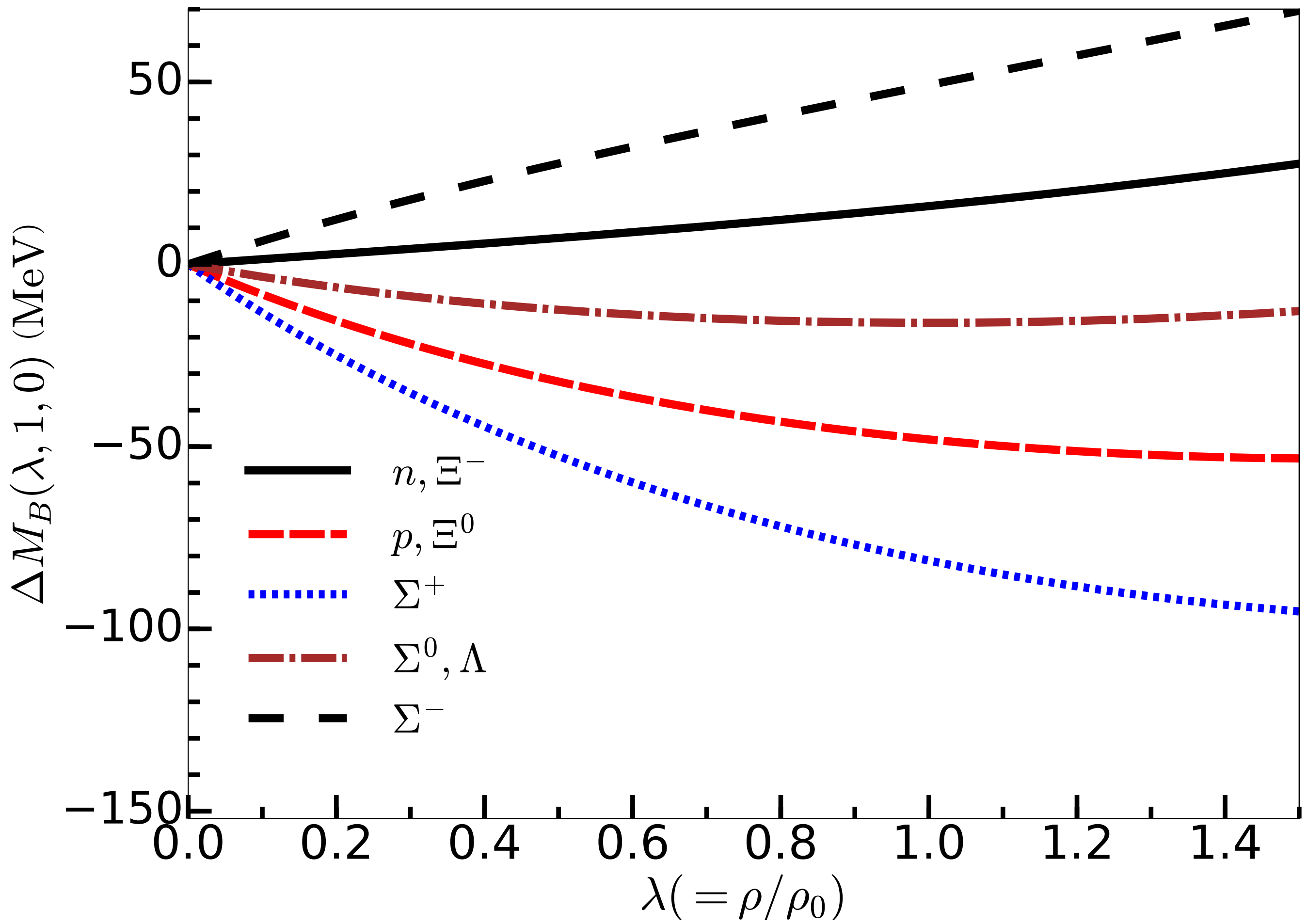
Pressure($\delta_s = s\chi$)



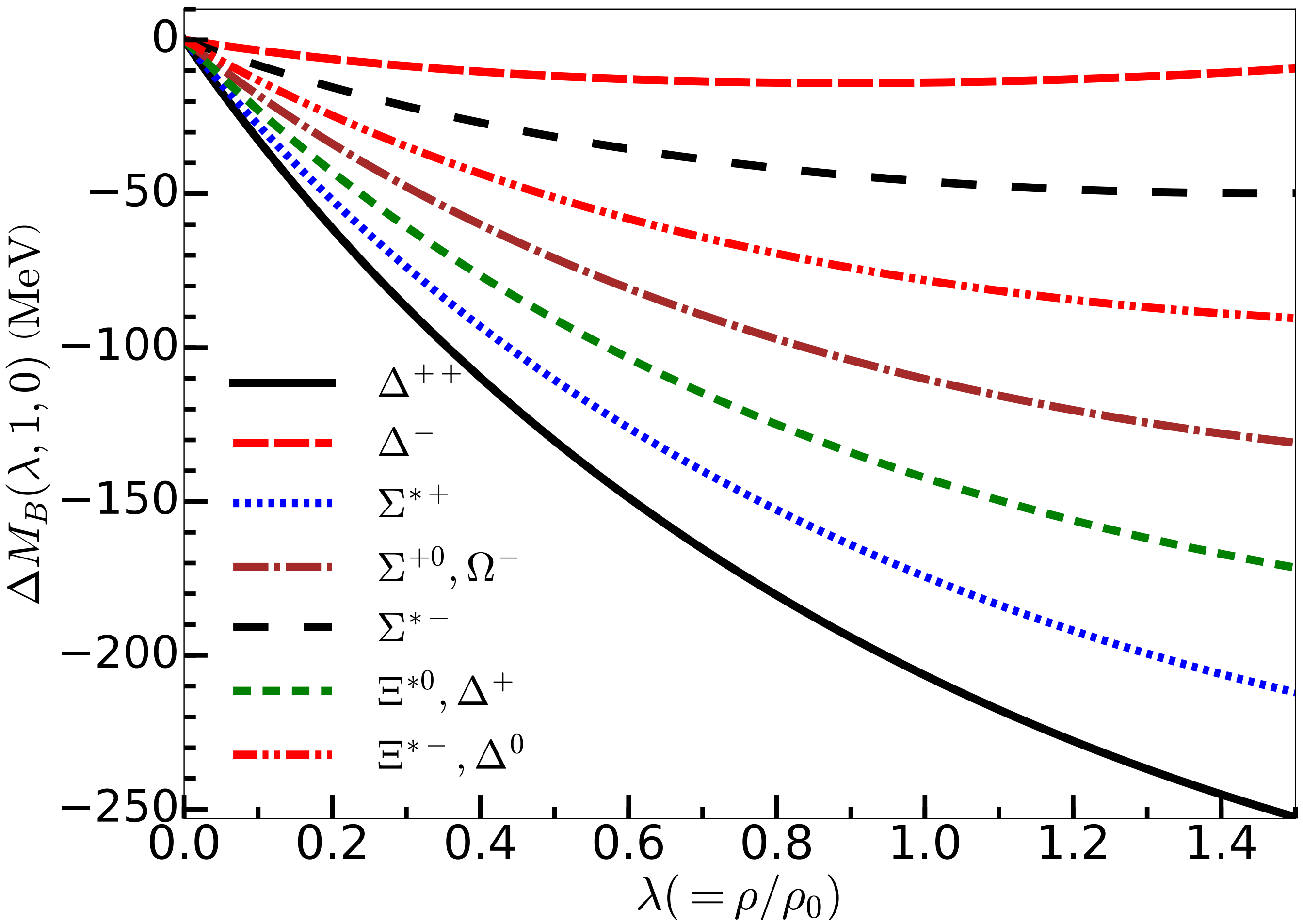
RESULTS

The light baryons in pure neutron matter

Octet baryon



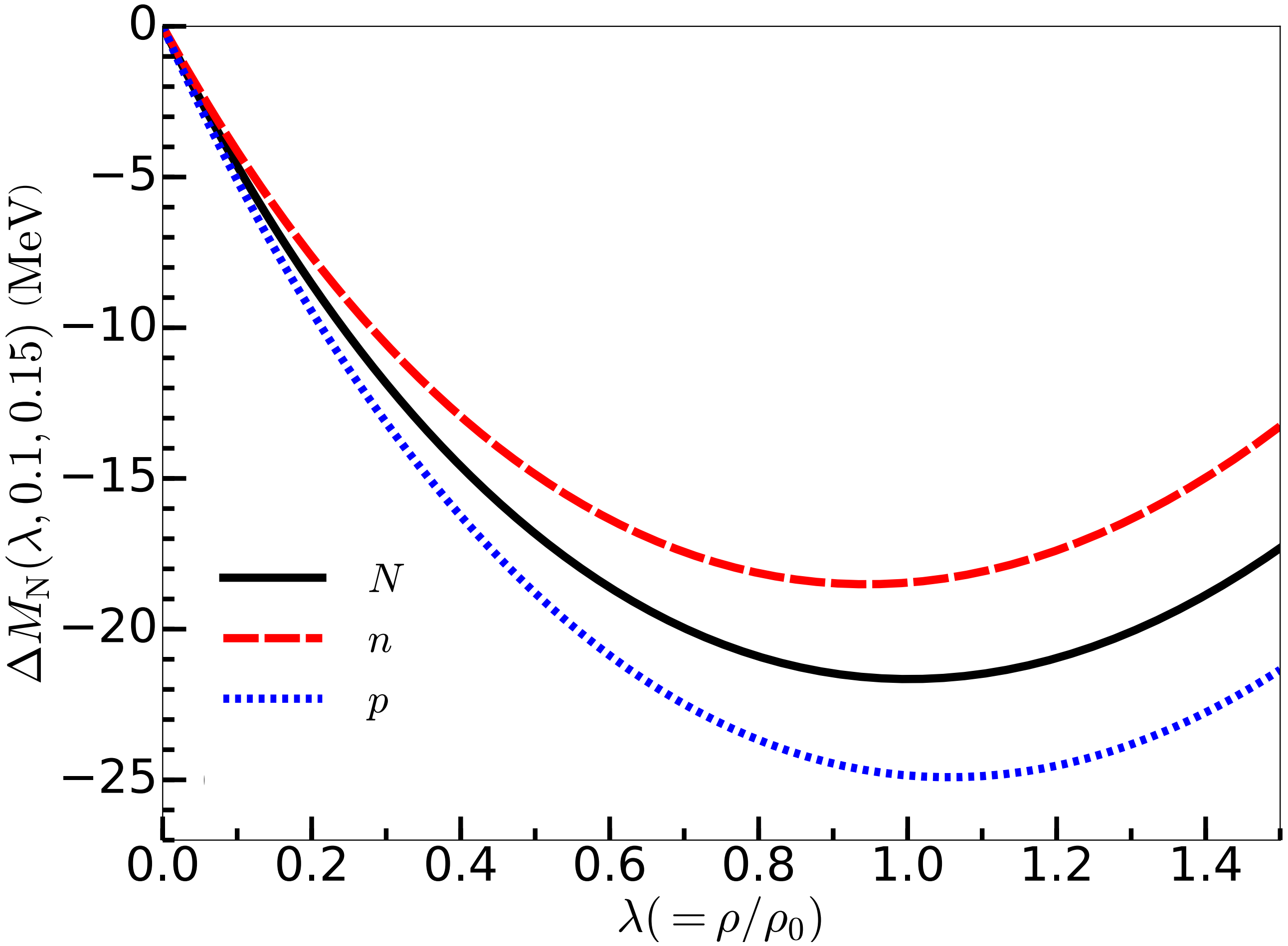
Decuplet baryon



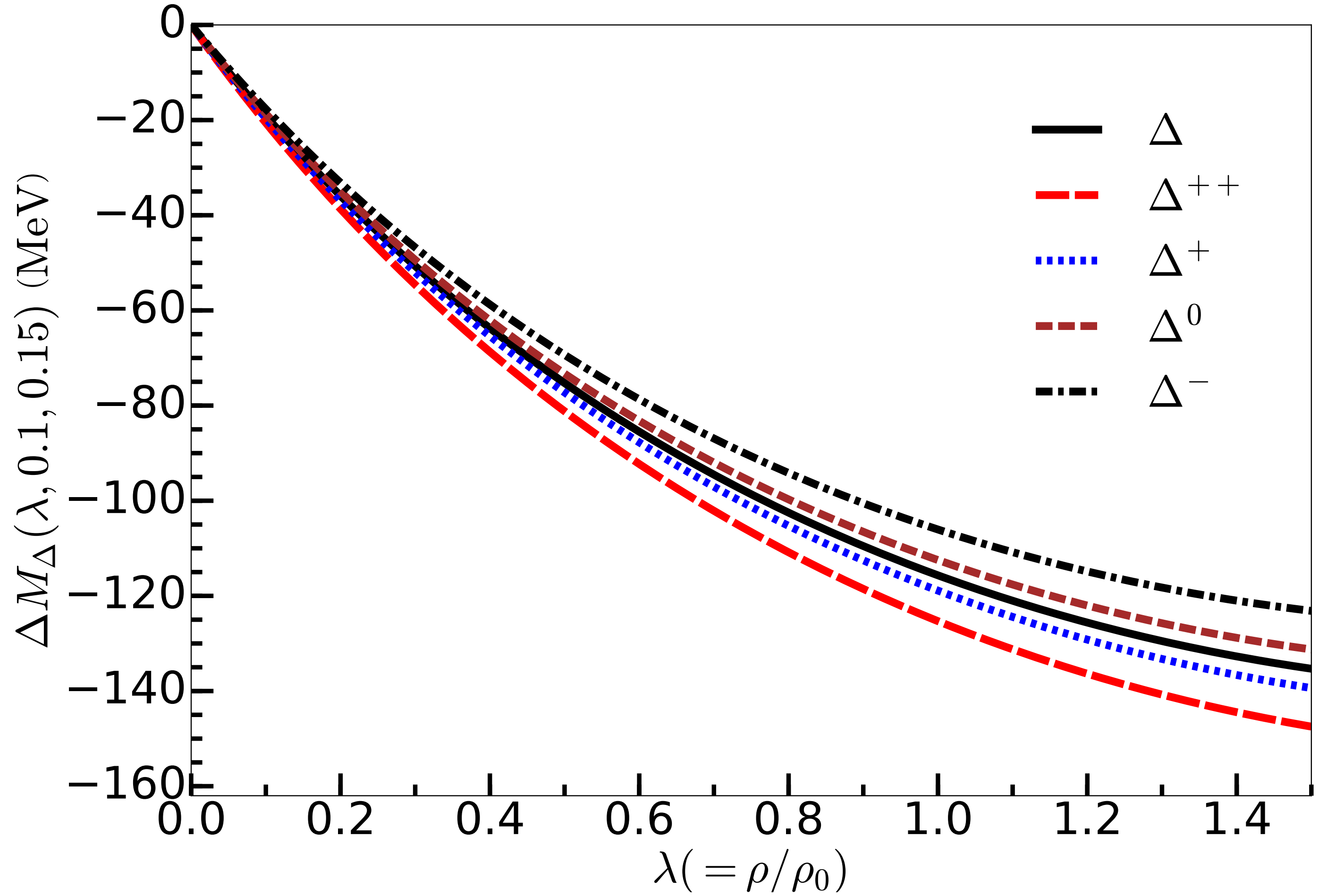
RESULTS

The light baryons in baryonic matter

Nucleon



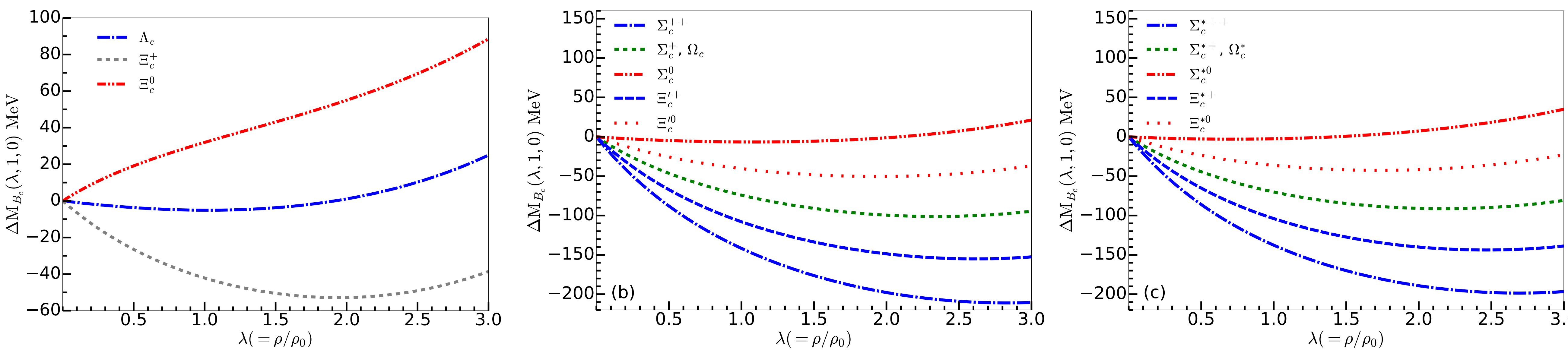
Delta Isobar



RESULTS

The singly heavy baryons in pure neutron matter.

Anti triplet　　Sextet(S=1/2)　　Sextet(S=3/2)



The change of singly heavy baryon masses in pure neutron matter

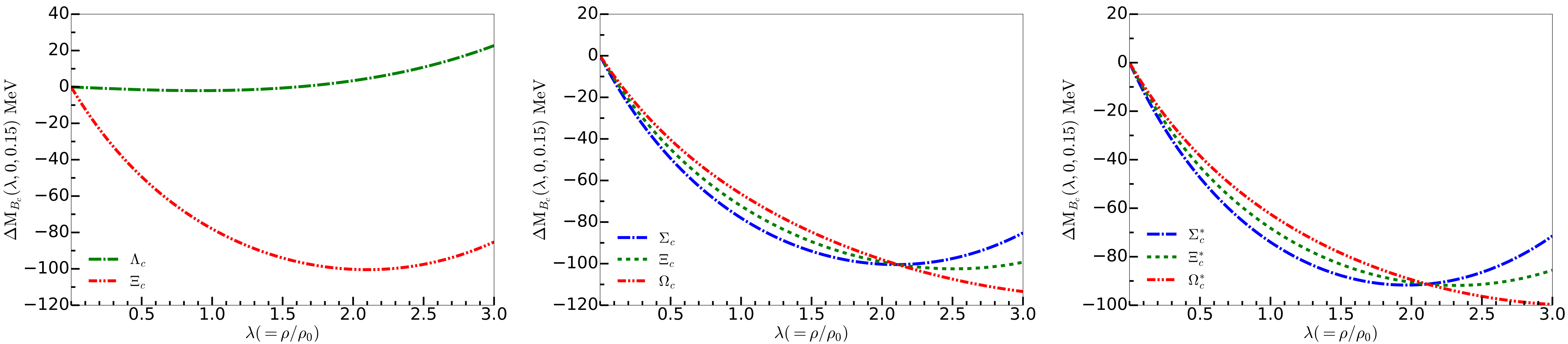
RESULTS

The singly heavy baryons in baryonic matter.

Anti triplet

Sextet(S=1/2)

Sextet(S=3/2)



The change of singly heavy baryon masses in hyperon mixed matter

Summary

- We investigated various baryonic matters and the medium modification of the masses of SU(3) baryons based on a pion mean-field approach and linear-response approximation.

- We determined the density-dependent parameters using the empirical data related to nuclear matter. The results are in good agreement with the data extracted from the empirical and experimental data.

- We also predicted the mass shifts of the low-lying SU(3) baryons including heavy baryons in various baryonic matters. The change of the baryon masses reveal very different dependence on the baryon density depending on their quantum number.

Thank you very much

Back up

- Spin-spin interaction(soliton-heavy quark)[3]

$$H_{LQ} = \frac{2}{3}\frac{\kappa}{m_Q M_{cl}} S_L \cdot S_Q$$

- Spin-spin interaction(light quark- light quark)[10]

$$H_{\mathrm{hf}} = \delta^{\mathrm{hf}} S_1 \cdot S_2$$

- EM interaction between soliton and heavy quark[10]

$$H^{\mathrm{Coul}}_{\mathrm{sol-h}} = \alpha^{\mathrm{sol-h}} \hat{Q}_{sol} \cdot \hat{Q}_h$$

[3] G. S. Yang H. Ch. Kim, Phys. Lett.B. **808**, 135619 (2020)
[10] G. S. Yang and H.-Ch. Kim, Phys. Rev. D. **94**, 07152 (2016).