Medium modification of charmed meson masses through one-boson exchange

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@Mesons in Nucleus 2016

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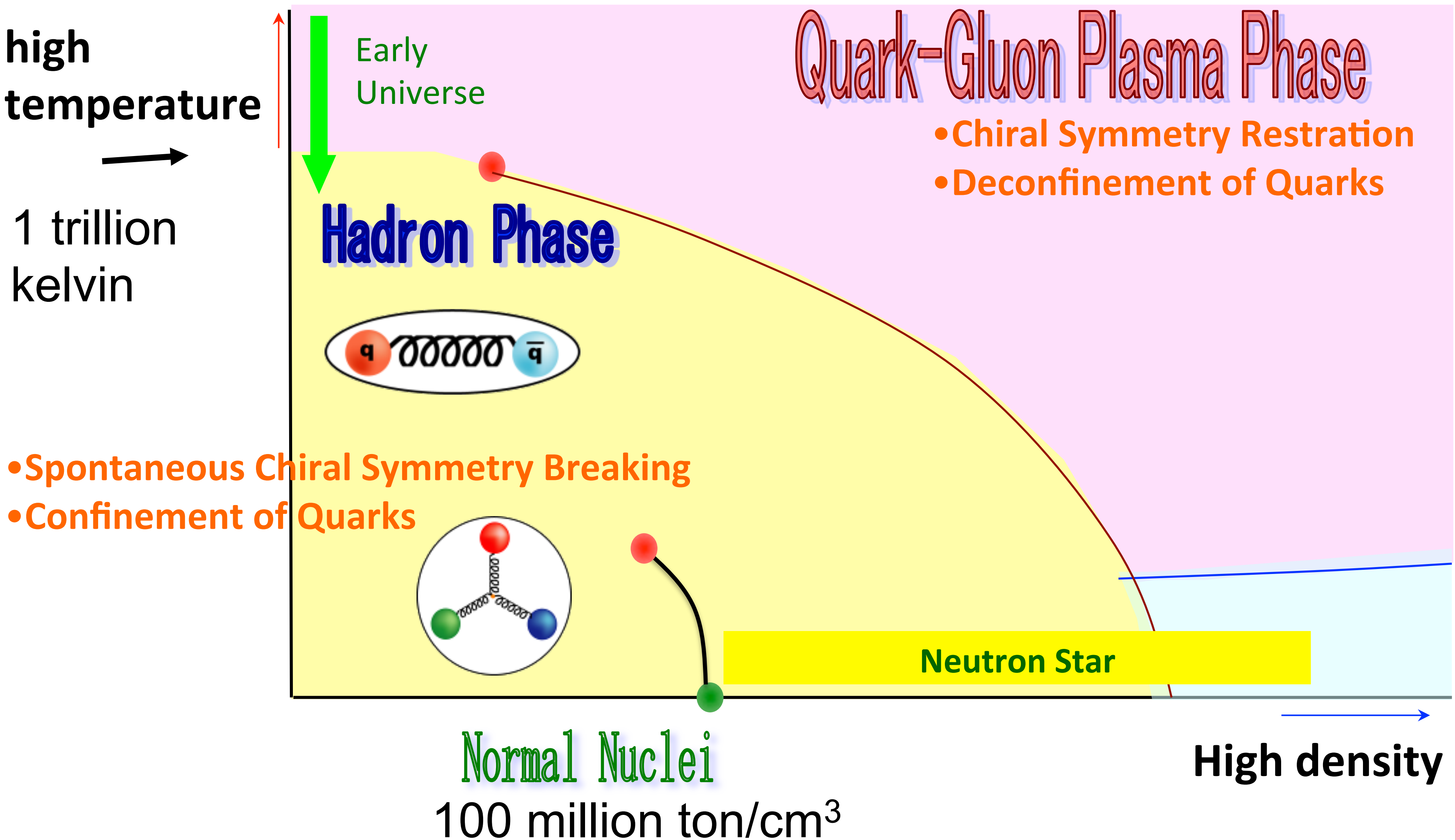
Based on

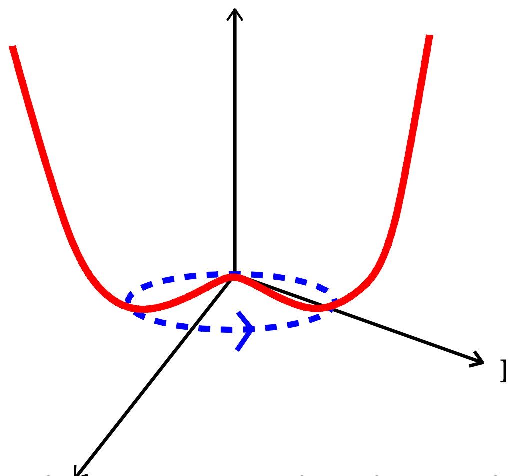
- M. Harada, Y.L. Ma, D. Suenaga, Y. Takeda, in preparation
- D.Suenga, B.R.He, Y.L.Ma. M.Harada, PRD 91, 036001 (2015)

1. Introduction

Phase diagram of Quark-Gluon system

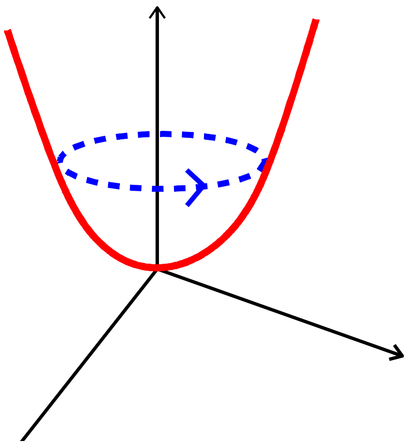


Important for understanding the spontaneous chiral symmetry breaking



chiral symmetry broken phase
at vacuum

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



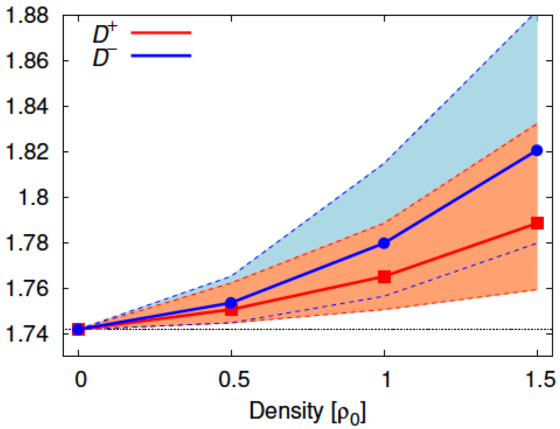
chiral symmetric phase
at high T and/or density

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

- The spontaneous chiral symmetry breaking is expected to generate a part of hadron masses.
- It causes mass difference between chiral partners.
- Changing T and/or density will cause some change of hadron masses.

Medium modification of charmed meson masses

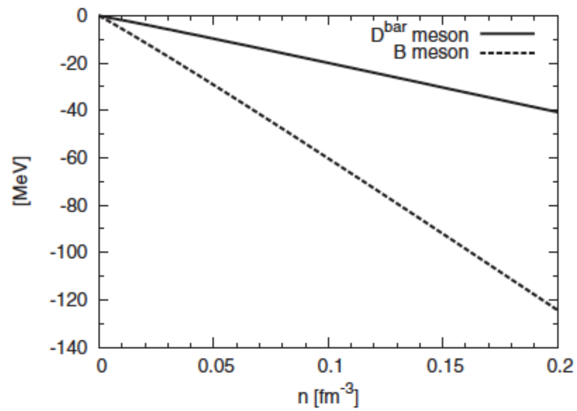
- QCD sum rule



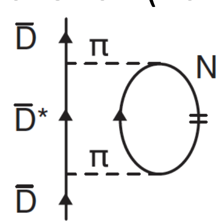
K.Suzuki, P.Gubler, M.Oka, PRC 93, 045209 (2016)

D meson mass is increased at finite density

- One-loop in an effective model

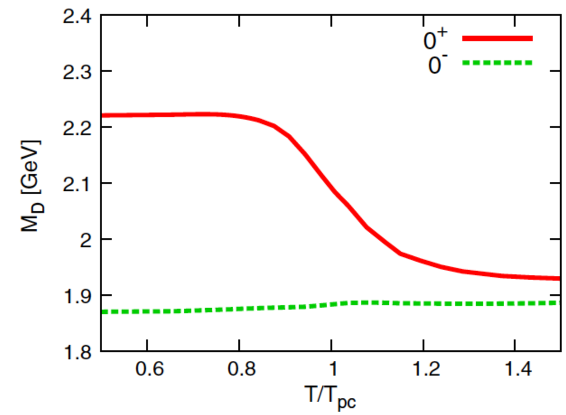


S.Yasui, K.Sudoh, PRC 87, 015202 (2013)

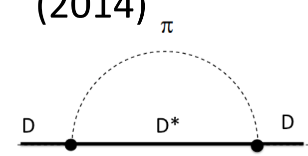


D meson mass is decreased at finite density

- One-loop in an effective model at finite temperature



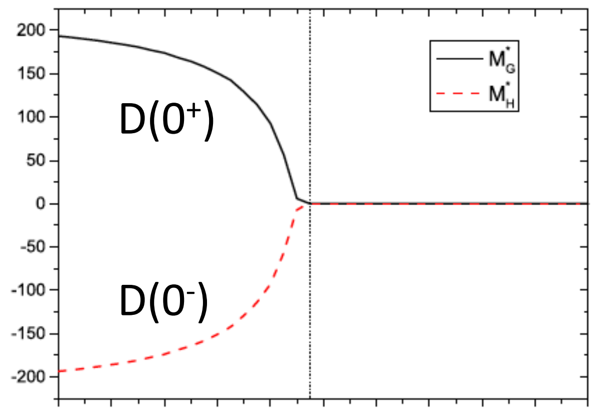
C.Sasaki, PRD 90, 114007 (2014)

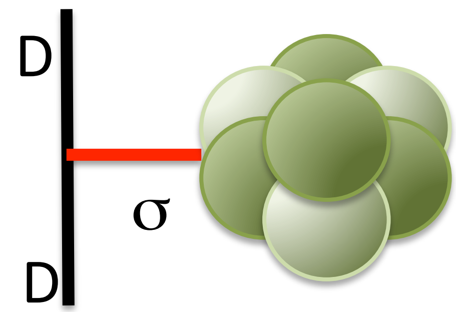


D meson mass is stable at finite temperature

One boson exchange contribution

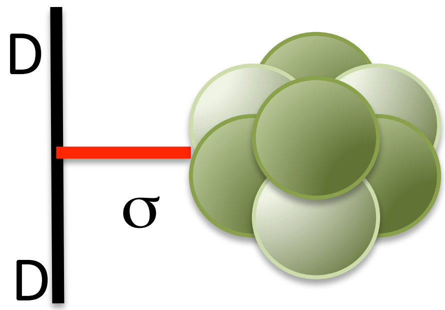
- Effective sigma meson exchange contribution
  - Nuclear matter is created in a Skyrme crystal approach
  - D meson ($J^P=0^-$) is included together with D_0^* ($J^P=0^+$) as the chiral partner
  - D.Suenga, B.R.He, Y.L.Ma. M.Harada, PRD 91, 036001 (2015)

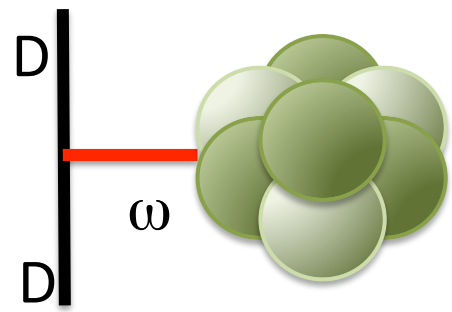




- D meson ($J^P=0^-$) mass is increased,
- D_0* ($J^P=0^+$) mass is decreased.
- They are degenerate when $\langle\sigma\rangle = 0$.

- In this talk, I introduce a main point of our recent work [M.Harada, Y.L.Ma, D.Suenaga, Y.Takeda, in preparation], where we study the charmed meson masses in nuclear matter through the exchange of sigma and omega mesons.
- We did not specify the Skyrme Crystal, but performed a more general analysis.





Outline

1. Introduction
2. An effective model for heavy mesons
3. Density dependence of effective masses
4. Summary

2. An effective model for heavy mesons

Chiral partner structure for charmed mesons

- M.A.Nowak, M.Rho and I.Zahed, PRD48, 4370 (1993)
- W.A.Bardeen and C.T.Hill, PRD49, 409 (1994)

- 2 heavy quark multiplets with J_l=1/2 are regarded as the chiral partner:

$$\left[D(0^-), D^*(1^-)\right] \xleftrightarrow[\text{chiral partner}]{} \left[D_0^*(0^+), D_1(1^+)\right]$$

- Mass difference is generated by the chiral condensate, and the value is roughly equal to the constituent quark mass.
- Experimental value implies that the chiral partner structure seems to work:

$$m\left(0^+\right) - m\left(0^-\right) \approx m\left(1^+\right) - m\left(1^-\right) \approx 0.43\,\text{GeV}$$

An effective Lagrangian

- 2 Heavy meson doublets for $J^P = (0^-, 1^-), (0^+, 1^+)$ mesons

$$H = \frac{1 + v^\mu \gamma_\mu}{2} \left[D^*_\mu \gamma^\mu + i D \gamma_5 \right] \ , \quad G = \frac{1 + v^\mu \gamma_\mu}{2} \left[D^*_0 - i \gamma^\mu D'_{1\mu} \gamma_5 \right]$$

- Chiral fields

$$\mathcal{H}_R = \frac{1}{\sqrt{2}} \left[G + i H \gamma_5 \right] \ , \quad \mathcal{H}_L = \frac{1}{\sqrt{2}} \left[G - i H \gamma_5 \right] \ , \quad \omega_\mu \ , \quad M = \sigma + i \sum_{a=1}^{3} \pi_a \tau_a$$

$$\mathcal{H}_{R,L} \to \mathcal{H}_{R,L}\, g^\dagger_{R,L} \quad \omega_\mu \to \omega_\mu \quad M \to g_L M g^\dagger_R \ , \quad \left(g_{R,L} \in \mathrm{SU}(2)_{R,L} \right)$$

- An effective Lagrangian invariant under chiral symmetry

$$\begin{aligned} \mathcal{L}/m =& \mathrm{tr} \left[\mathcal{H}_L (i v \cdot \partial) \bar{\mathcal{H}}_L \right] + \mathrm{tr} [\mathcal{H}_R (i v \cdot \partial) \bar{\mathcal{H}}_R] \\ & - g_{\omega D D} \, \mathrm{Tr} \left[\mathcal{H}_L v^\mu \omega_\mu \bar{\mathcal{H}}_L + \mathcal{H}_R v^\mu \omega_\mu \bar{\mathcal{H}}_R \right] \\ & + \frac{\Delta_M}{2 f_\pi} \mathrm{tr} \left[\mathcal{H}_L M \bar{\mathcal{H}}_R + \mathcal{H}_R M^\dagger \bar{\mathcal{H}}_L \right] \\ & - i \frac{g_A}{2 f_\pi} \mathrm{tr} \left[\mathcal{H}_R \gamma_5 \gamma^\mu \partial_\mu M^\dagger \bar{\mathcal{H}}_L - \mathcal{H}_L \gamma_5 \gamma^\mu \partial_\mu M \bar{\mathcal{H}}_R \right] \end{aligned}$$

Masses of charmed mesons in nuclear matter

- Relevant interactions for D($J^P=0^-$), D($J^P=0^+$)

$$\mathcal{L}/m = -2D\left[v^\mu\left(i\partial_\mu + g_{\omega DD}\omega_\mu\right) - \frac{1}{2}\Delta_M\frac{\sigma}{f_\pi}\right]D^\dagger$$
$$+2D_0^*\left[v^\mu\left(i\partial_\mu + g_{\omega DD}\omega_\mu\right) + \frac{1}{2}\Delta_M\frac{\sigma}{f_\pi}\right](D_0^*)^\dagger$$

- Effective masses for D($J^P=0^-$), D($J^P=0^+$) in nuclear matter

$$m^{(\mathrm{eff})}_{D(-)} = m - \frac{1}{2}\Delta_M\frac{\langle\sigma\rangle}{f_\pi} + g_{\omega DD}\langle\omega_0\rangle$$
$$m^{(\mathrm{eff})}_{D(+)} = m + \frac{1}{2}\Delta_M\frac{\langle\sigma\rangle}{f_\pi} + g_{\omega DD}\langle\omega_0\rangle$$

- Effective masses for anti-charmed mesons

$$m^{(\mathrm{eff})}_{\bar{D}(-)} = m - \frac{1}{2}\Delta_M\frac{\langle\sigma\rangle}{f_\pi} - g_{\omega DD}\langle\omega_0\rangle$$
$$m^{(\mathrm{eff})}_{\bar{D}(+)} = m + \frac{1}{2}\Delta_M\frac{\langle\sigma\rangle}{f_\pi} - g_{\omega DD}\langle\omega_0\rangle$$

3. Density dependence of effective masses

Linear density approximation

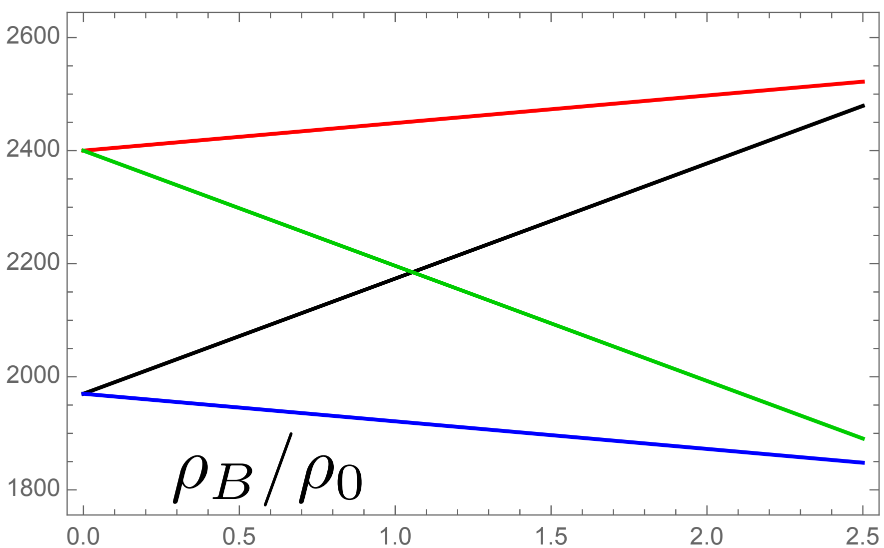
$$\langle \omega_0 \rangle = \frac{g_{\omega NN}}{m_\omega^2} \rho_B \ , \qquad \frac{\langle \sigma \rangle}{\langle \sigma \rangle_0} = 1 - \frac{\sigma_{\pi N}}{m_\pi^2 f_\pi^2} \rho_B$$

$$m_{D(-)}^{(\mathrm{eff})} = m - \frac{1}{2}\Delta_M \frac{\langle \sigma \rangle}{f_\pi} + g_{\omega DD} \langle \omega_0 \rangle \quad m_{\bar{D}(-)}^{(\mathrm{eff})} = m - \frac{1}{2}\Delta_M \frac{\langle \sigma \rangle}{f_\pi} - g_{\omega DD} \langle \omega_0 \rangle$$

$$m_{D(+)}^{(\mathrm{eff})} = m + \frac{1}{2}\Delta_M \frac{\langle \sigma \rangle}{f_\pi} + g_{\omega DD} \langle \omega_0 \rangle \quad m_{\bar{D}(+)}^{(\mathrm{eff})} = m + \frac{1}{2}\Delta_M \frac{\langle \sigma \rangle}{f_\pi} - g_{\omega DD} \langle \omega_0 \rangle$$

An example $|g_{\omega DD}| = 6 \ , \quad |g_{\omega NN}| = 10 \ , \quad \sigma_{\pi N} = 45$ MeV

$g_{\omega DD} g_{\omega NN} < 0 \qquad g_{\omega DD} g_{\omega NN} > 0$



Increasing or decreasing of D(-) meson mass only is not enough for measuring the chiral symmetry restoration.

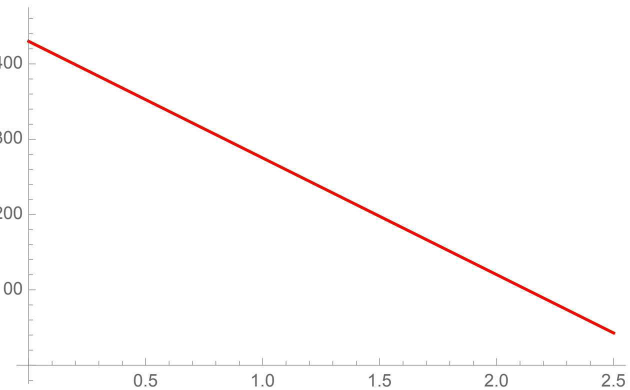
Partial chiral symmetry restoration

$$\frac{\langle\sigma\rangle}{\langle\sigma\rangle_0} = 1 - \frac{\sigma_{\pi N}}{m_\pi^2 f_\pi^2}\rho_B$$

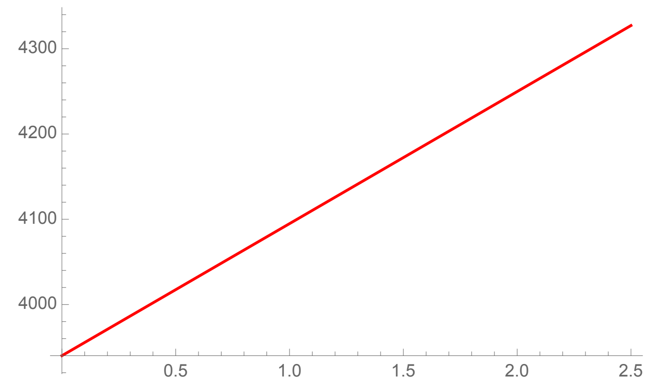
$$m_{D(-)}^{(\text{eff})} = m - \frac{1}{2}\Delta_M \frac{\langle\sigma\rangle}{f_\pi} + g_{\omega DD}\langle\omega_0\rangle \quad m_{\bar{D}(-)}^{(\text{eff})} = m - \frac{1}{2}\Delta_M \frac{\langle\sigma\rangle}{f_\pi} - g_{\omega DD}\langle\omega_0\rangle$$

$$m_{D(+)}^{(\text{eff})} = m + \frac{1}{2}\Delta_M \frac{\langle\sigma\rangle}{f_\pi} + g_{\omega DD}\langle\omega_0\rangle \quad m_{\bar{D}(+)}^{(\text{eff})} = m + \frac{1}{2}\Delta_M \frac{\langle\sigma\rangle}{f_\pi} - g_{\omega DD}\langle\omega_0\rangle$$

$$D(+) - D(-)$$



$$D(-) + \overline{D}(-)$$

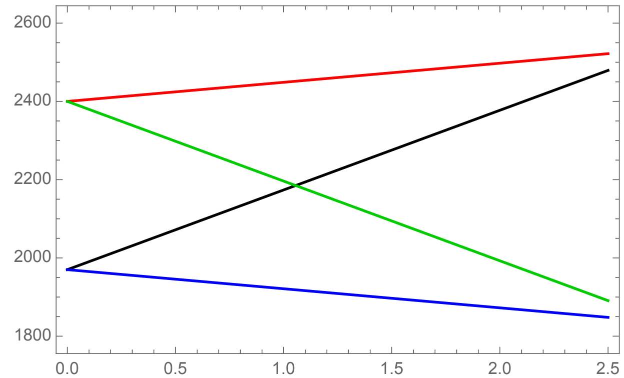


- In addition to study the mass difference of chiral partners, taking average of particle and anti-particle will give a clue for partial chiral symmetry restoration.
- Threshold energy for production of D and anti-D meson pair in medium is larger than vacuum reflecting the partial chiral symmetry restoration.

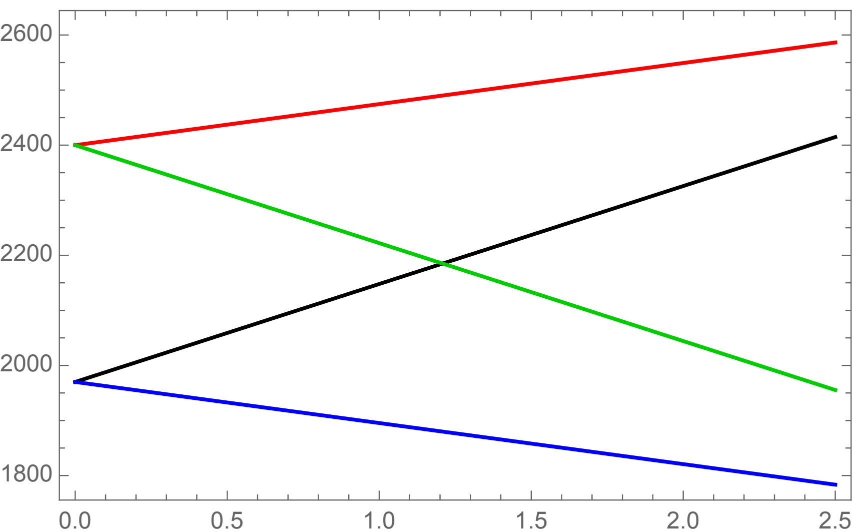
- These 2 plots are essentially same at mean field level.
- Some difference from higher order corrections such as pion loop, Λ_c-N loop, etc..

Dependence on πN sigma term

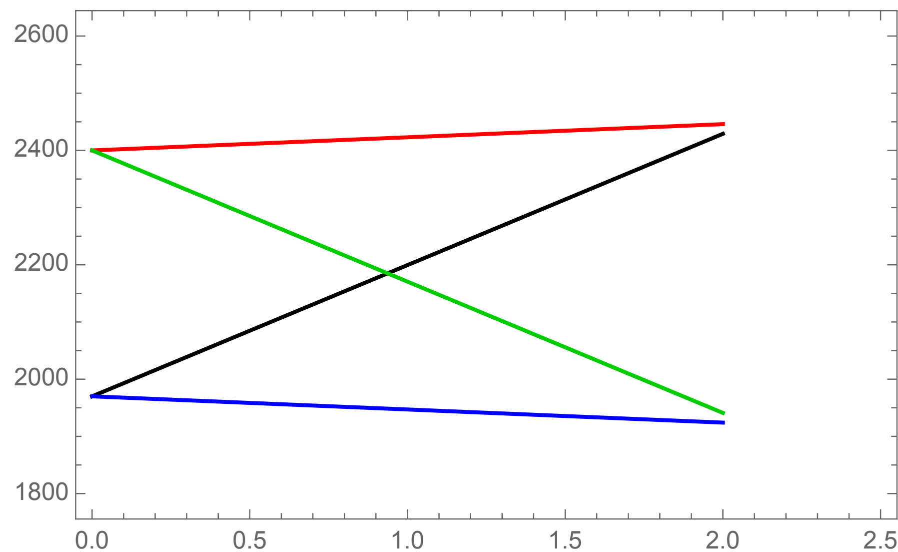
$\sigma_{\pi N} = 45\,\text{MeV}$ $|g_{\omega DD}| = 6\ ,\quad |g_{\omega NN}| = 10\ ;$



$\sigma_{\pi N} = 30\,\text{MeV}$

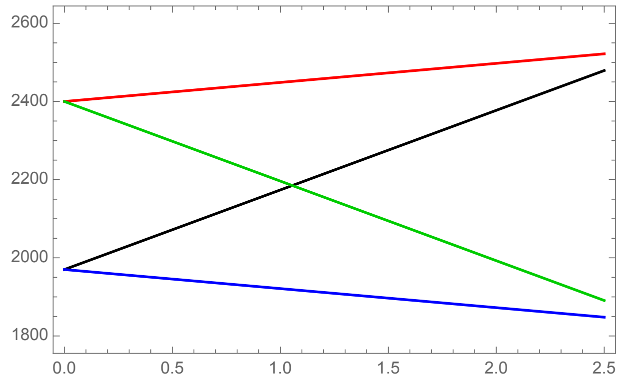


$\sigma_{\pi N} = 60\,\text{MeV}$

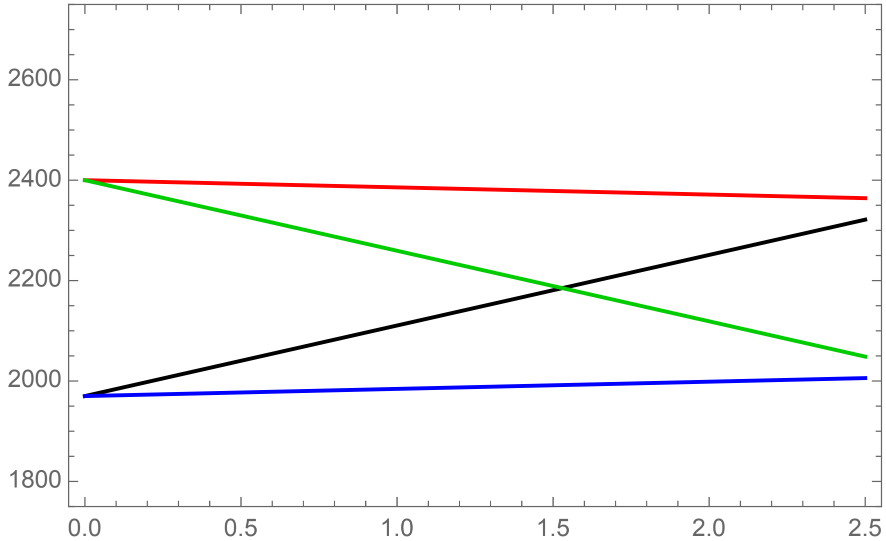


Dependence on ωDD coupling

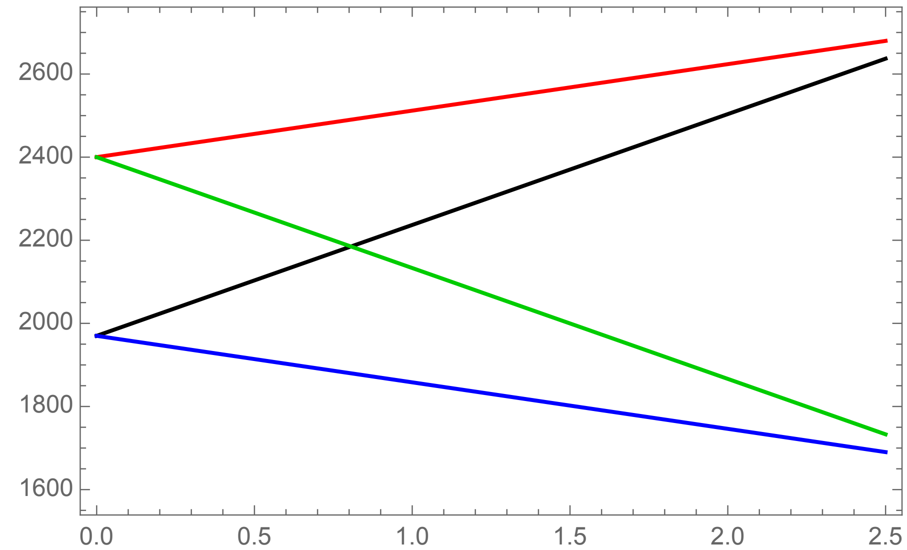
$|g_{\omega DD}| = 6$, $|g_{\omega NN}| = 10$, $\sigma_{\pi N} = 45$ MeV



$|g_{\omega DD}| = 3$



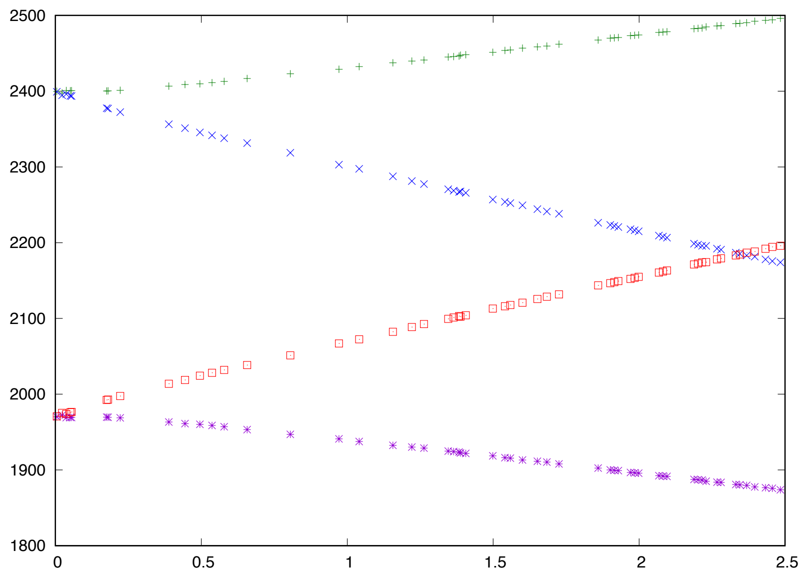
$|g_{\omega DD}| = 9$



Nuclear matter from a parity doublet model

- In [Y. Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015)], we constructed a mean field model of Walecka type, using a parity doublet model for nucleon, which reproduces the properties of nuclear matter at normal nuclear matter density.
- Here we use the model to determine the mean fields of sigma and omega.

$g_{\omega DD} < 0$ $g_{\omega DD} > 0$



$\overline{D}(+)$ $D(+)$

$\overline{D}(-)$ $D(-)$

$D(+)$ $\overline{D}(+)$

$D(-)$ $\overline{D}(-)$

$$m^{(\mathrm{eff})}_{D(-)} = m - \frac{1}{2}\Delta_M \frac{\langle\sigma\rangle}{f_\pi} + g_{\omega DD}\langle\omega_0\rangle$$

$$m^{(\mathrm{eff})}_{D(+)} = m + \frac{1}{2}\Delta_M \frac{\langle\sigma\rangle}{f_\pi} + g_{\omega DD}\langle\omega_0\rangle$$

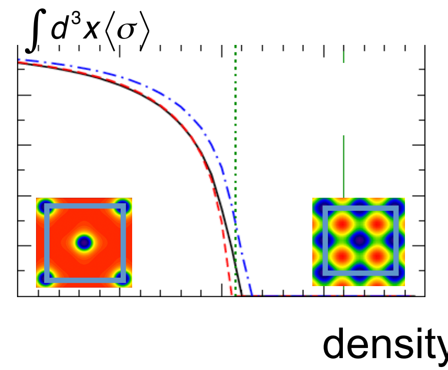
$$m^{(\mathrm{eff})}_{\bar{D}(-)} = m - \frac{1}{2}\Delta_M \frac{\langle\sigma\rangle}{f_\pi} - g_{\omega DD}\langle\omega_0\rangle$$

$$m^{(\mathrm{eff})}_{\bar{D}(+)} = m + \frac{1}{2}\Delta_M \frac{\langle\sigma\rangle}{f_\pi} - g_{\omega DD}\langle\omega_0\rangle$$

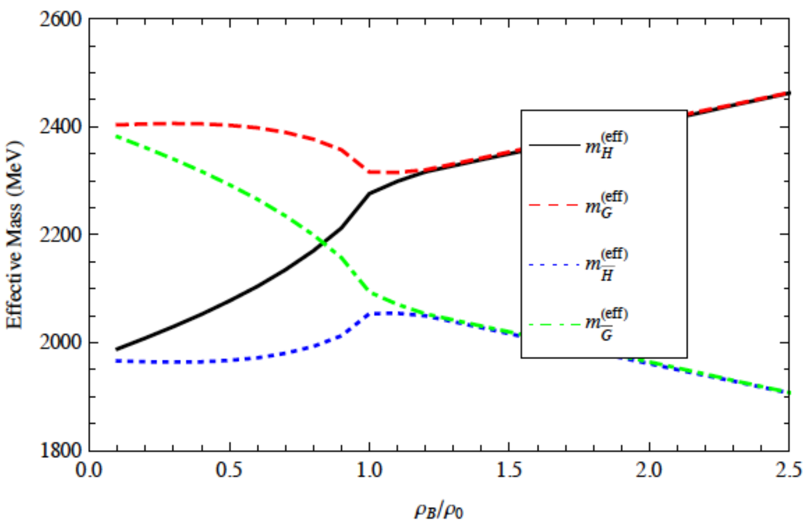
Density dependence is quite similar to the one in the linear density approximation.

Nuclear matter from Skyrme crystal

- 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
- M. Harada, H.K. Lee, Y.-L. Ma, M. Rho, PRD91, (2015) 096011
- D.Suenga, B.R.He, Y.L.Ma. M.Harada, PRD 91, 036001 (2015)



- In the Skyrme crystal model, there exists the "half-Skyrmion phase", where the space average of the sigma condensate vanishes.

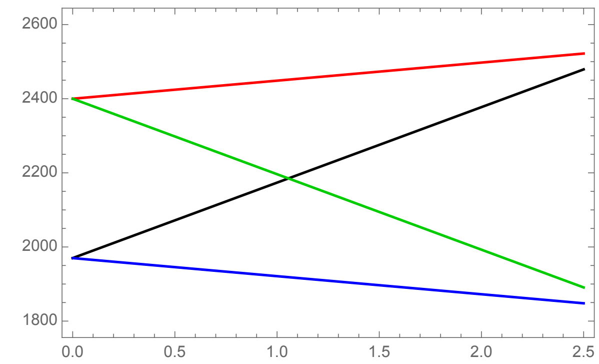


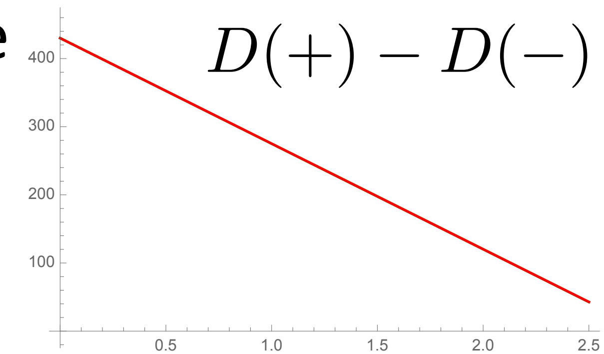
$g_{\omega DD} < 0$	$g_{\omega DD} > 0$
$\overline{D}(+)$	$D(+)$
$\overline{D}(-)$	$D(-)$
$D(+)$	$\overline{D}(+)$
$D(-)$	$\overline{D}(-)$

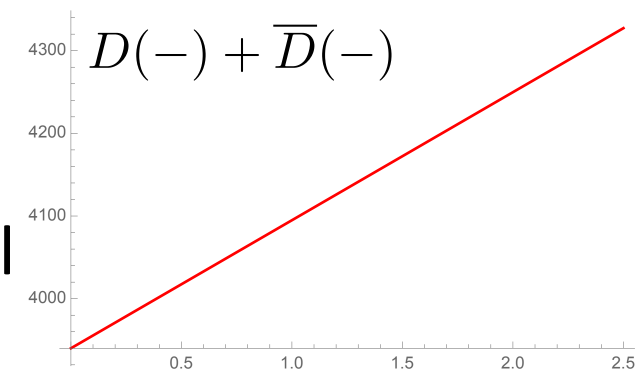
Chiral partners are degenerate with each other in the half-Skyrmion phase.
Properties in the normal nuclear matter are similar to the other cases.

4. Summary

- We studied density dependence of charmed meson masses from the mean field contributions of sigma and omega mesons.
- Increasing or decreasing of D(-) meson mass only is not enough for measure the chiral symmetry restoration.
- In addition to study the mass difference of chiral partners, taking average of particle and anti-particle will give a clue for partial chiral symmetry restoration.
- Threshold energy for production of D and anti-D meson pair in medium is larger than vacuum reflecting the partial chiral symmetry restoration.

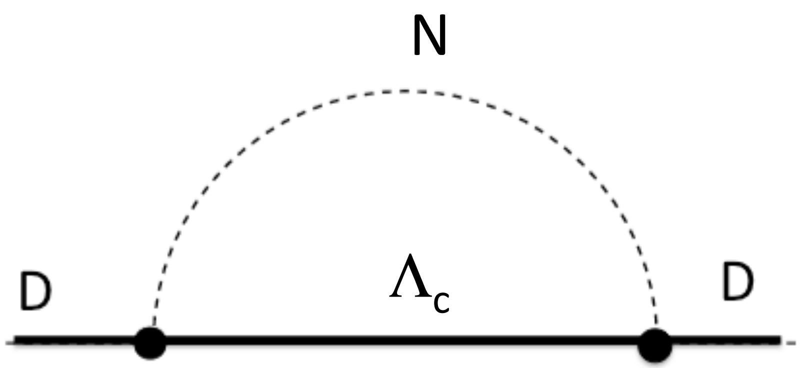






The End

Contribution of Λ_c-N loop



$$\Delta M(D) \simeq \frac{g^2}{2m_D\, m_N}\, \rho_B$$

- Although details depends on the value of the coupling, one can say that the contribution is suppressed by the heavy meson mass, compared with mean field contributions.