Delta matter in a parity doublet model

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@JAEA

(May 22, 2017)

Based on

- Yusuke Takeda, Youngman Kim, M.Harada, arXiv:1704.04357

See also

- M. Harada, Y.L. Ma, D. Suenaga, Y. Takeda, arXiv:1612.03496
- Y. Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015); Erratum: Phys. Rev. C 95, 059903 (2017).

Introduction

Origin of Mass ?

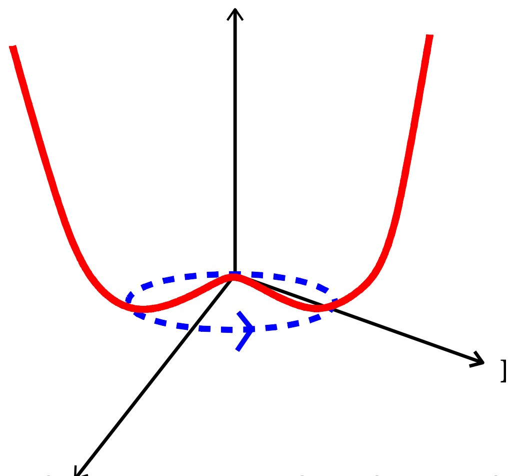
of Hadrons

of Us

=

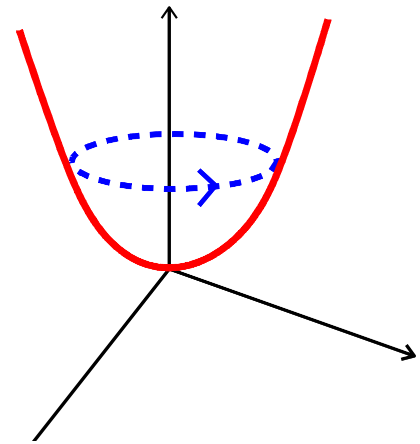
One of the Interesting problems of QCD

Mass generated by the spontaneous chiral symmetry breaking



chiral symmetry broken phase
at vacuum

$\langle \bar{q}q \rangle \neq 0$ (chiral condensate)

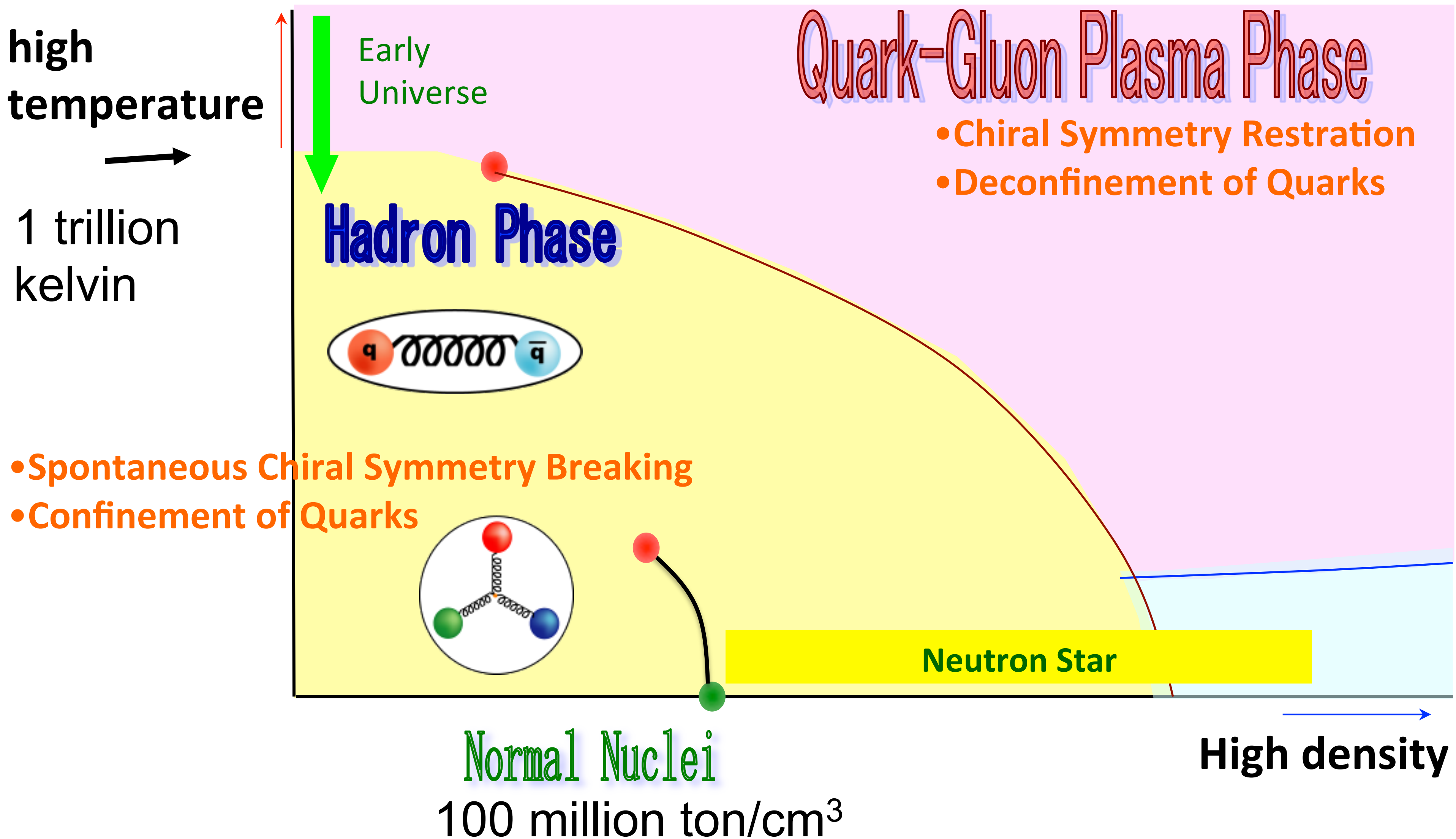


chiral symmetric phase
at high T and/or density

$\langle \bar{q}q \rangle = 0$

- The spontaneous chiral symmetry breaking is expected to generate a part of hadron masses.
- It causes mass difference between chiral partners.

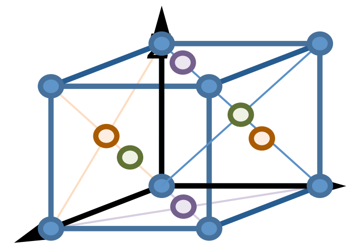
Phase diagram of Quark-Gluon system



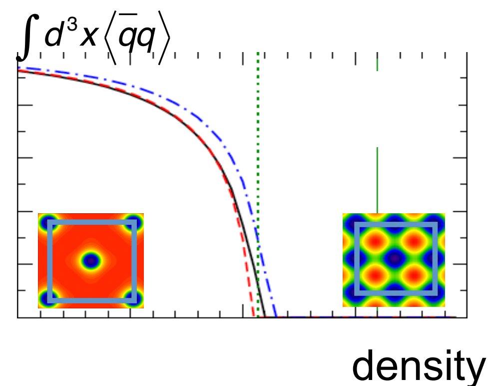
Dense nuclear matter by a Skyrme-crystal model

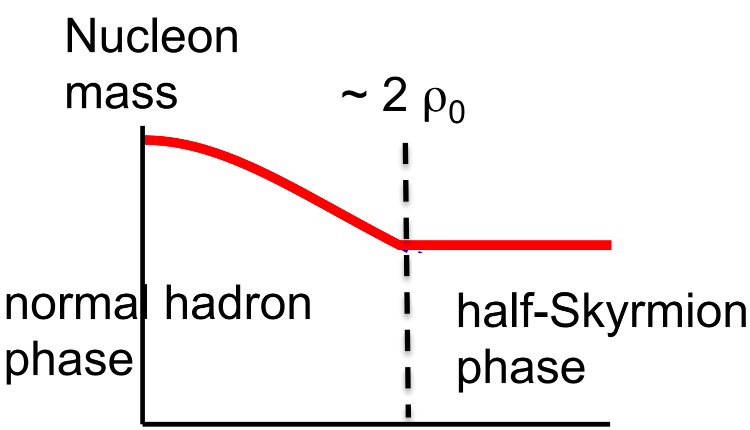
- Y. –L. Ma, M. Harada, H.K. Lee, Y. Oh, B. –Y. Park, M. Rho, PRD88 (2013) 014016
- Y. –L. Ma, M. Harada, H.K. Lee, Y. Oh, B. –Y. Park, M. Rho, PRD90 (2014) 34105

- There exists the "half-Skyrmion phase" where the space-average of the chiral condensate vanishes.



- Nucleon mass decreases with density in the normal phase, while i
is stable In the half-Skyrmion phase.





Chiral invariant mass ?

Chiral Invariant Mass of Hadrons ?

- Parity doublet model for light baryons
  - In [C.DeTar, T.Kunihiro, PRD39, 2805 (1989)], N*(1535) is regarded as the chiral partner to the N(939) having the chiral invariant mass.

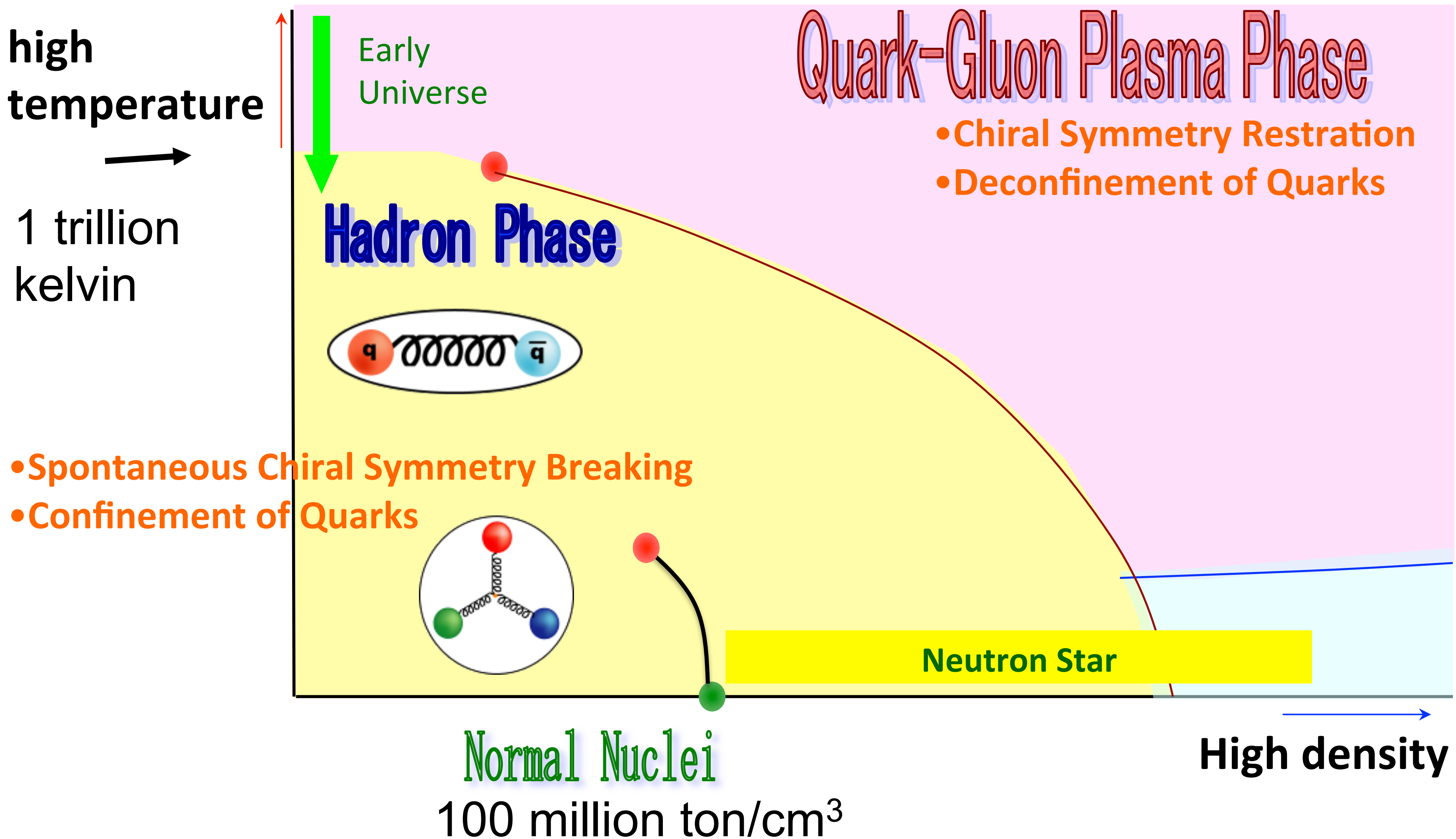
$$m_B = m_{0B} + m_{\langle \bar{q}q \rangle}$$

chiral invariant mass (m_{0B})

spontaneous chiral symmetry breaking ($m_{\langle \bar{q}q \rangle}$)

- How much mass of nucleon is from the spontaneous chiral symmetry breaking ?
- What is the value of the chiral invariant mass ?

Phase diagram of Quark-Gluon system



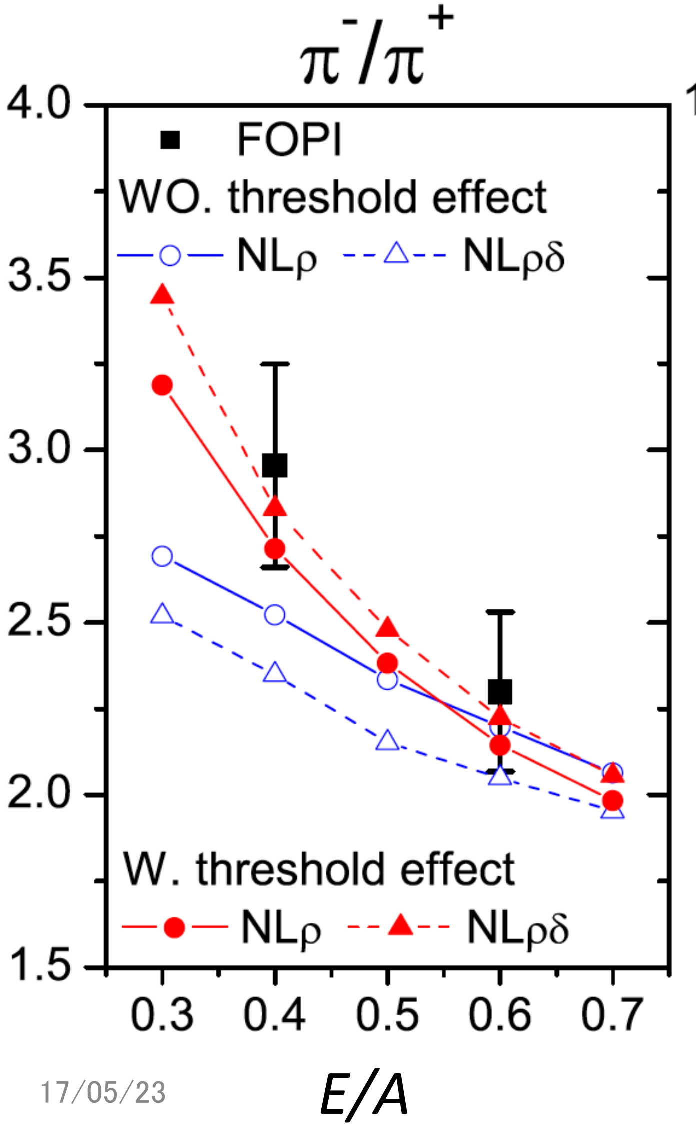
In [Y. Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015)], we studied nuclear matter using a parity doublet model, and showed some relations between the chiral invariant mass of nucleon and the phase structure. We also presented a density dependence of the nucleon mass, which changes reflecting the partial chiral symmetry restoration.

What happens to the masses of other hadrons in nuclear matter ?

In this talk, I focus on the mass of Delta baryon in matter.

π^-/π^+ ratio in low-energy Heavy-Ion Collision

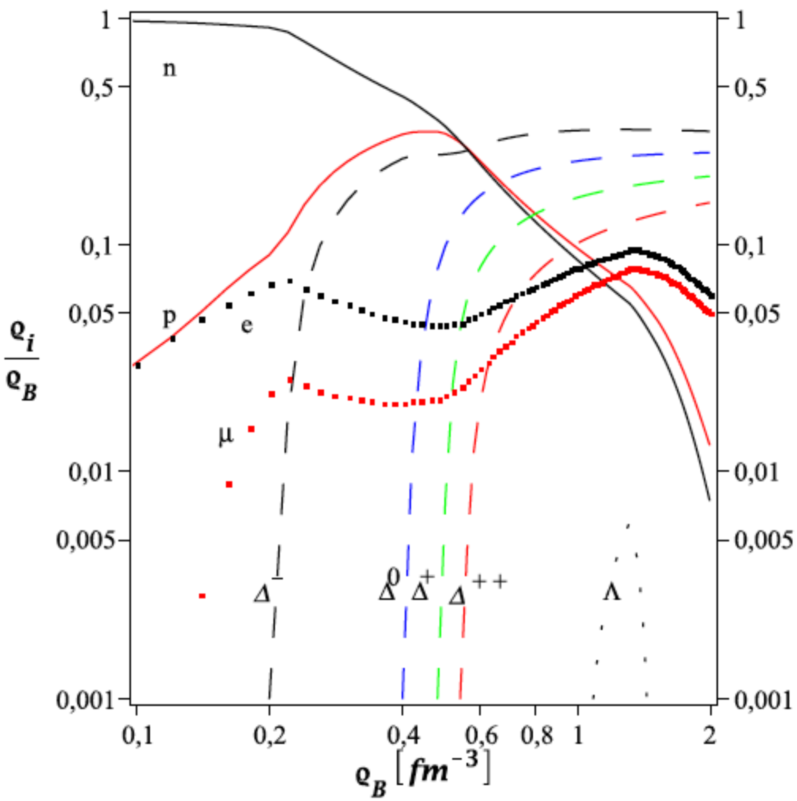
T.Song, C.M.Ko, Phys. Rev. C91, 014901 (2015)



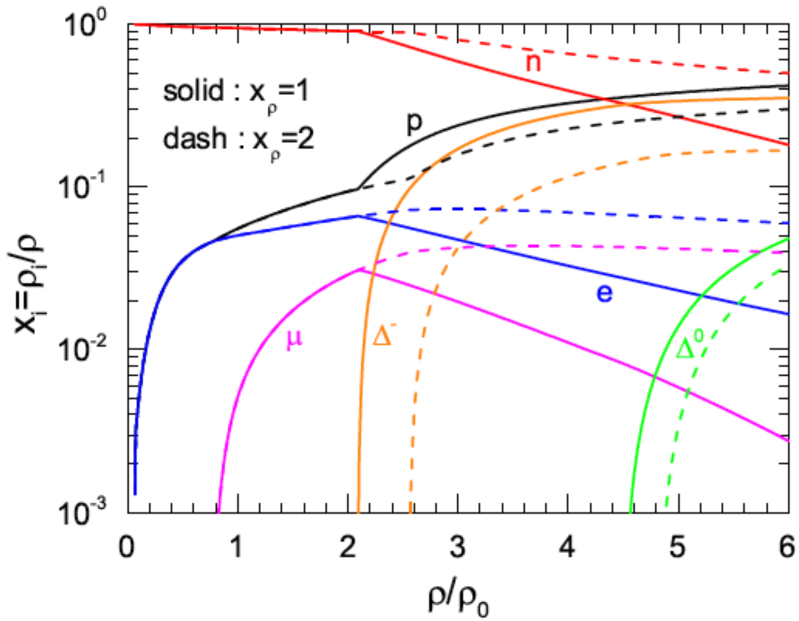
- Solid and dashed curves correspond to two different models which predict different values for the symmetry energy.
- Red curves include the mass shift of Delta baryon.
- The effect of symmetry energy is reversed by the effect of mass shift of Δ.

Delta matter in Neutron Star

T.Schurhoff, S. Schramm, V.Dexheimer, Astrophys. J. 724, L74 (2010).



B. J. Cai, F. J. Fattoyev, B. A.Li, W.G.Newton, Phys. Rev. C 92, 015802 (2015).



There may exist Delta matter in $\rho_B > 2\ \rho_0$.

Delta Matter in low-E HIC ?

- In [Y.Takeda, Y.Kim, M.Harada, arXiv: 1704.04357], we study the possibility of Delta matter using a hadronic model based on the parity doublet structure for Delta baryons and nucleons.
- There are some differences of HIC with Neutron star: e.g.
  - Weak interaction does not contribute in HIC.
  - Hadrons including strange quark can be neglected in low-energy HIC.

Outline

1. Introduction
2. Nuclear matter from a parity doublet model
3. Effective mass of Delta in nuclear matter
4. Delta matter
5. Predictions of Delta matter
6. Summary

2. Nuclear matter from a parity doublet model

Y. Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015)

Parity Doublet model

C.DeTar, T.Kunihiro, PRD39, 2805 (1989)
D.Jido, M.Oka, A.Hosaka, PTP106, 873 (2001)

- An excited nucleon with negative parity such as N*(1535) is regarded as the chiral partner to the N(939) which has the positive parity.
- These nucleons have a chiral invariant mass in addition to the mass generated by the spontaneous chiral symmetry breaking.
- In this model, the origin of our mass is not only the chiral symmetry breaking.

Determination of the parameters at vacuum

- Masses of parity eigenstates

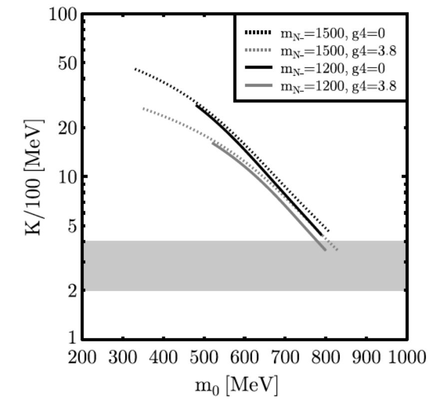
$$m_\pm = \frac{1}{2}\left[\sqrt{(g_1+g_2)^2\,\bar{\sigma}^2 + 4m_0^2} \mp (g_2 - g_1)\,\bar{\sigma}\right]$$

- Determination of parameters at vacuum (D.Jido et al., PTP106, 873 (2001))
  - Inputs : m_+ = 939 MeV, m_- = 1535 MeV, $\sigma_0 = f_\pi$ = 93 MeV, and $g_{\pi N+N-}$ = 0.7 obtained from $\Gamma_{N^*\to\pi N}$ = 75 MeV.
  - Outputs : m_0 = 270 MeV , g_1 = 9.8 , g_2 = 16 .
- Global fit in an extended model (S.Gallas et al., PRD82, 014004 (2010)) shows m_0 = 460 +- 136 MeV.

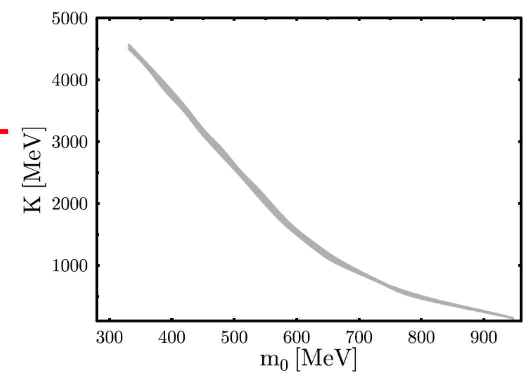
Nuclear matter in parity doublet models

- A parity doublet model including omega meson with 4-point interaction is used in a Walecka-type mean field analysis.
  - Large value of m_0 is needed to reproduce the incompressibility.
- Rho meson is further included with 4-point interaction.
  - $m_0 > 800$ MeV is needed to have 100 < K < 400 MeV
- In our analysis [Y.Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015)], we construct a model with a 6-point interaction of sigma, but without 4-point interaction for vector mesons.
- Our results show that K = 240 MeV is reproduced for m_0 = 500 - 900 MeV.

D.Zschiesche et al., PRC75, 055202 (2007)



V.Dexheimer et al., PRC77, 025803 (2008)



Model parameters : Inputs from vacuum phenomenology

- We include sigma and omega mesons as well as the pion and rho meson in our model
- We have 11 parameters.
  - 3 parameters in the scalar potential

$$\bar{\mu}\,,\ \lambda\,,\ \lambda_6\ :\ V_\sigma = \frac{1}{2}\bar{\mu}^2\sigma^2 + \frac{1}{4}\lambda\sigma^4 - \frac{1}{6}\lambda_6\sigma^6$$

  - 3 masses for π, ρ, ω : $m_\pi\,,\ m_\rho\,,\ m_\omega$
  - 5 parameters in the baryon sector

    m_0 : chiral invariant mass ; $g_1\,,\ g_2$: Yukawa couplings

    $g_{\rho NN}\,,\ g_{\omega NN}$: ρNN and ωNN couplings

- We determine 10 parameters for a given value of the chiral invariant mass m_0 .
- We use the following 6 inputs at vacuum

m_+	m_-	m_ω	m_ρ	f_π	m_π
939	1535	783	776	93	140

Inputs from medium property

- We calculate the thermodynamic potential in the nuclear medium in our model, using the mean field approximation.
- Then, we determine the 4 remaining parameters from the following physical inputs for a given value of the chiral invariant mass m_0.
  - Nuclear saturation density

$$\rho(\mu_B^* = 923 \text{ MeV}) = \rho_0 = 0.16\,\text{fm}^{-3}$$

  - Binding energy at normal nuclear density

$$\left[\frac{E}{A} - m_+\right]_{\rho_0} = \left[\frac{\epsilon}{\rho_B} - m_+\right]_{\rho_0} = -16 \text{ MeV}$$

  - Incompressibility

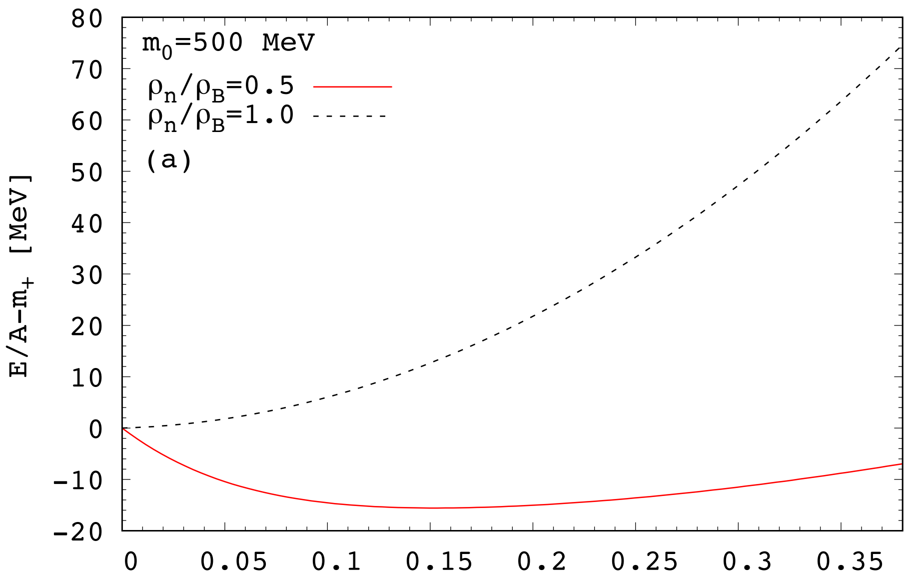
$$K = 9\rho_0^2 \frac{\partial^2 (E/A)}{\partial \rho^2}\bigg|_{\rho_0} = 9\rho_0 \frac{\partial \mu_B}{\partial \rho}\bigg|_{\rho_0} = 240 \text{ MeV}$$

  - Symmetry energy : $E_{sym}(\rho_0) = 31$ MeV

Binding Energy, Pressure

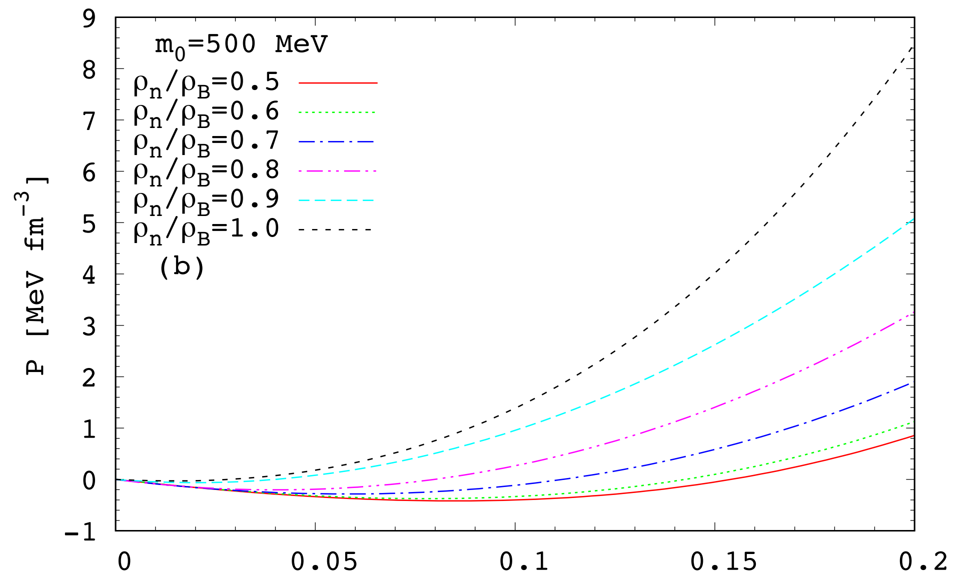
Y. Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015);
Erratum: Phys. Rev. C 95, 059903 (2017).

Binding Energy



ρ_B (fm^3)

Pressure

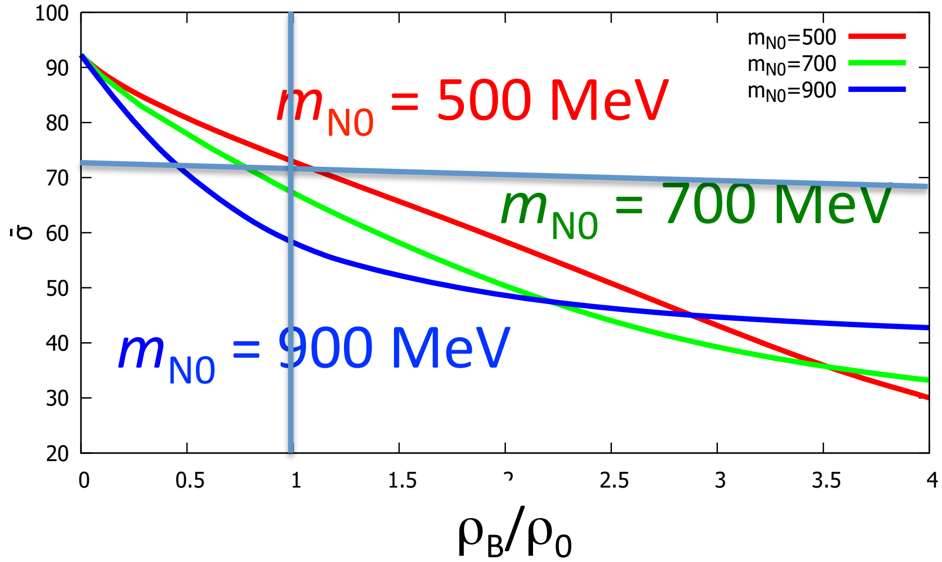


ρ_B (fm^3)

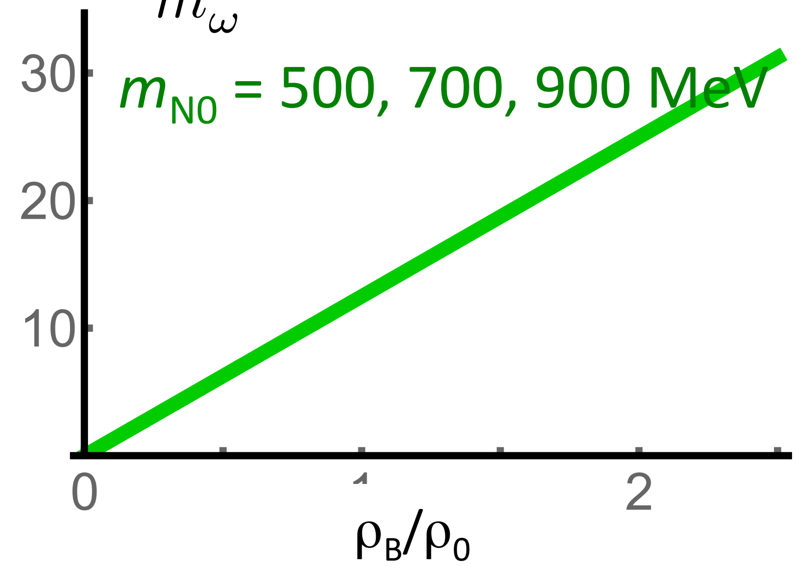
m_{N0} = 500 MeV

Density Dependence of Mean fields

$\langle\sigma\rangle$ (MeV)



$$\langle\omega\rangle = \frac{g_{\omega NN}}{m_\omega^2}\rho_B \quad \text{(MeV)}$$



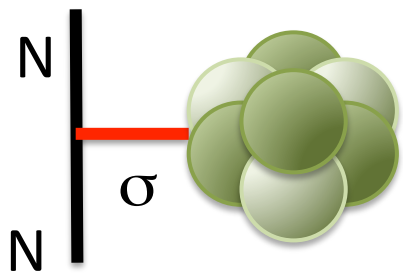
An experiment shows $f_\pi^*/f_\pi \sim 0.8$ at $\rho_B = \rho_0$.

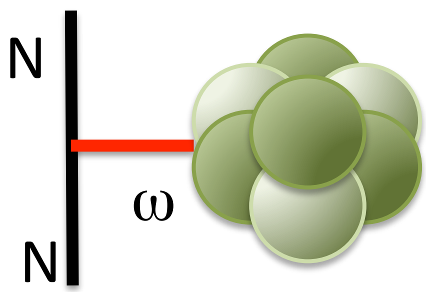
[K. Suzuki et al., Phys. Rev. Lett. 92, 072302 (2004)]

⇒ We use m_{N0} = 500, 700 MeV as typical examples

Effective masses of nucleons

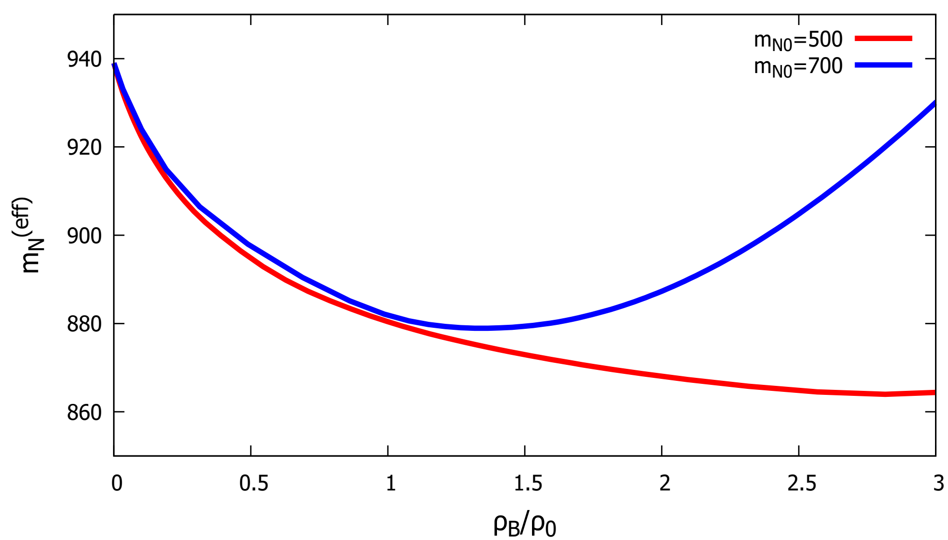
- We define effective masses of nucleons by including effects of exchanging the sigma and omega mesons in the mean field approximation in symmetric nuclear matter, following our recent work [M.Harada, Y.L.Ma, D.Suenaga, Y.Takeda, arXiv:1612.03496].





$$m_N^{(\mathrm{eff})} = m_N + g_{\omega NN}\bar{\omega}$$

$$m_N = \frac{1}{2}\left[\sqrt{(g_1+g_2)^2\bar{\sigma}^2 + 4m_0^2} - (g_2 - g_1)\bar{\sigma}\right]$$



3. Effective mass of Delta in nuclear matter

Chiral Partner Structure of Delta

D.Jido, T.Hatsuda, T.Kunihiro, PRL84, 3252 (2000)
D.Jido, M.Oka, A.Hosaka, PTP106, 873 (2001)

- Δ(1232) and Δ(1700) are regarded as chiral partners.

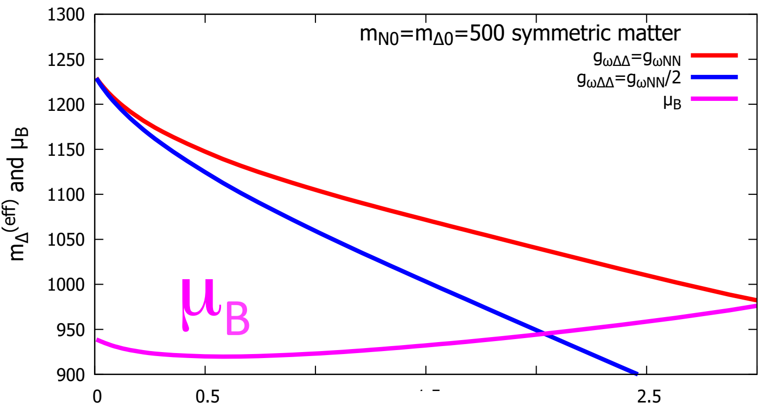
$$m_{\Delta^\pm} = \sqrt{(g_{\Delta 1} + g_{\Delta 2})^2 \bar{\sigma}^2 + m_{\Delta 0}^2} \mp (g_{\Delta 1} - g_{\Delta 2})\bar{\sigma}$$

- We regard $m_{\Delta 0}$ as a parameter.
- We use masses of D(1232) and D(1700) as inputs to determine the values of $g_{\Delta 1}$ and $g_{\Delta 2}$ for a given value of $m_{\Delta 0}$.
- We study dependence of our results on the value of $m_{\Delta 0}$.

Effective masses vs. Chemical potential

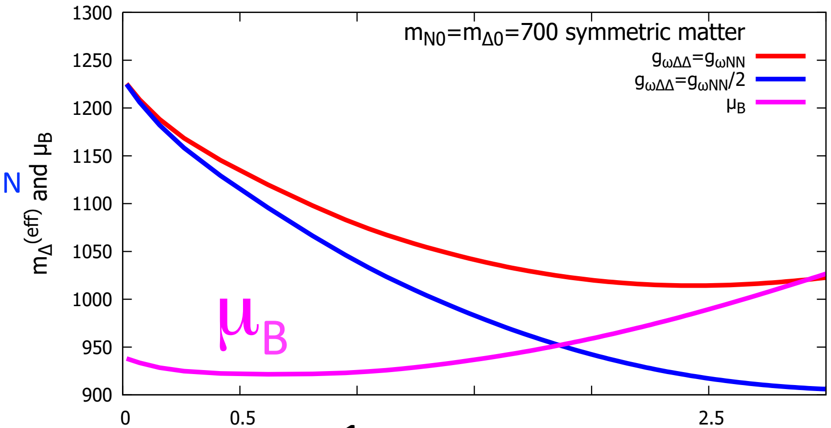
$$m_{\Delta}^{(\mathrm{eff})} = \sqrt{(g_{\Delta 1}+g_{\Delta 2})^2\,\bar{\sigma}^2 + m_{\Delta 0}^2} - (g_{\Delta 1}-g_{\Delta 2})\bar{\sigma} + g_{\omega\Delta\Delta}\bar{\omega}$$

$m_{N0} = m_{D0} = 500$ MeV



1 ρ_B/ρ_0 2 3

$m_{N0} = m_{D0} = 700$ MeV



1 ρ_B/ρ_0 2 3

$g_{\omega\Delta\Delta} = g_{\omega NN}$

$g_{\omega\Delta\Delta} = 0.5\, g_{\omega NN}$

- Mass of Delta baryon becomes smaller than the chemical potential μ_B.
- This indicate that the Delta baryon is populated in the ground state, forming Delta Fermi sea.

Delta Matter ?

4. Delta Matter

Thermodynamic Potential

- We constructed the thermodynamic potential at mean field level including the effect of Delta baryon.

$$\Omega = -\frac{1}{2}m_\rho^2\bar{\rho}^2 - \frac{1}{2}m_\omega^2\bar{\omega}^2 + \frac{1}{2}\bar{\mu}^2\bar{\sigma}^2 - \frac{1}{4}\lambda_4\bar{\sigma}^4 + \frac{1}{6}\lambda_6\bar{\sigma}^6 + \bar{m}\epsilon\bar{\sigma}$$
$$-\sum_{\alpha=p,n}\int\frac{dk}{\pi^2}k^2(\mu_\alpha - E_\alpha)\,\theta(\mu_\alpha - E_\alpha)$$

contribution of the Delta baryon

$$-2\sum_{a=++,+,0,-}\int\frac{dk}{\pi^2}k^2(\mu_{\Delta^a} - E_{\Delta^a})\,\theta(\mu_{\Delta^a} - E_{\Delta^a})$$

$$\mu_{\Delta^{++}} = \mu_B + \frac{3}{2}\mu_I\ , \quad \mu_{\Delta^+} = \mu_B + \frac{1}{2}\mu_I$$

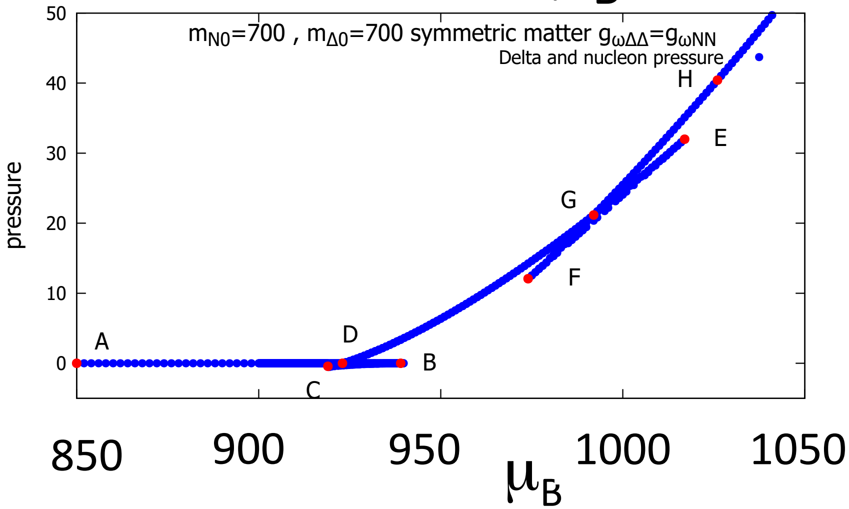
$$\mu_{\Delta^0} = \mu_B - \frac{1}{2}\mu_I\ , \quad \mu_{\Delta^-} = \mu_B - \frac{3}{2}\mu_I$$

μ_B: Baryon chemical potential
μ_I: Isospin chemical potential

Pressure, Density, Phase structure

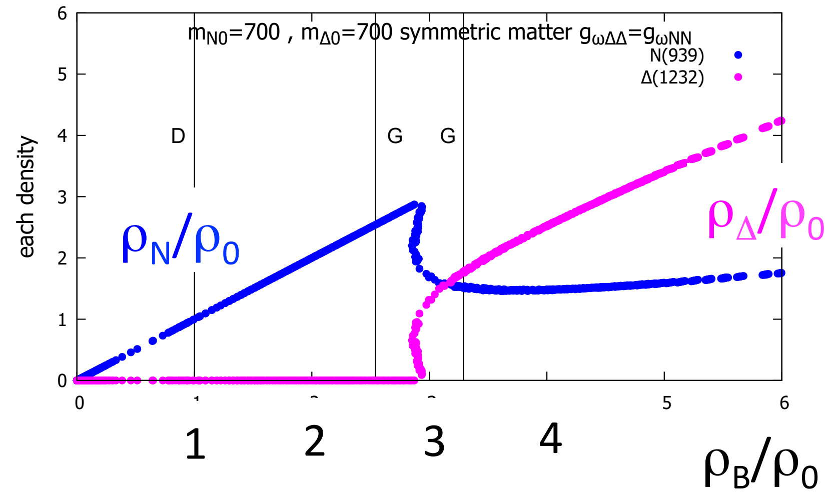
$g_{\omega\Delta\Delta} = g_{\omega NN}$

Pressure vs. μ_B

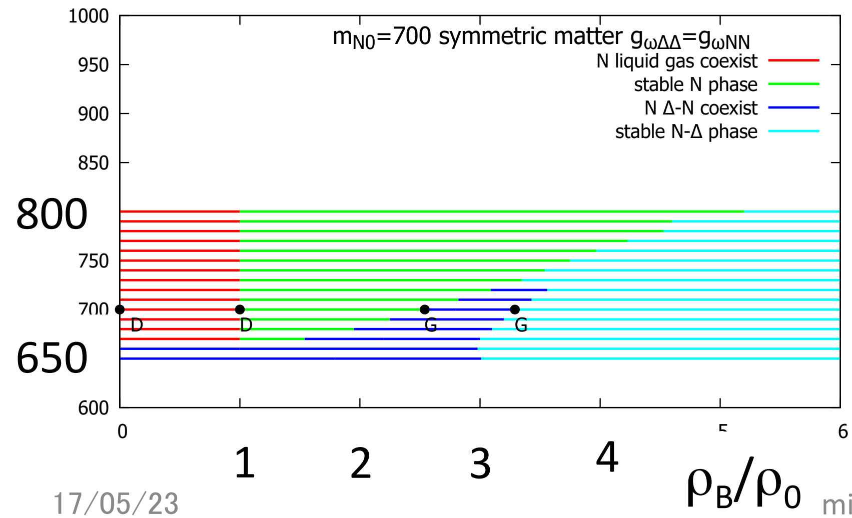


$m_{N0} = m_{D0} = 700$ MeV

number Density vs. ρ_B



$m_{\Delta 0}$ Phase structure

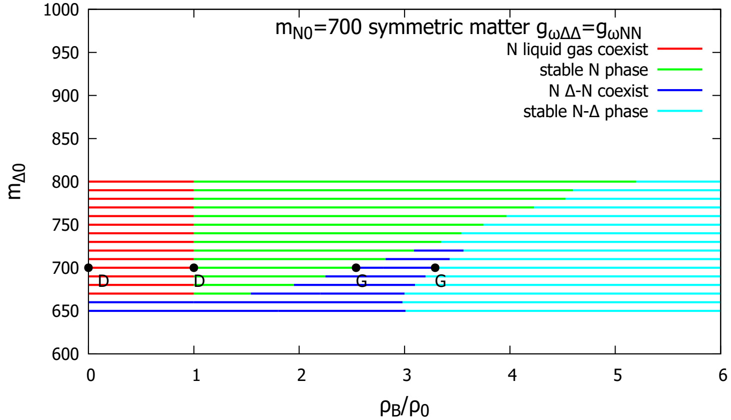


- N liquid-gas coexistence phase
- stable N phase
- coexistence phase of Delta-N matter and nuclear matter
- stable N-Delta phase

Dependence of the phase structure on ωΔΔ coupling

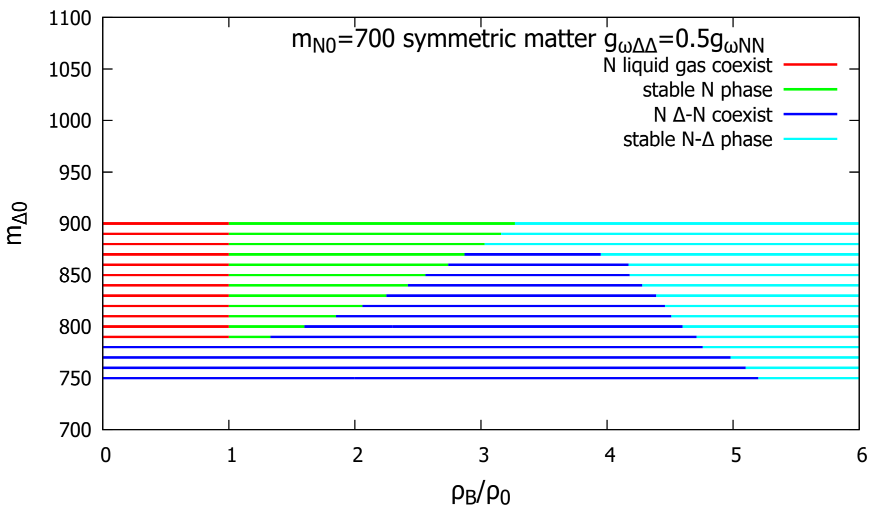
$m_{N0} = m_{D0} = 700$ MeV

$g_{\omega\Delta\Delta} = g_{\omega NN}$

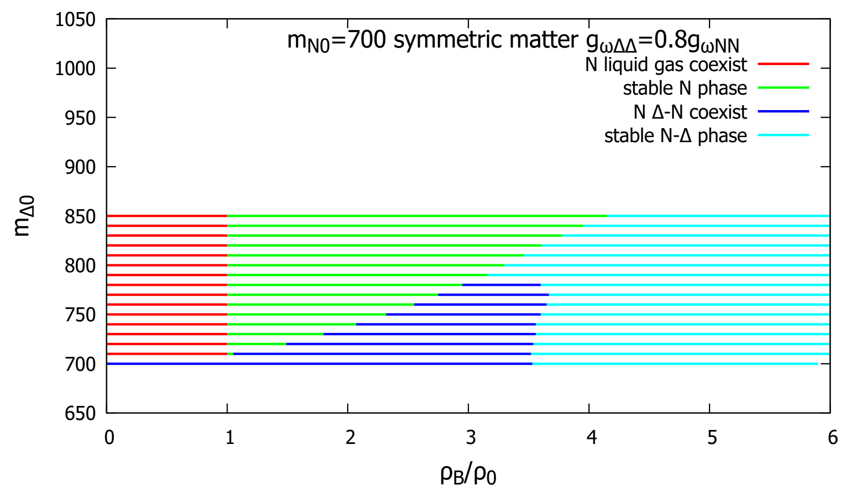


- N liquid-gas coexistence phase
- stable N phase
- coexistence phase of Delta-N matter and nuclear matter
- stable N-Delta phase

$g_{\omega\Delta\Delta} = 0.5\ g_{\omega NN}$



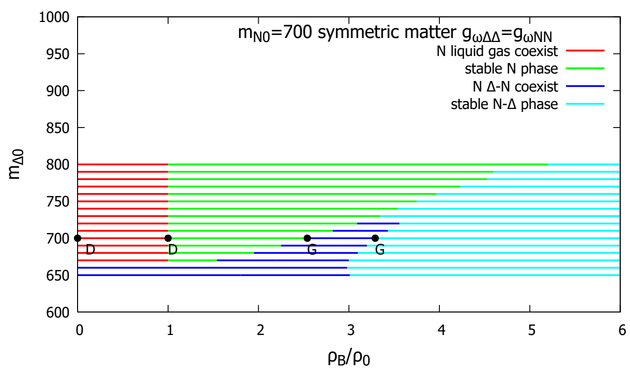
$g_{\omega\Delta\Delta} = 0.8\ g_{\omega NN}$

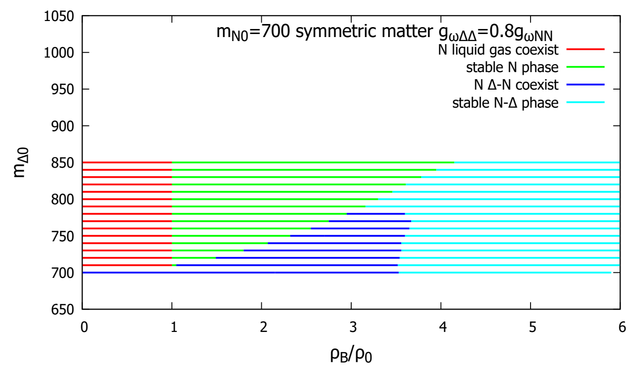


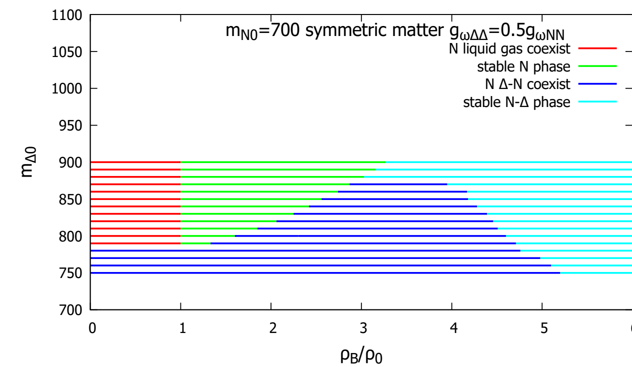
Dependence of phase structure on m_{N0}

m_{N0} = 700 MeV

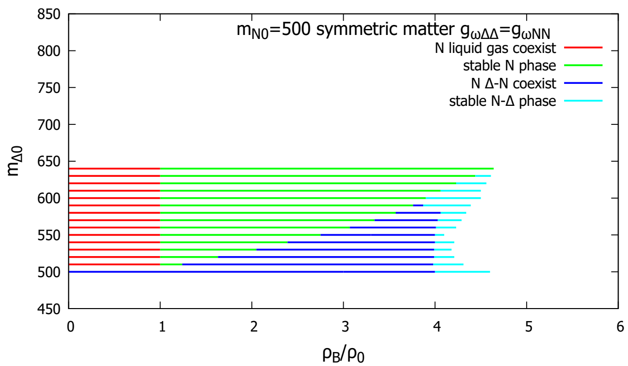
$g_{\omega\Delta\Delta} = g_{\omega NN}$ $\quad$ $g_{\omega\Delta\Delta} = 0.8\, g_{\omega NN}$ $\quad$ $g_{\omega\Delta\Delta} = 0.5\, g_{\omega NN}$

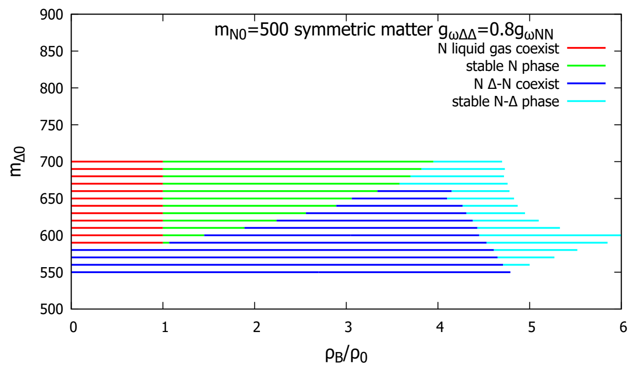


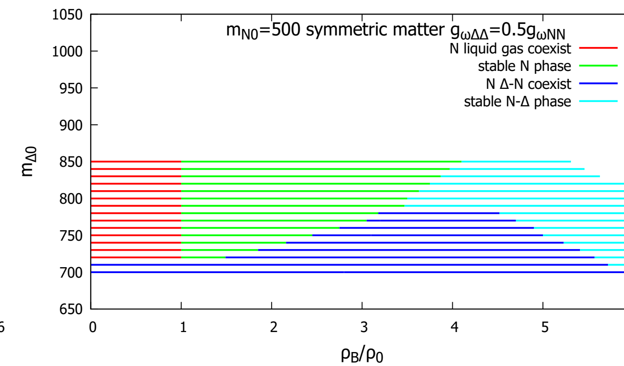




m_{N0} = 500 MeV







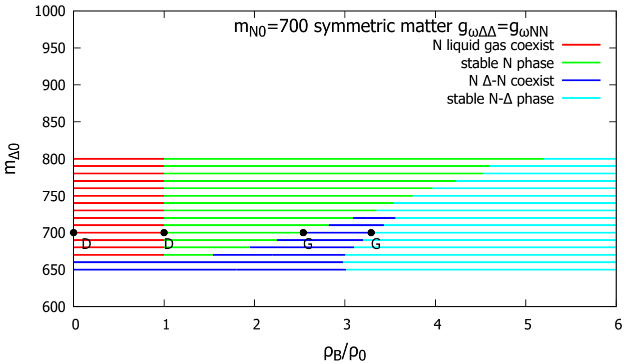
Phase structure in Asymmetric matter

- neutron matter phase
- neutron-proton matter phase
- coexistence phase of Delta-N matter and nuclear matter
- stable N - Δ^- phase
- stable N – Δ^- - Δ^0 phase
- stable N – Δ^- - Δ^0 – Δ^+ phase
- stable N – Δ phase

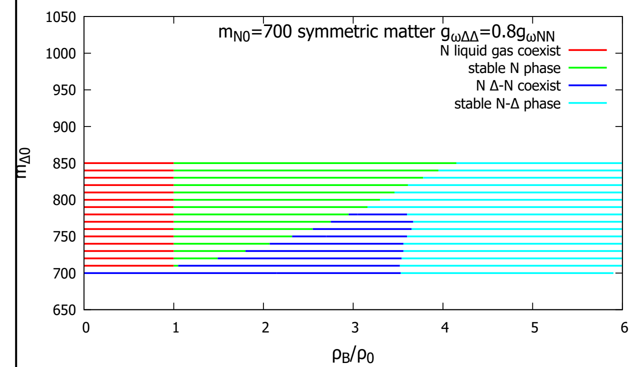
m_{N0} = 700 MeV

symmetric matter (μ_I=0)

$g_{\omega\Delta\Delta} = g_{\omega NN}$

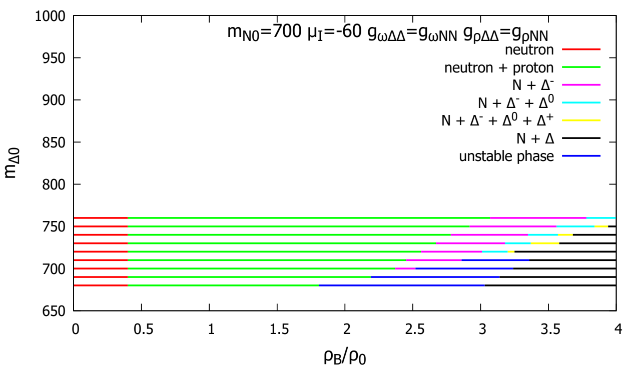


$g_{\omega\Delta\Delta} = 0.8\, g_{\omega NN}$

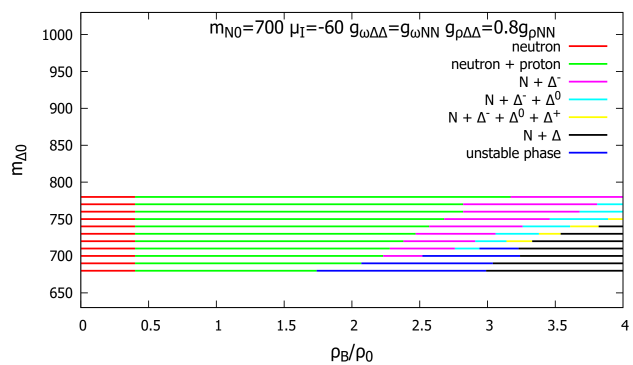


asymmetric matter (μ_I=-60MeV)

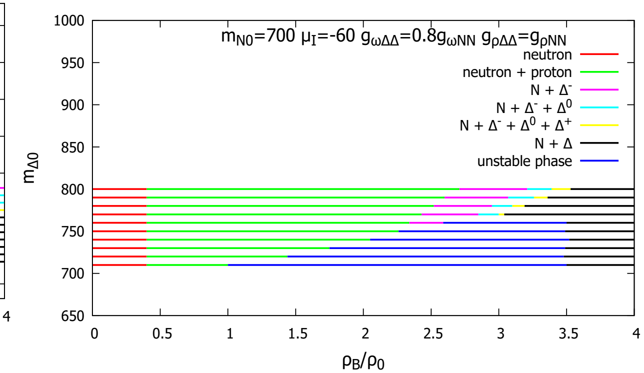
$g_{\omega\Delta\Delta} = g_{\omega NN}$; $g_{\rho\Delta\Delta} = g_{\rho NN}$



$g_{\omega\Delta\Delta} = g_{\omega NN}$; $g_{\rho\Delta\Delta} = 0.8\, g_{\rho NN}$



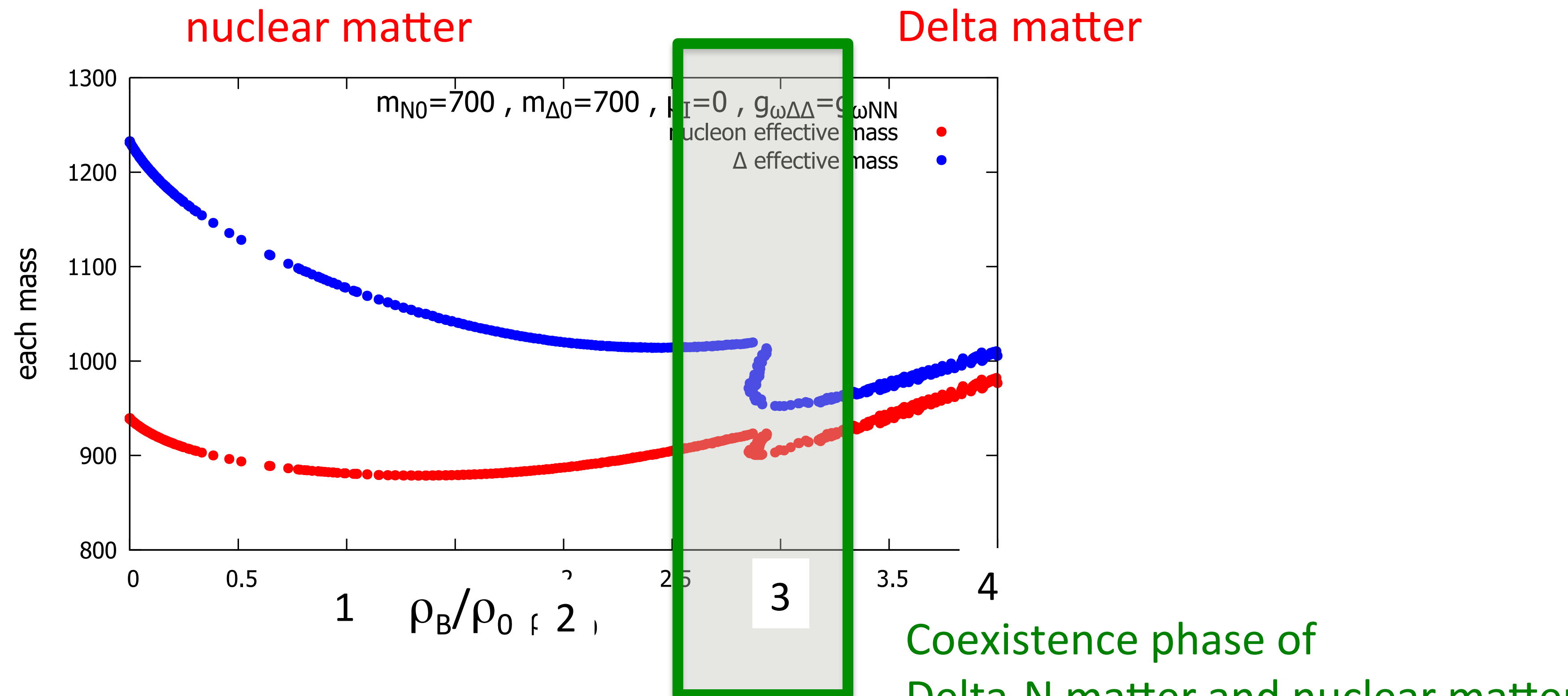
$g_{\omega\Delta\Delta} = 0.8\, g_{\omega NN}$; $g_{\rho\Delta\Delta} = g_{\rho NN}$



5. Predictions of Delta Matter

Effective masses

$m_{N0} = m_{\Delta 0} = 700$ MeV; $g_{\omega\Delta\Delta} = g_{\omega NN}$



Both the effective masses of nucleon and Delta suddenly change their values associated with the appearance of the Delta baryons in matter.

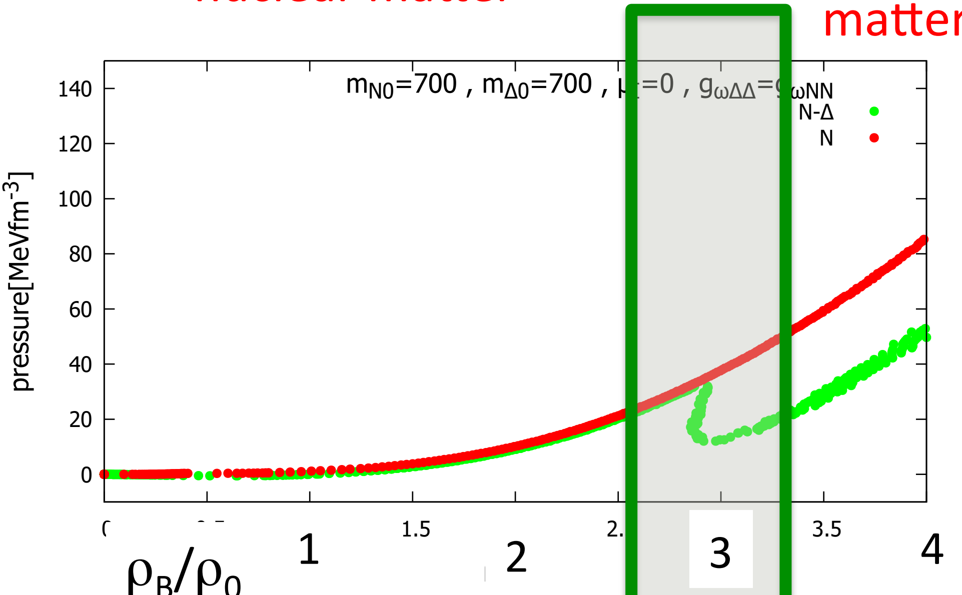
Pressure

symmetric matter

$m_{N0} = m_{\Delta 0}$ = 700 MeV; $g_{\omega\Delta\Delta} = g_{\omega NN}$

nuclear matter

Delta matter



Coexistence phase of

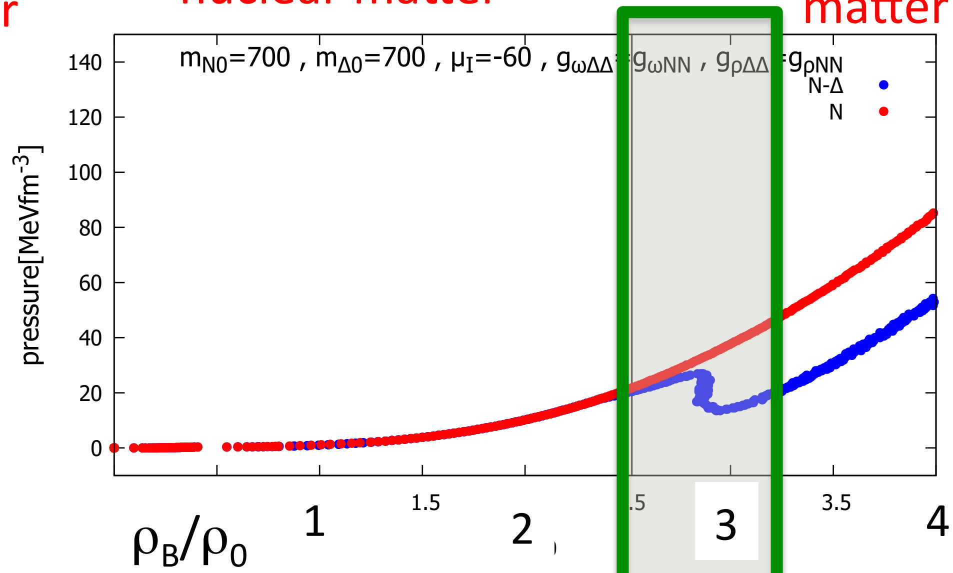
Delta-N matter and nuclear matter

asymmetric matter (μ_I = - 60 MeV)

$m_{N0} = m_{\Delta 0}$ = 700 MeV; $g_{\omega\Delta\Delta} = g_{\omega NN}$

nuclear matter

Delta matter



Coexistence phase of

Delta-N matter and nuclear matter

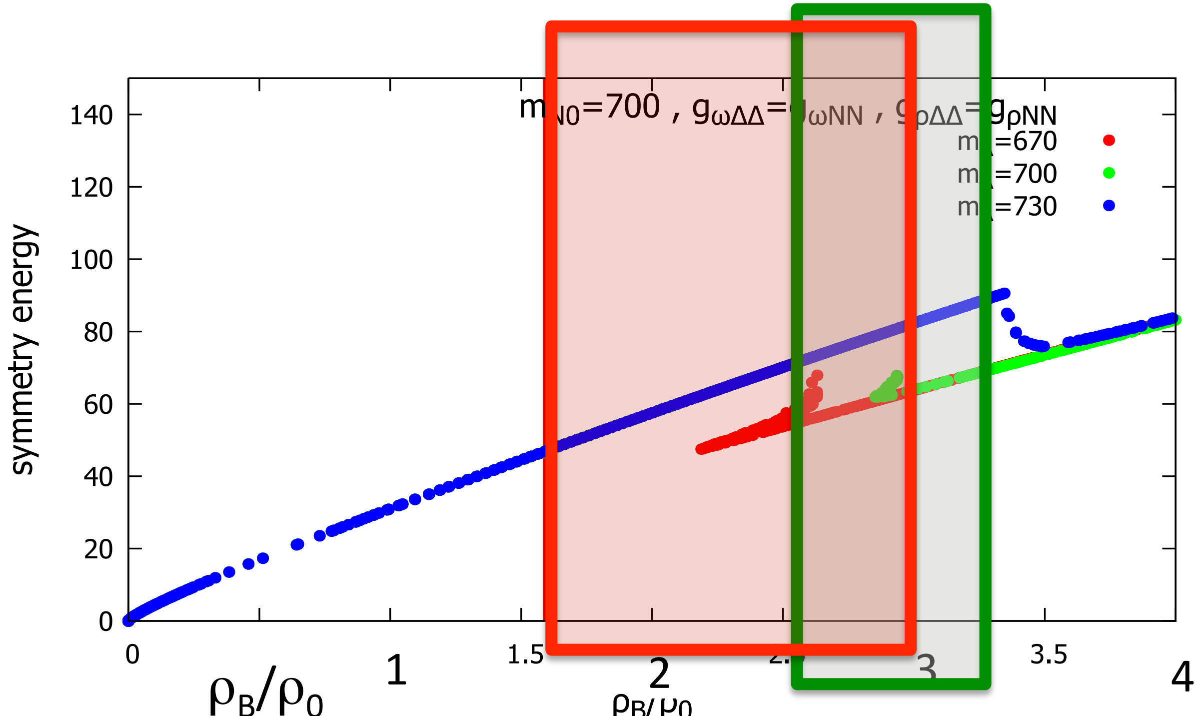
The pressure of N-Delta matter is smaller than that of the ordinary nuclear matter.

⇒ The Delta softens the equation of state as expected.

Symmetry Energy

m_{N0} = 700 MeV; $g_{\omega\Delta\Delta} = g_{\omega NN}$; $g_{\rho\Delta\Delta} = g_{\rho NN}$

$m_{\Delta 0}$ = 670 , 700 , 730 MeV



coexistence phase for $m_{\Delta 0}$ = 670 MeV

coexistence phase for $m_{\Delta 0}$ = 700 MeV

The symmetry energy suddenly changes its value around the density where Delta enters the matter.

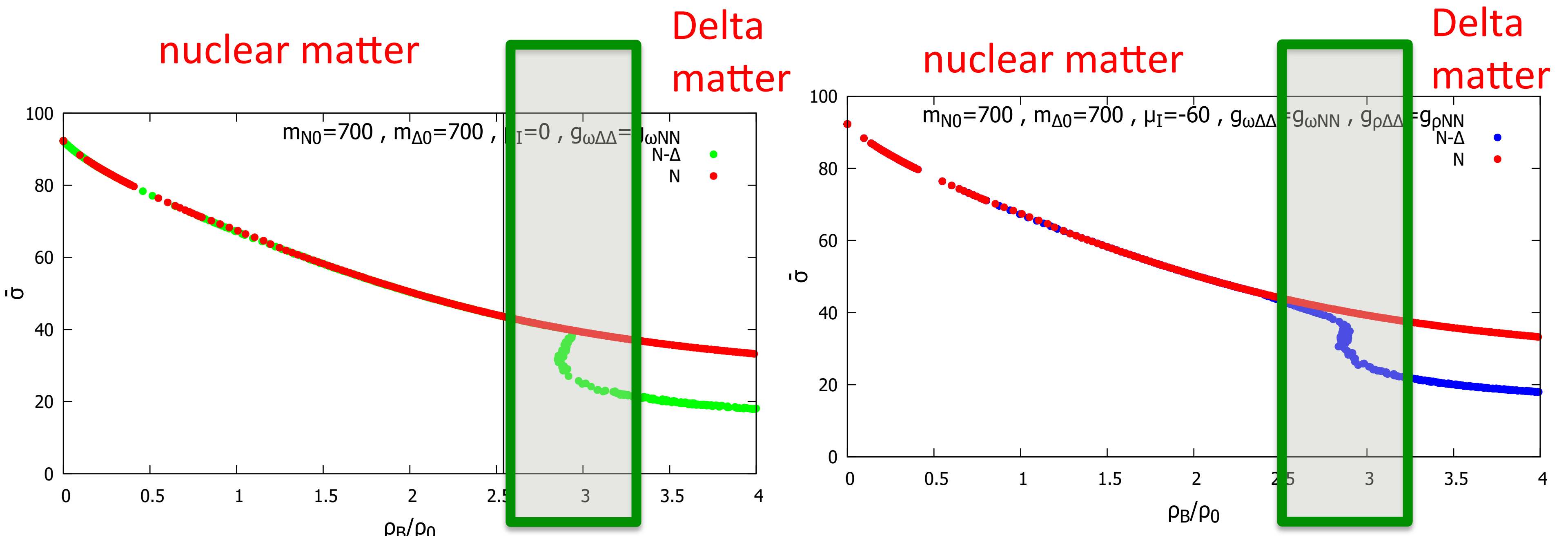
Chiral Condensate

symmetric matter

$m_{N0} = m_{\Delta 0} = 700$ MeV; $g_{\omega\Delta\Delta} = g_{\omega NN}$

asymmetric matter (μ_I = - 60 MeV)

$m_{N0} = m_{\Delta 0} = 700$ MeV; $g_{\omega\Delta\Delta} = g_{\omega NN}$



Coexistence phase of Delta-N matter and nuclear matter

Coexistence phase of Delta-N matter and nuclear matter

The appearance of Delta matter accelerates the restoration of the chiral symmetry.

6. Summary

- We include the Δ baryon based on the parity doublet structure, with the chiral invariant mass $m_{\Delta 0}$.
- We study density dependence of Δ baryon masses from the mean field contributions of sigma and omega mesons, relating it with partial chiral symmetry restoration.
- We explore phase structure and find that
  - Stable Delta matter exists for $\rho_B > 3\ \rho_0$.
  - The onset density of Delta matter can be smaller than $2\rho_0$.
- We also observed in symmetric dense matter that larger m_{N0} tends to lower the transition density to the ``stable *N*-Δ phase'' and the phase structure changes significantly with the finite isospin chemical potentials.
- We then calculated the in-medium chiral condensate, effective masses, pressure and symmetry energy to observe that the appearance of $¥Delta$ matter accelerates the chiral symmetry restoration, and that their density-dependence changes drastically around the onset density of $¥Delta$ matter.

Discussion

- In the present study we do not consider any possibility of having hyperon matter because strangeness is conserved with strong interactions and terrestrial dense matter from low-intermediate heavy ion collisions sustains much short compared to the time scale of weak interactions.
- It will be interesting to see how the observations made in this study such as the transition to Δ matter affect the observables in heavy ion collisions such as neutron-proton collective flows and π^+/π^- ratio at low and/or intermediate energy in a transport model simulation, which is relegated to our future study.
- The fate of pion condensation with Delta matter in heavy ion collisions will be investigated.

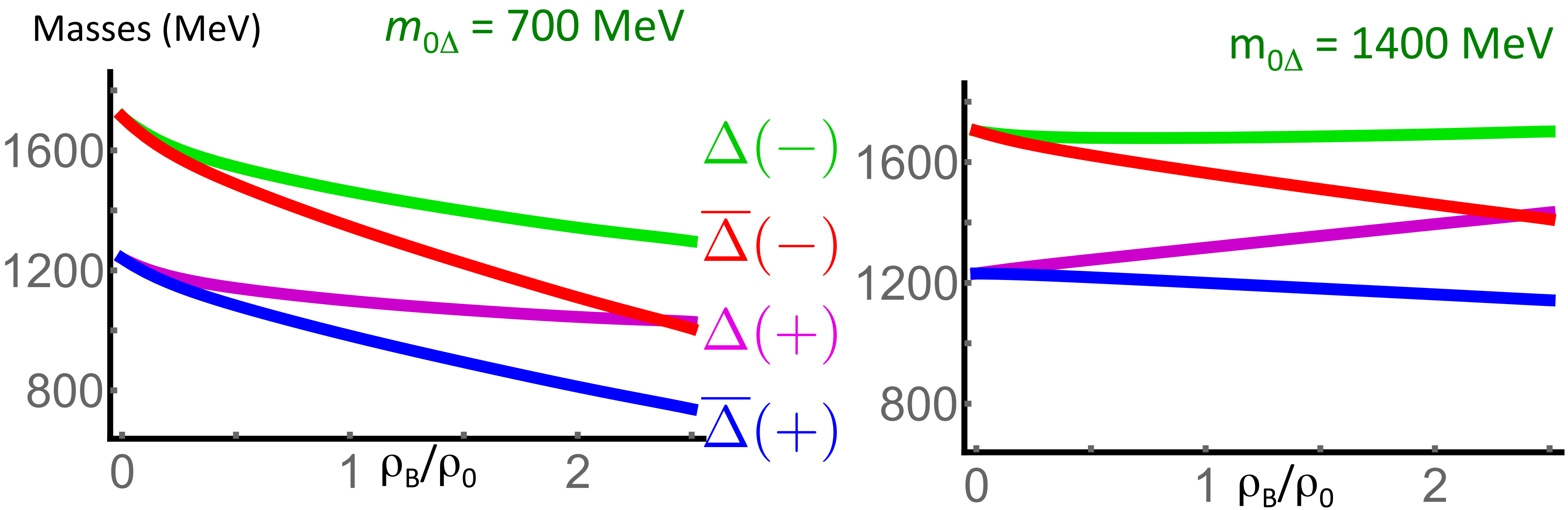
The End

Density dependence of effective masses

$$m^{(\mathrm{eff})}_{\Delta\pm} = \sqrt{(g_{\Delta 1}+g_{\Delta 2})^2\,\bar\sigma^2 + m^2_{\Delta 0}} \mp (g_{\Delta 1}-g_{\Delta 2})\bar\sigma + g_{\omega\Delta\Delta}\bar\omega \quad (\Delta\ )$$

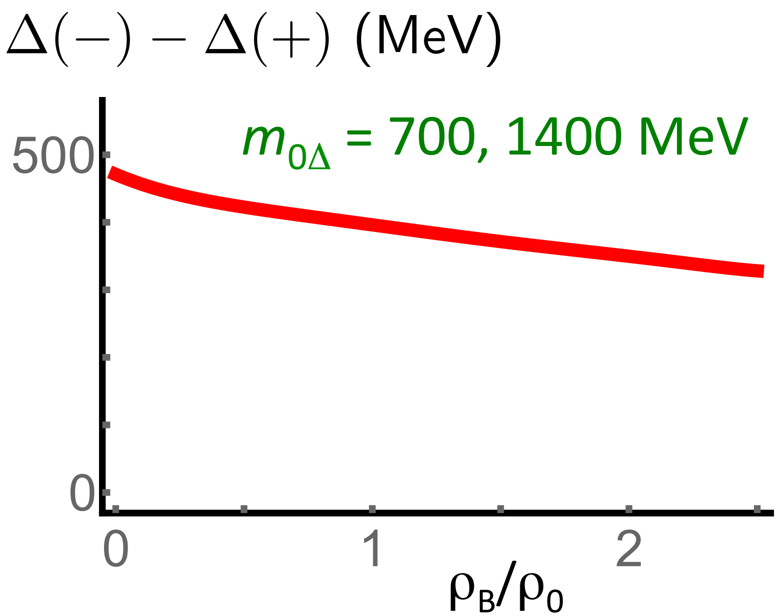
$$\overline{m}^{(\mathrm{eff})}_{\Delta\pm} = \sqrt{(g_{\Delta 1}+g_{\Delta 2})^2\,\bar\sigma^2 + m^2_{\Delta 0}} \mp (g_{\Delta 1}-g_{\Delta 2})\bar\sigma - g_{\omega\Delta\Delta}\bar\omega \quad (\text{anti-}\Delta\ )$$

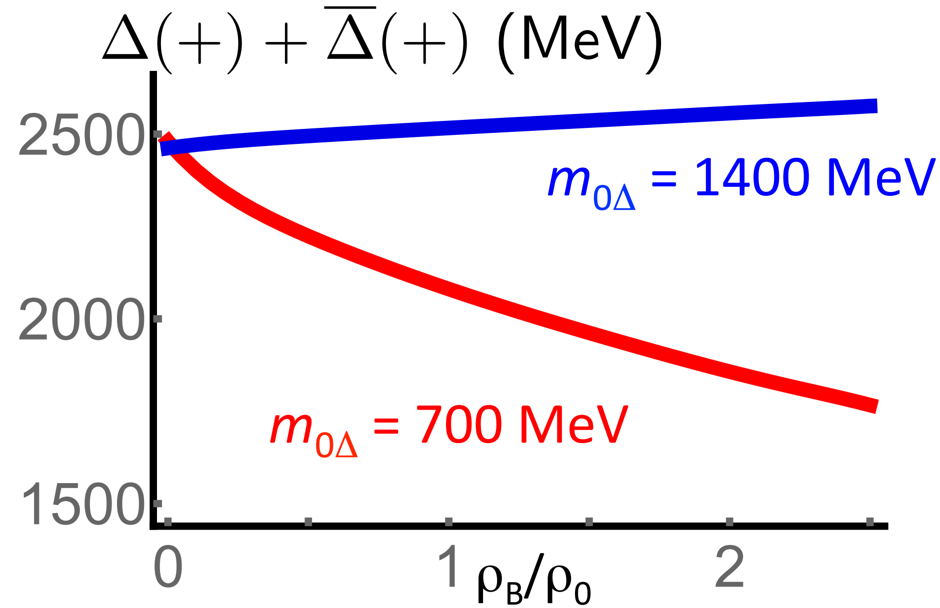
I use $g_{\omega\Delta\Delta} = g_{\omega NN} = 5.4$ as a typical example.



Increasing or decreasing of $\Delta(+)$ baryon mass only is not enough for measuring the chiral symmetry restoration.

Partial chiral symmetry restoration





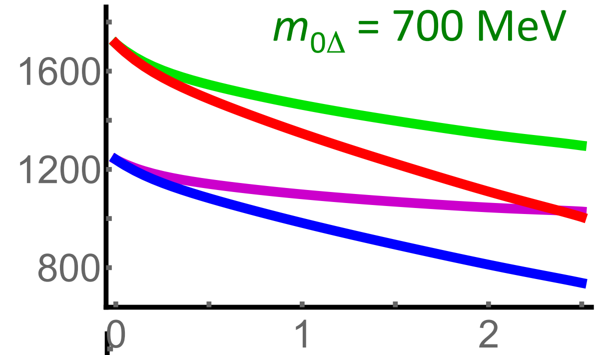
- Studying the mass difference of chiral partners gives a clue for partial chiral symmetry restoration, independently of the value of $m_{0\Delta}$.
- Taking sum of particle and anti-particle will give a clue for chiral invariant mass.

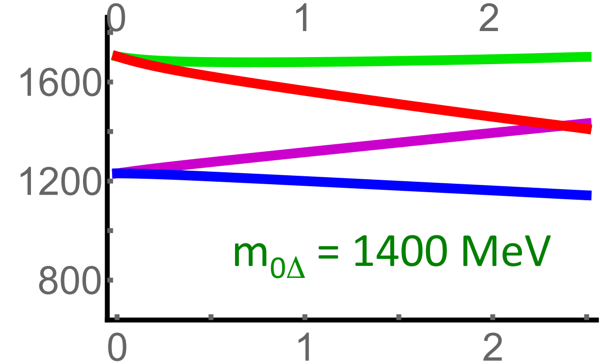
$$m_{\Delta\pm}^{(\mathrm{eff})} = \sqrt{(g_{\Delta 1} + g_{\Delta 2})^2\, \bar{\sigma}^2 + m_{\Delta 0}^2} \mp (g_{\Delta 1} - g_{\Delta 2})\bar{\sigma} + g_{\omega\Delta\Delta}\bar{\omega} \quad (\Delta\ )$$

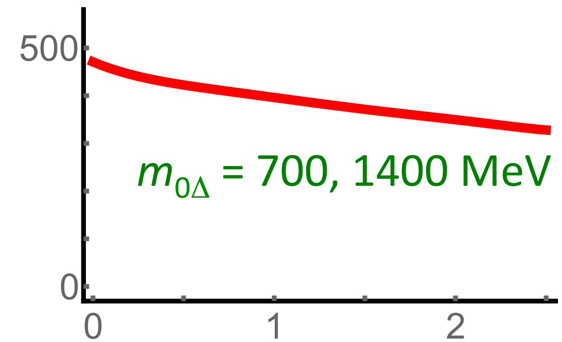
$$\overline{m}_{\Delta\pm}^{(\mathrm{eff})} = \sqrt{(g_{\Delta 1} + g_{\Delta 2})^2\, \bar{\sigma}^2 + m_{\Delta 0}^2} \mp (g_{\Delta 1} - g_{\Delta 2})\bar{\sigma} - g_{\omega\Delta\Delta}\bar{\omega} \quad (\text{anti-}\Delta\ )$$

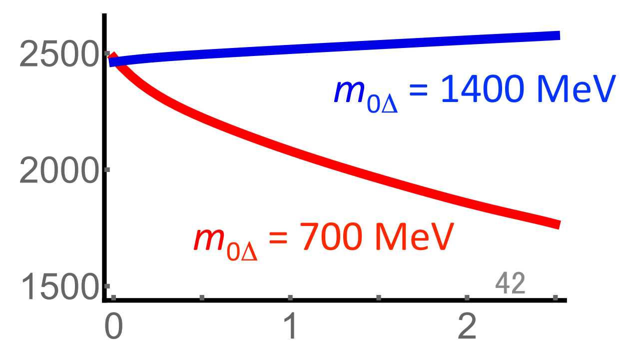
4. Summary

- We studied density dependence of Delta baryon masses from the mean field contributions of sigma and omega mesons.
- Increasing or decreasing of Δ(+) baryon mass only is not enough for measuring the chiral symmetry restoration.
- Studying the mass difference of chiral partners gives a clue for partial chiral symmetry restoration, independently of the value of $m_{0\Delta}$.
- Taking sum of particle and anti-particle will give a clue for the chiral invariant mass m_{0D}.









Discussions

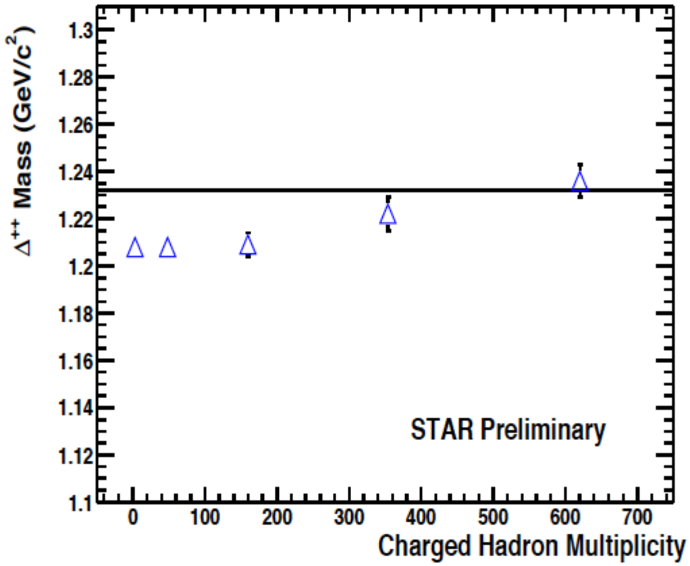
- For more realistic study of Δ mass in matter, we should check the effect of π-N loop, which is needed to study the in-medium spectral function.
- There seems still a difference of the estimated value of the chiral invariant mass of nucleon between the one at vacuum and the one in the matter.
- The analysis in the 3-flavor parity doublet model shows that the chiral partner of the positive parity nucleon, N(939), is not N*(1535), but a mixture of N*(1440), N*(1535), N*(1650), … [H.Nishihara and M.Harada, Phys. Rev. D92, 054022 (2015), and work in preparation.]
- It is interesting to include 2 parity doublets for nucleon into a model.

In [Y. Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015)], we studied nuclear matter using a parity doublet model, and showed some relations between the chiral invariant mass of nucleon and the phase structure. We also presented a density dependence of the nucleon mass, which changes reflecting the partial chiral symmetry restoration.

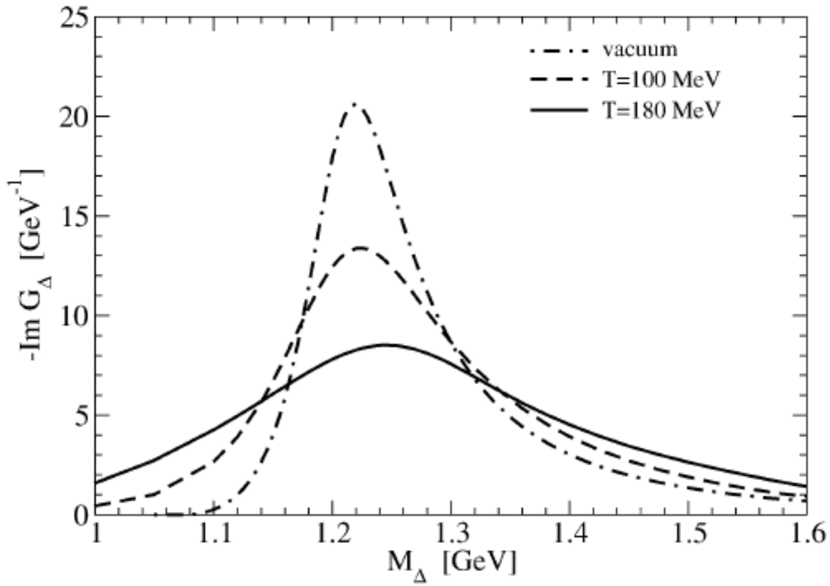
What happens to the mass of Delta baryon ?

Change of Delta at RHIC ?

STAR: arXiv:nucl-ex/040301



In-medium spectral funcion of Δ
by Hees-Rapp, PLB606, 59 (2005)



These show that medium effects push up the Δ mass at high temperature.

- What happens at high density ?
- What is the relation to the partial chiral symemtry restoration ?

- In this talk, I will show a preliminary study of the mass of Δ baryon at high density, based on a parity doublet structure.

Outline

1. Introduction
2. Nuclear matter from a parity doublet model
3. Density dependence of effective mass of Delta baryon
4. Summary

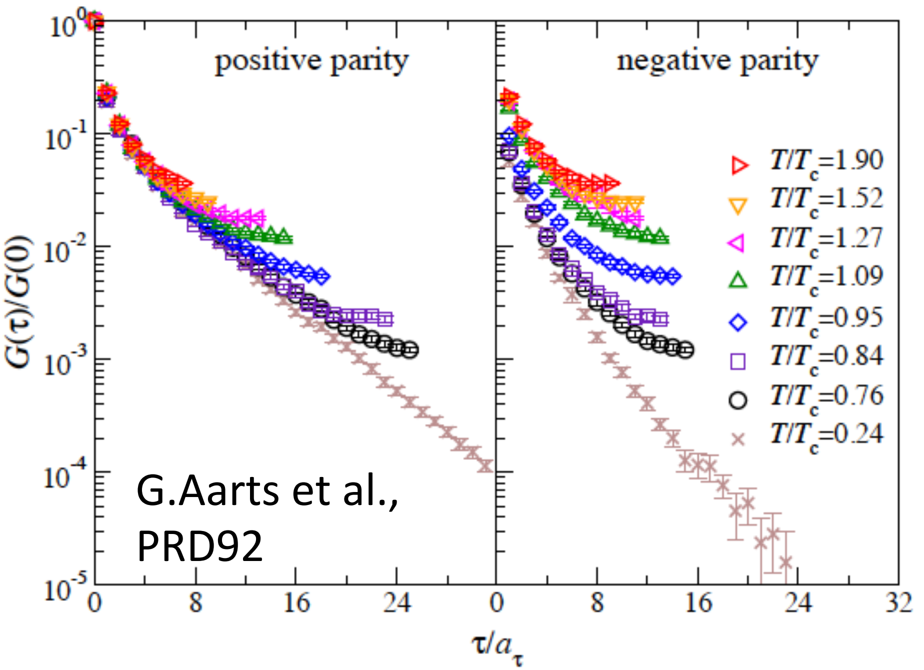
Parity Doublet model for nucleon

C.DeTar, T.Kunihiro, PRD39, 2805 (1989)
D.Jido, M.Oka, A.Hosaka, PTP106, 873 (2001)

- An excited nucleon with negative parity such as N*(1535) is regarded as the chiral partner to the N(939) which has the positive parity.
- These nucleons have a chiral invariant mass in addition to the mass generated by the spontaneous chiral symmetry breaking which is caused by the existence of the sigma condensate, $\langle \sigma \rangle \neq 0$.

Lattice analysis

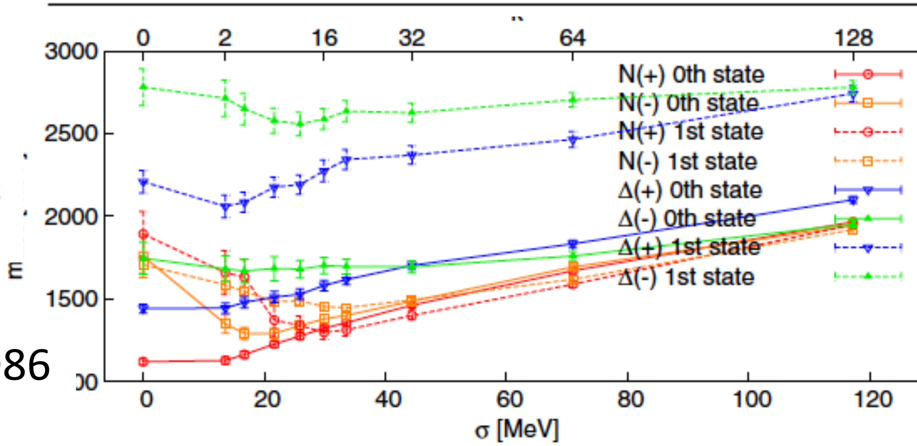
- The result in [G. Aarts, C. Allton, S. Hands, B. Jaeger, C. Praki, and J. I.Skullerud, Phys. Rev. D 92, 014503 (2015)] and [L.Y.Glozman, C.B.Lang, M. Schrock, Phys. Rev. D86, 014507 (2012)] seems to show the existence of large chiral invariant mass.



G.Aarts et al., PRD92

G. Aarts et al., PRD92

T/T_c	$a_\tau m_+$	$a_\tau m_-$	m_+ [GeV]	m_- [GeV]
0.24	0.213(5)	0.33(5)	1.20(3)	1.9(3)
0.76	0.209(16)	0.28(3)	1.18(9)	1.6(2)
0.84	0.192(17)	0.28(2)	1.08(9)	1.6(1)
0.95	0.198(25)	0.22(4)	1.12(14)	1.3(2)



Y.L. Glozman et al., PRD86

Model parameters : Inputs from vacuum phenomenology

- We include sigma and omega mesons as well as the pion and rho meson in our model
- We have 11 parameters.
  - 3 parameters in the scalar potential

$$\bar{\mu}\,,\ \lambda\,,\ \lambda_6\ \ :\ V_\sigma = \frac{1}{2}\bar{\mu}^2\sigma^2 + \frac{1}{4}\lambda\sigma^4 - \frac{1}{6}\lambda_6\sigma^6$$

  - 3 masses for π, ρ, ω : $m_\pi\,,\ m_\rho\,,\ m_\omega$
  - 5 parameters in the baryon sector

    m_0 : chiral invariant mass ; $g_1\,,\ g_2$: Yukawa couplings

    $g_{\rho NN}\,,\ g_{\omega NN}$: ρNN and ωNN couplings

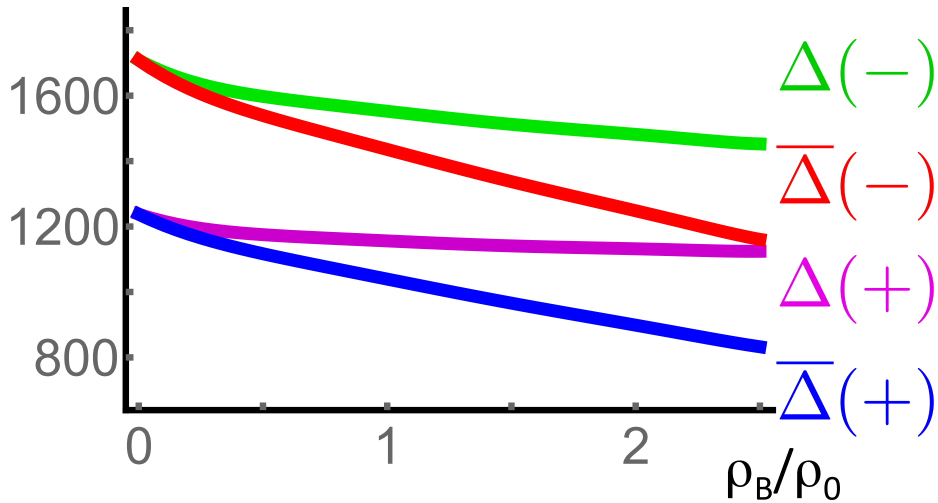
- We determine 10 parameters for a given value of the chiral invariant mass m_0 .
- We use the following 6 inputs at vacuum

m_+	m_-	m_ω	m_ρ	f_π	m_π
939	1535	783	776	93	140

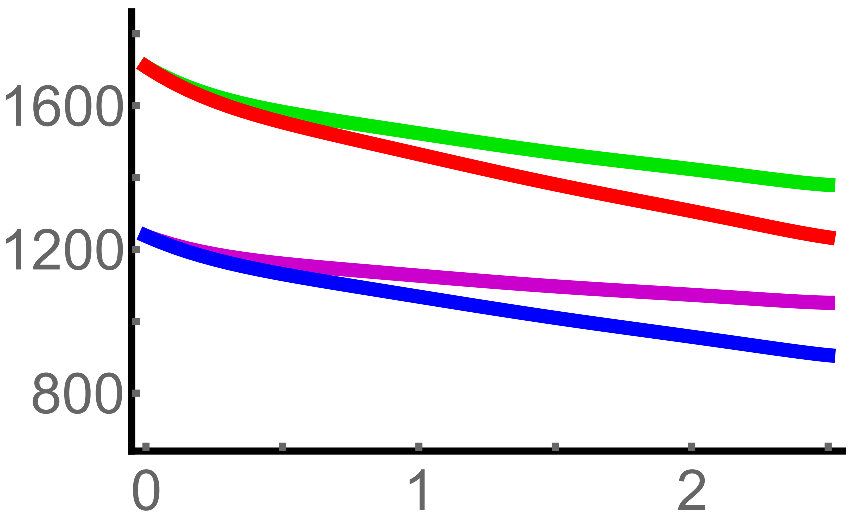
Dependence on the $\omega\Delta\Delta$ coupling

$m_{0\Delta}$ = 700 MeV

$g_{\omega\Delta\Delta}$ = 5.4



$g_{\omega\Delta\Delta}$ = 2.7



$g_{\omega\Delta\Delta}$ = 8.1