A study of neutron star matter based on a parity doublet model with a0(980) meson effect

Masayasu Harada (Nagoya University)

@ Quarks and Compact Stars (QCS2023)

(September 23, 2023)

Based on
T. Minamikawa, T. Kojo and M. Harada, Phys. Rev. C 103, 045205 (2021).
T. Minamikawa, T. Kojo and M. Harada, Phys. Rev. C 104, 065201 (2021).
T. Minamikawa, B. Gao, T. Kojo and M. Harada, Symmetry 15, 745 (2023).
Y.-K. Kong, T. Minamikawa and M. Harada, arXiv:2306.08140

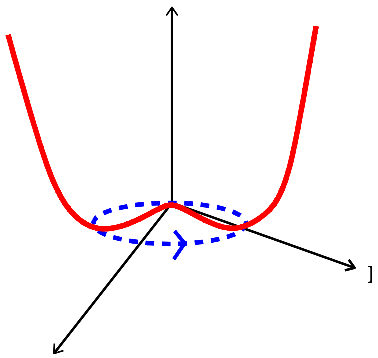
Introduction

Origin of Mass of Hadrons / of Us **?**

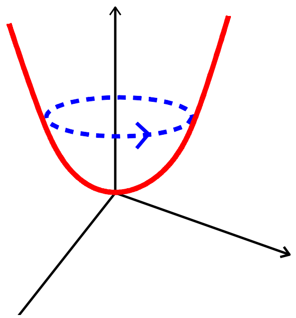
||

One of the Interesting problems of QCD

Spontaneous chiral symmetry breaking



chiral symmetry broken phase at vacuum



chiral symmetric phase at high T and/or density

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

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

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

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

Parity Doublet models for nucleons

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

- A 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.

$$m_N = m_0 + m_{\langle \bar{q} q \rangle}$$

m_0 ← chiral invariant mass

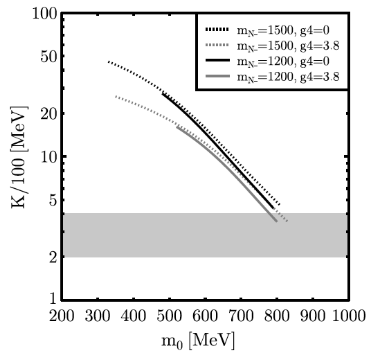
$m_{\langle \bar{q} q \rangle}$ ← spontaneous chiral symmetry breaking

- This model can be extended to include different excited nucleons.

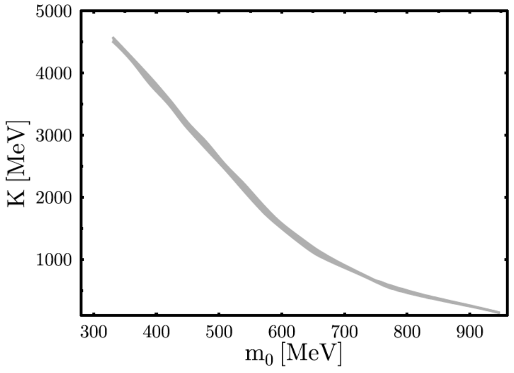
Nuclear matter in parity doublet models

- 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 constructed 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 (20



NS observable to microscopic quantities

1. Construction of nuclear matter from a PDM
   - Y.Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015)
2. Study of a constraint to the chiral invariant mass in a PDM from the neutron star properties
   - T. Yamazaki and M. Harada, Phys. Rev. C 100, 025205 (2019).
3. Construction of a unified EOS connecting a PDM and an NJL-type quark model, and study of a constraint to the chiral invariant mass in a PDM from the neutron star properties
   - T. Minamikawa, T. Kojo and M. Harada, Phys. Rev. C 103, 045205 (2021).
4. Study of density dependence of the chiral condensate from the unified EOS.
   - T. Minamikawa, T. Kojo and M. Harada, Phys. Rev. C 104, 065201 (2021).
5. Study of effect of U(1) axial anomaly
   1. B. Gao, T. Minamikawa, T. Kojo and M. Harada, Phys. Rev. C 106, 065205 (2022)
6. Review of the above 3 analysis
   1. T. Minamikawa, B. Gao, T. Kojo and M. Harada, Symmetry 15, 745 (2023)
7. Study of effect of iso-triplet a0(980) meson
   1. Y. K. Kong, T. Minamikawa and M. Harada, [arXiv:2306.08140 [nucl-th]].

Outline

1. Introduction
2. Nuclear matter from a PDM
3. A unified EOS for NS and M-R relation
4. Effect of iso-triplet scalar meson [a_0(980) meson]
5. Summary

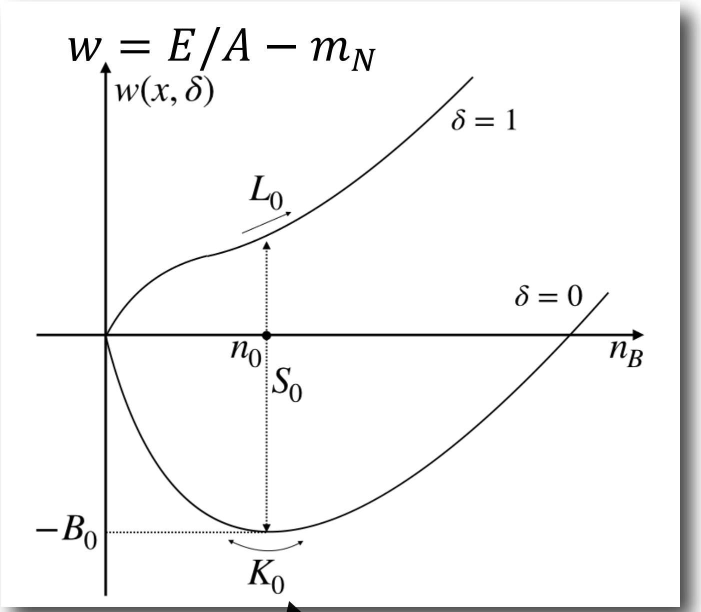
2. Nuclear matter from PDM

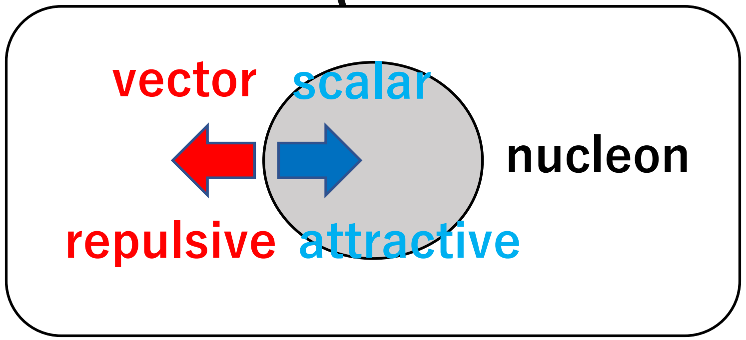
A relativistic mean field (RMF) approach based on the parity doublet model

- N(939), N*(1535) as chiral partners
  - $m_{\pm} = \frac{1}{2}\left[\sqrt{(g_1 + g_2)^2\sigma^2 + 4m_0^2} \mp (g_1 - g_2)\sigma\right]$
  - $m_+ = m\big(N(939)\big)$, $m_- = m\big(N^*(1535)\big)$
  - m_0: chiral invariant mass
  - g_1, g_2: Yukawa couplings to σ meson
- mean fields
  - σ: reflects the spontaneous chiral symmetry breaking ; attractive force
  - ω: repulsive force
  - ρ: iso-spin dependent force

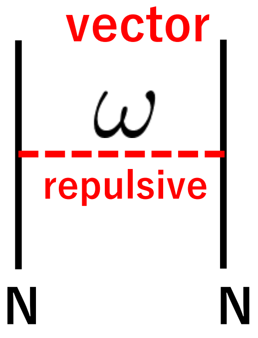
Nuclear Matter at normal nuclear density

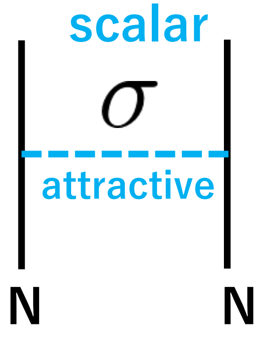
Y. Motohiro, Y. Kim, M. Harada, Phys. Rev. C 92, 025201 (2015); Erratum: Phys. Rev. C 95, 059903 (2017).





- Nuclear saturation density
  - $\rho(\mu_B^* = 923\text{MeV}) = n_0 = 0.16\text{fm}^{-3}$
- Binding energy at normal nuclear density
  - $w = \left[\frac{E}{A} - m(939)\right]_{n_0} = -16\text{MeV}$
- Incompressibility
  - $K_0 = 9\rho_0^2 \left.\frac{\partial^2(E/A)}{\partial\rho^2}\right|_{n_0} = 240\text{MeV}$
- Symmetry energy
  - $S_0 = 31$ MeV





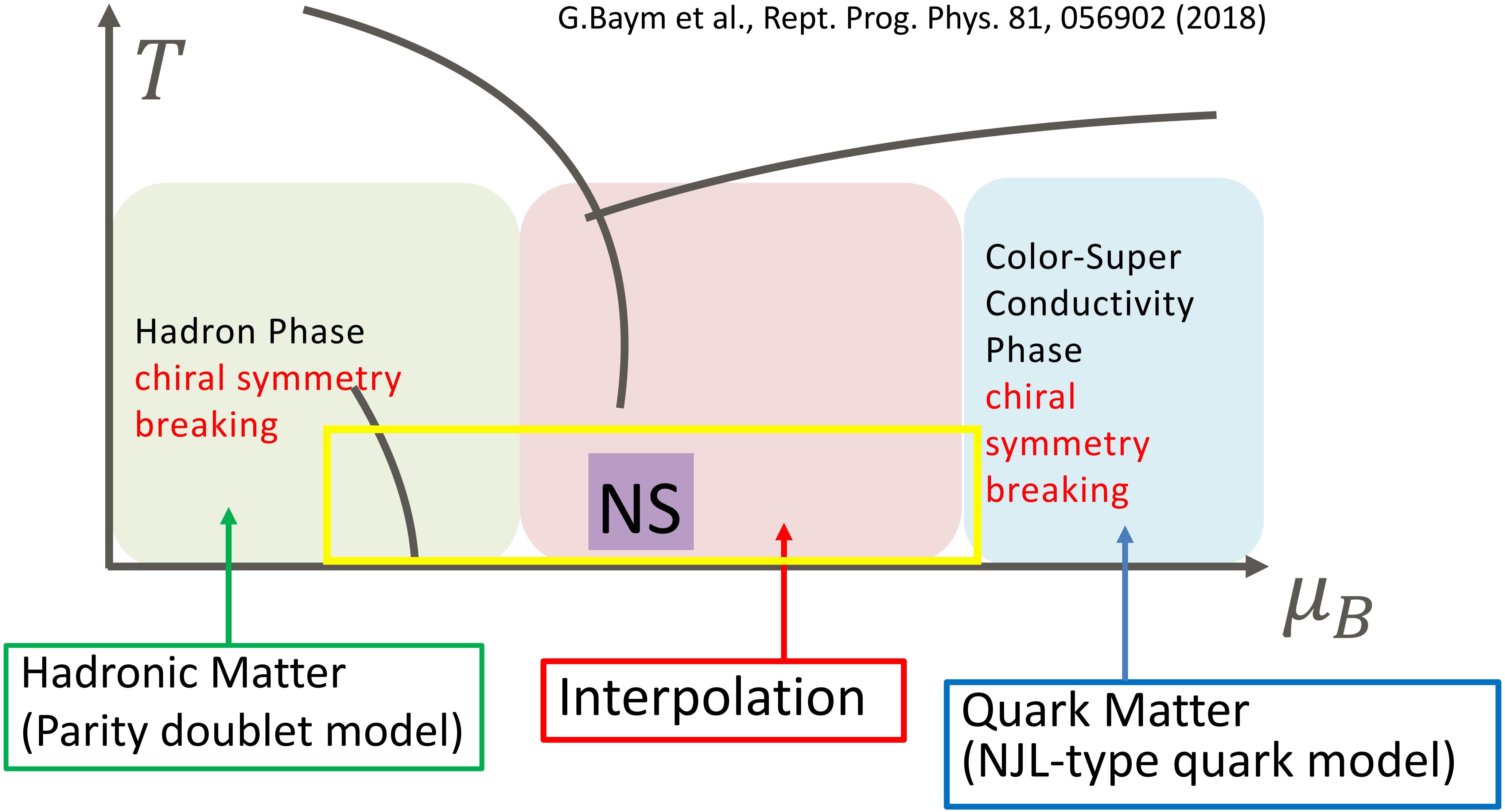
3. A unified EOS for NS and M-R relation

T. Minamikawa, T. Kojo and M. Harada, Phys. Rev. C 103, 045205 (2021).

T. Minamikawa, T. Kojo and M. Harada, Phys. Rev. C 104, 065201 (2021).

Three-Region Structure

G.Baym et al., Rept. Prog. Phys. 81, 056902 (2018)



Quark Matter (High density region)

- The Color-Super Conductivity is expected to occur in the high density limit of QCD, in which two quarks make a Cooper pair breaking the color symmetry and the chiral symmetry.
- In the present analysis, we use a model of NJL-type including the following 4-point interaction terms:
  - Attractive force between two quarks

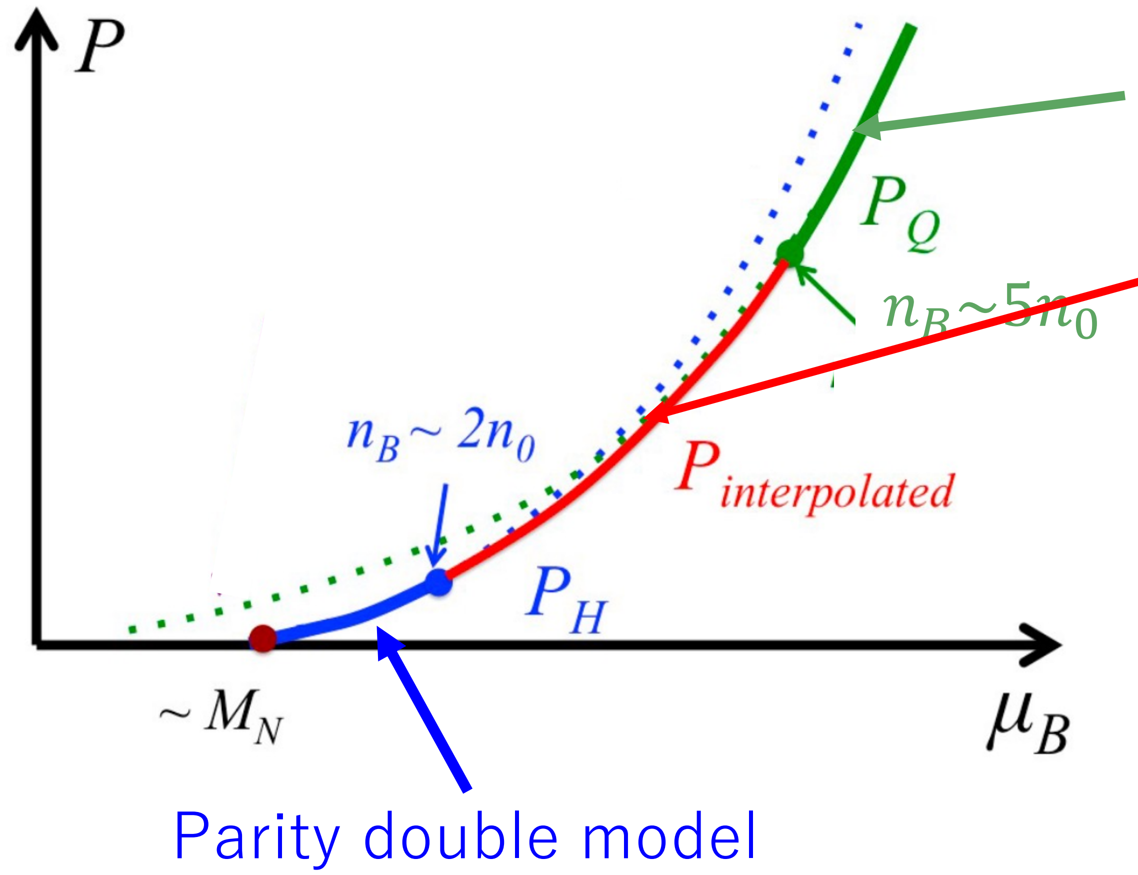
$$H \sum_{A,A'=2,5,7} \left[\left(\bar{q} i\gamma_5 \tau_A \lambda_{A'} C \bar{q}^T\right) \left(q^T C i\gamma_5 \tau_A \lambda_{A'} q\right) + \left(\bar{q} \tau_A \lambda_{A'} C \bar{q}^T\right) \left(q^T C \tau_A \lambda_{A'} q\right) \right]$$

  - Repulsive force between two quarks

$$-g_V \left(\bar{q} \gamma^\mu q\right)^2$$

Unified EOS for NS in 3-window picture

G. Baym et al., Rept. Prog. Phys. 81, 056902 (2018).
T. Minamikawa, T. Kojo and M.H., Phys. Rev. C 103, 045205 (2021).



Interpolation

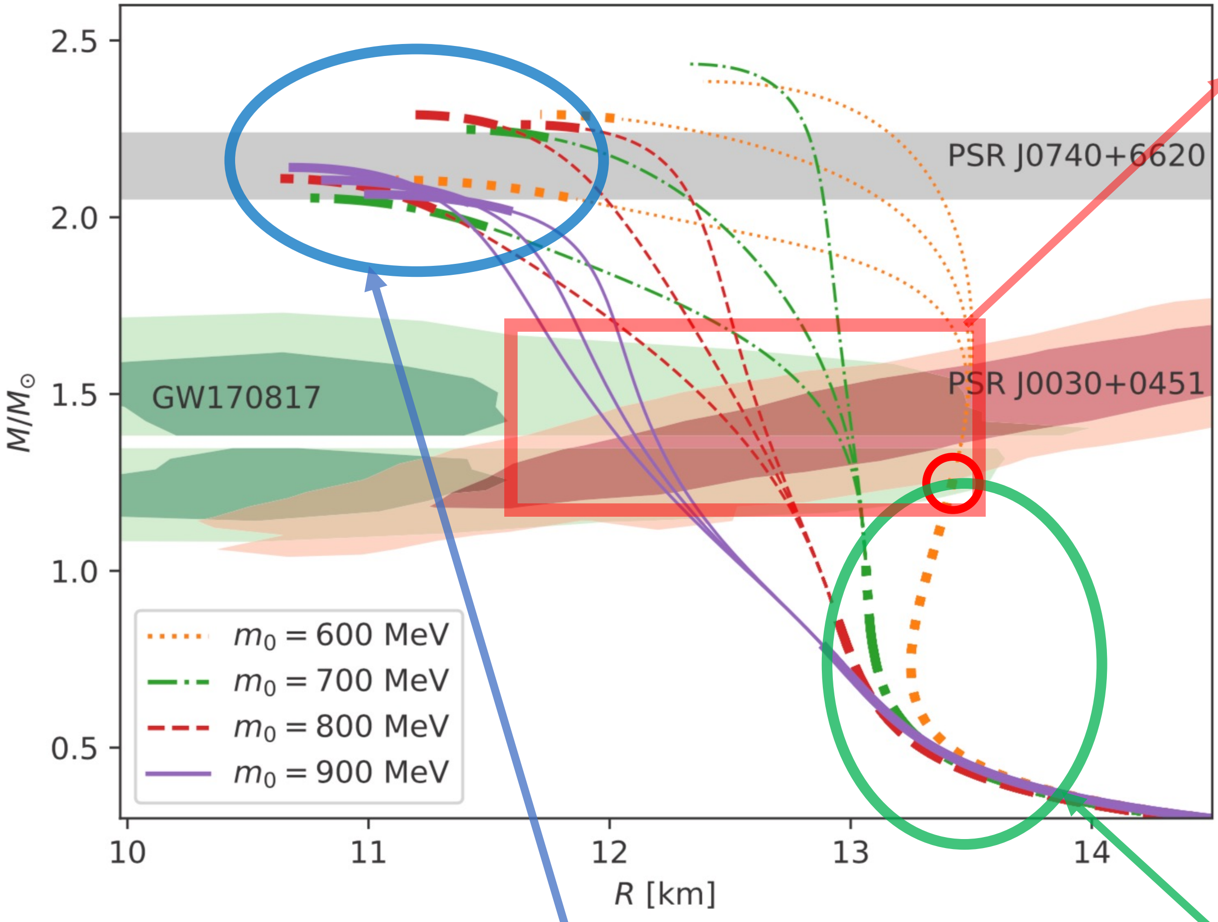
We use 5-th order polynomial of μ for the pressure *P*.
6-coefficients are determined by connecting P to the second order at $2n_0$ and $5n_0$.

$$P_{had} = P_{int},$$

$$\frac{\partial P_{had}}{\partial \mu} = \frac{\partial P_{int}}{\partial \mu}, \quad \frac{\partial^2 P_{had}}{\partial \mu^2} = \frac{\partial^2 P_{int}}{\partial \mu^2}$$

M-R relation

T. Minamikawa, T. Kojo and M.H., Phys. Rev. C 103, 045205 (2021).



$$600\text{MeV} \leq m_0 \leq 900\text{MeV}$$

Mass formula

$$m_{\pm} = \sqrt{m_0^2 + \left(\frac{g_1 + g_2}{2}\right)^2 \sigma^2} \mp \frac{g_1 - g_2}{2}\sigma$$

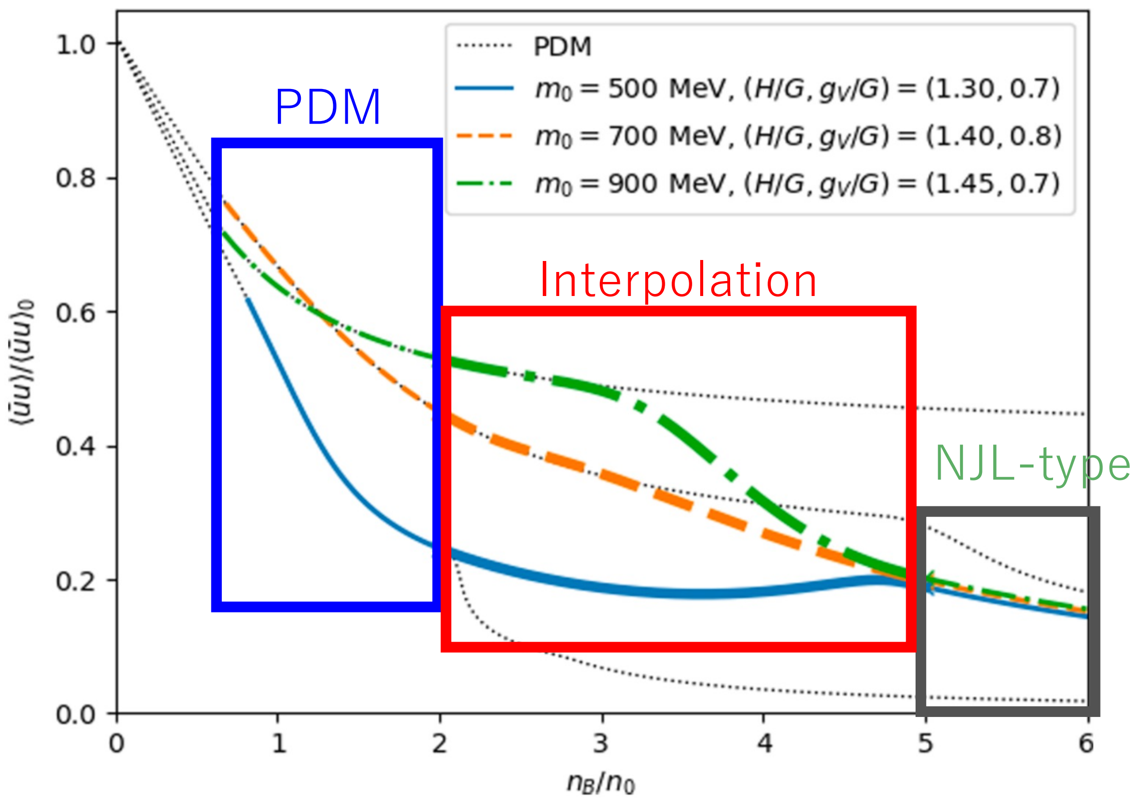
m_0	interaction	Attractive force by σ	Repulsive force by ω	EOS
small	strong	strong	strong	stiff
large	weak	weak	weak	soft

NS includes quark matter inside.

NS is made from only hadronic matter.

Density dependence of chiral condensate

T. Minamikawa, T. Kojo and M. Harada, Phys. Rev. C 104, 065201 (2021).



$$\langle \bar{q}q \rangle = -\frac{\partial P}{\partial m_q}$$

Hellmann-Feynman theorem

NS observation of M-R relation
(Macroscopic information)

- $R \lesssim 13.5\ km$ for $M \sim 1.4 M_{\odot}$

$m_0 \gtrsim 600 MeV$

Constraint to
Chiral condensate at high density
(Microscopic information)

- ${\langle \bar{q}q \rangle_{n_B}} / {\langle \bar{q}q \rangle_0} \gtrsim 0.4\ at\ n_B = 2n_0$

4. Effect of iso-triplet scalar meson [a_0(980) meson]

Y.-K. Kong, T. Minamikawa and M. Harada, arXiv:2306.08140

PDM with $a_0(980)$ meson

- Lightest iso-vector scalar meson
- Non-zero mean field in asymmetric matter
- Affects to asymmetric matter properties (i.e. neutron star)

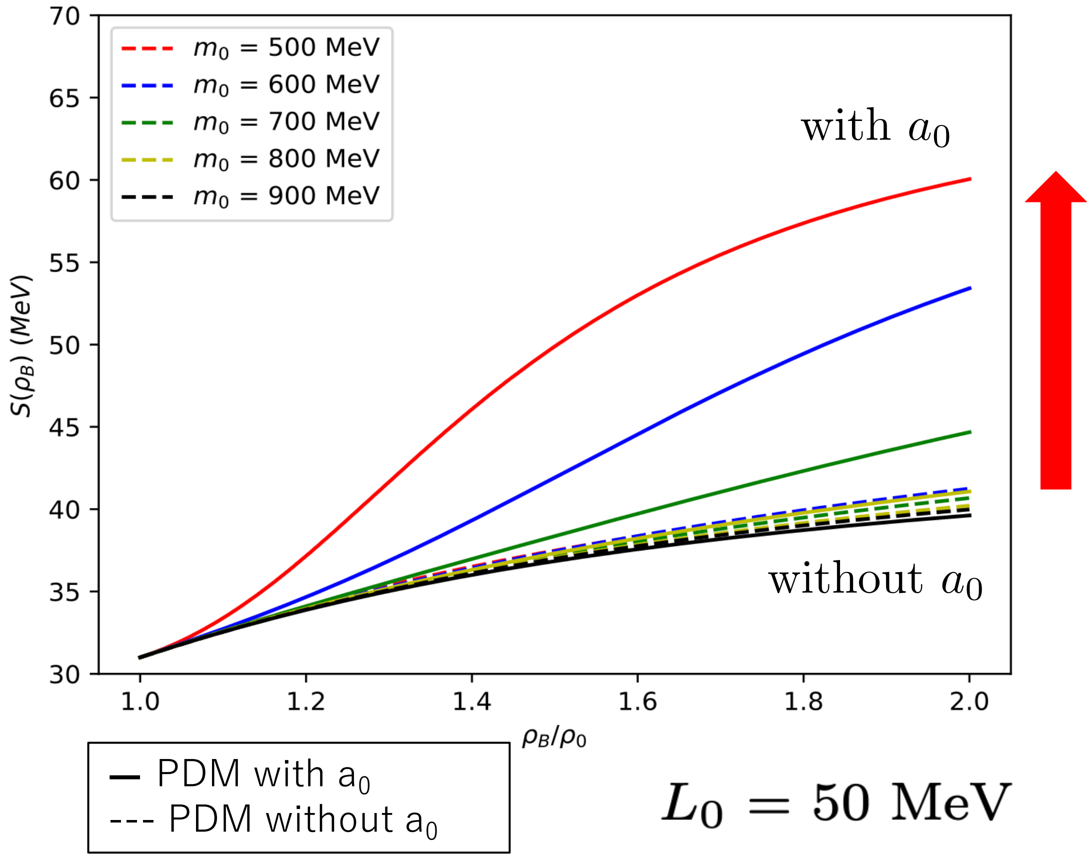
- Previous analysis of $a_0(980)$ in the relativistic mean field(RMF) models:
  - F. Li et al. (2022)
  - T. Miyatsu et al.(2022)
  - V. Thakur et al. (2022) etc…

➔ Stiffening of NS EoS!

We construct a 2-flavor PDM with $a_0(980)$ meson and study its effects in neutron stars!

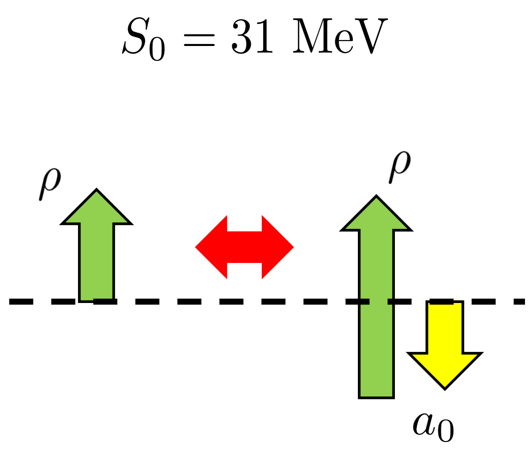
Y.-K. Kong, T. Minamikawa and M. Harada, arXiv:2306.08140

Symmetry energy $S(n_B)$

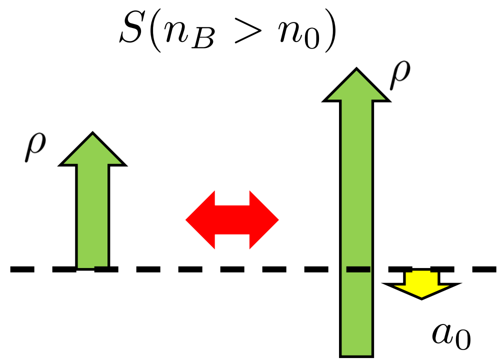


$L_0 = 50$ MeV

Since we determine the ρ coupling by **fitting saturation properties,** the ρ coupling of the a_0 model is stronger than that of NO a0 model to fit S_0=31 MeV



When $n_B > n_0$, the repulsive force of ρ becomes larger and attractive force of a_0 becomes smaller



Neutron star M-R relation

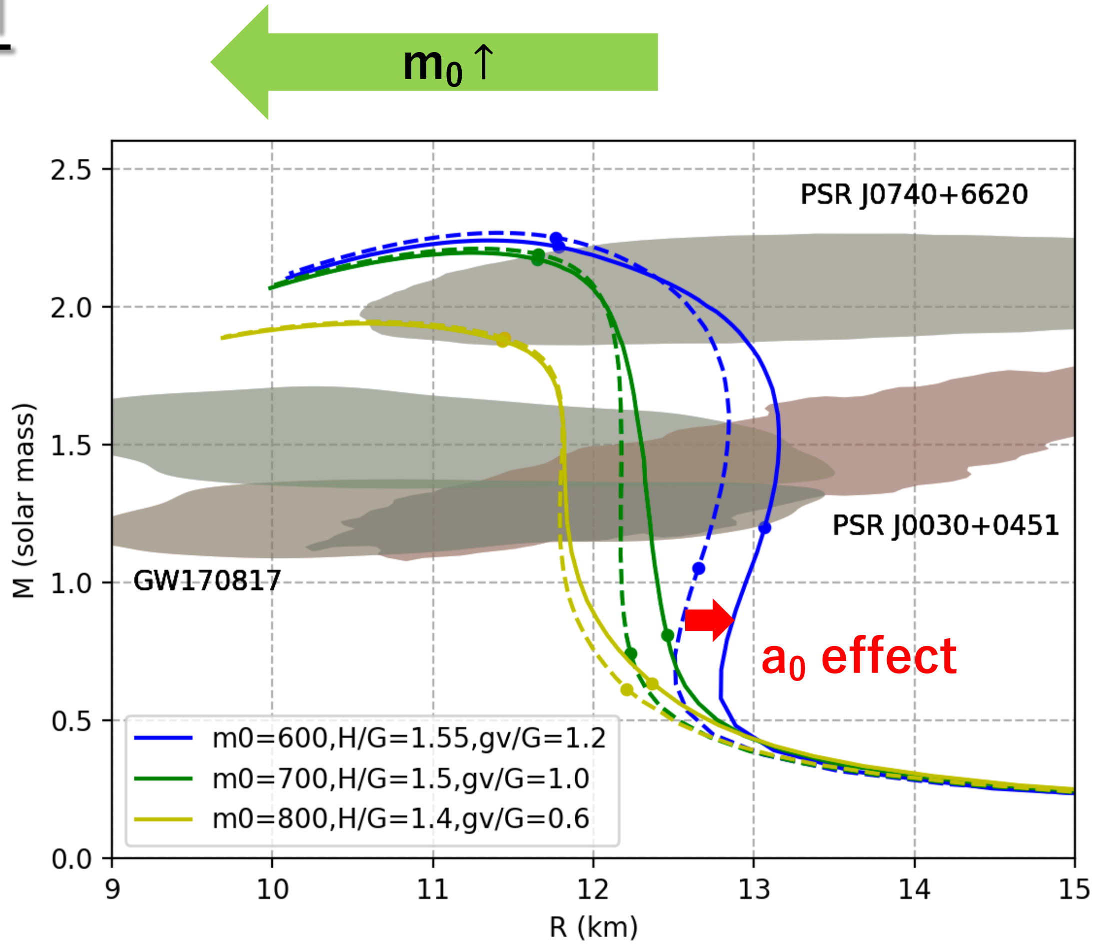
- We compute the M-R relation by solving the TOV equation

- Effect of a_0(980) **increases the radius of intermediate mass NS**

$$520 \text{ MeV} \lesssim m_0 \lesssim 850 \text{ MeV}$$

a_0(980)

$$\boxed{560 \text{ MeV} \lesssim m_0 \lesssim 840 \text{ MeV}}$$

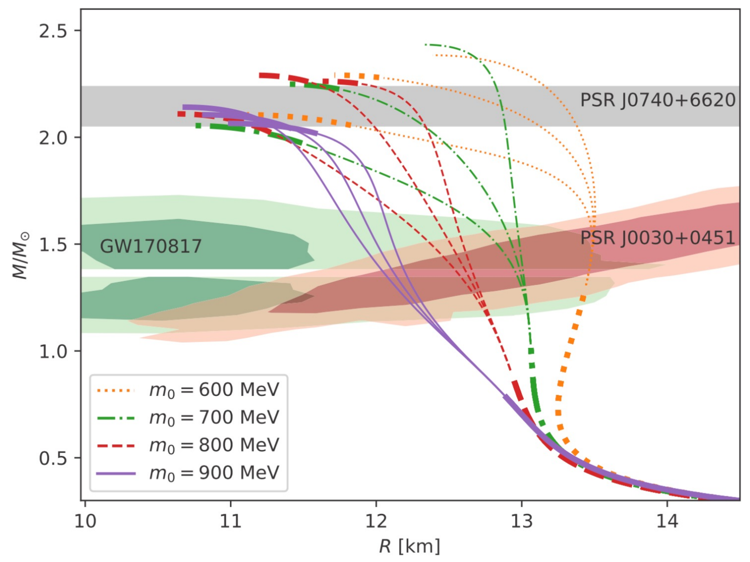


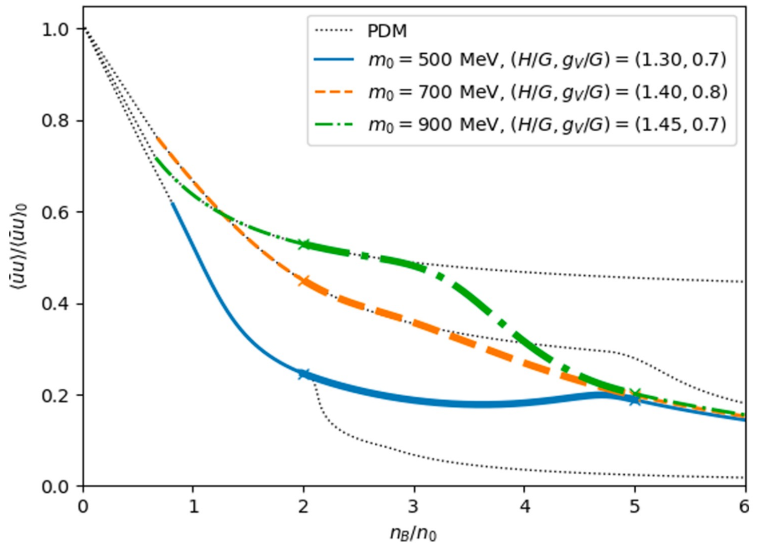
— PDM with a_0
--- PDM without a_0

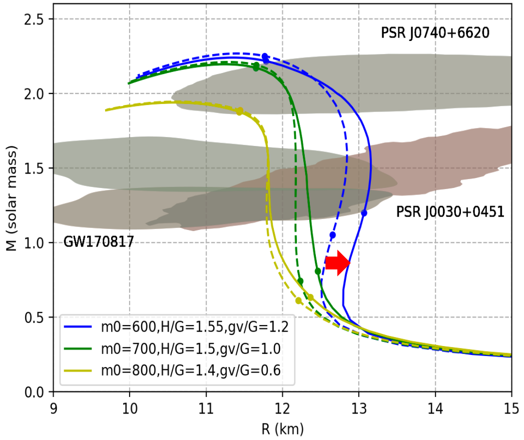
$L_0 = 50$ MeV

Summary

- NS properties such as M-R relation (macroscopic information) gives constraint to the chiral condensate (microscopic information).
  - $R \lesssim 13.5\ km$ for $M \sim 1.4 M_\odot$
  - $m_0 \gtrsim 600 MeV$
  - $\langle\bar{q}q\rangle_{n_B} / \langle\bar{q}q\rangle_0 \gtrsim 0.4\ at\ n_B = 2n_0$
- Effect of iso-triplet a0(980) meson only slightly increases the radius.







Thank you very much for your attention !