A study of neutron star property based on the PDM-NJL crossover model

Masayasu Harada (Nagoya University)

@ Compact Stars in the QCD phase diagram (CSQCD2024)

(October 7, 2024)

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).

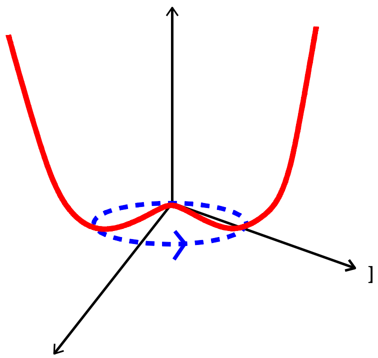
Introduction

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

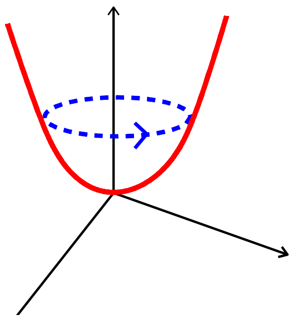
=

One of the Interesting problems of QCD

Spontaneous chiral symmetry breaking



$\langle \bar{q}q \rangle \neq 0$ (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 ?**

- 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.

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

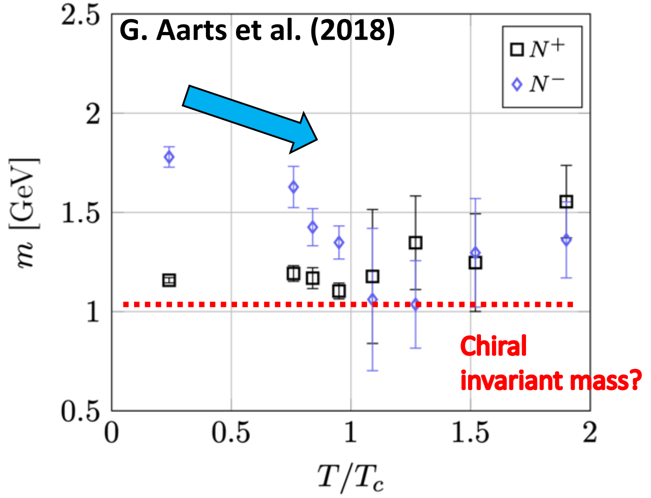
← spontaneous chiral symmetry breaking

↑ chiral invariant mass

- A Lattice QCD analysis at non-zero T supports parity doublet structure.

⇨ What happens in dense nuclear matter ?

e.g. Finite-T lattice calculation



Study of nuclear matter using parity doublet models (PDMs)

1. Construction of nuclear matter from a PDM
   Y.Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015)
2. Study of effect of $\Delta(1232)$ to the chiral symmetry breaking in a PDM
   Y. Takeda, Y. Kim and M. Harada, Phys. Rev. C 97, 065202 (2018).
3. Study of a new dual chiral density wave (DCDW) in a PDM.
   Y. Takeda, H. Abuki and M. Harada, Phys. Rev. D 97, 094032 (2018).
4. 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).
5. 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).
6. 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).
7. Study of effect of U(1) axial anomaly
   B. Gao, T. Minamikawa, T. Kojo and M. Harada, Phys. Rev. C 106, 065205 (2022)
8. Review of the above 3 analysis
   T. Minamikawa, B. Gao, T. Kojo and M. Harada, Symmetry 15, 745 (2023)
9. Study of effect of iso-triplet a0(980) meson -> Kong's presentation
   Y. K. Kong, T. Minamikawa and M. Harada, Phys. Rev. C 108, 055206 (2023).
10. Reconciling constraints from the supernova remnant HESS J1731-347 with the parity doublet model
    B. Gao, Y. Yan and M. Harada, Phys. Rev. C 109, 065807 (2024). -> Gao's presentation
11. Nuclear matter and finite nuclei: recent studies based on Parity Doublet Model
    Y.K. Kong, Y. Kim and M. Harada, Symmetry 2024, 16(9), 1238.
12. Exploring the first-order phase transition in neutron stars using the parity doublet model and NJL-type quark model
    B. Gao, W. L. Yuan, M. Harada and Y.L. Ma, To appear in Phys. Rev. C. [arXiv:2407.13990 [nucl-th]].

Outline

1. Introduction
2. Nuclear matter from a PDM
3. A unified EOS for NS and M-R relation
4. Summary

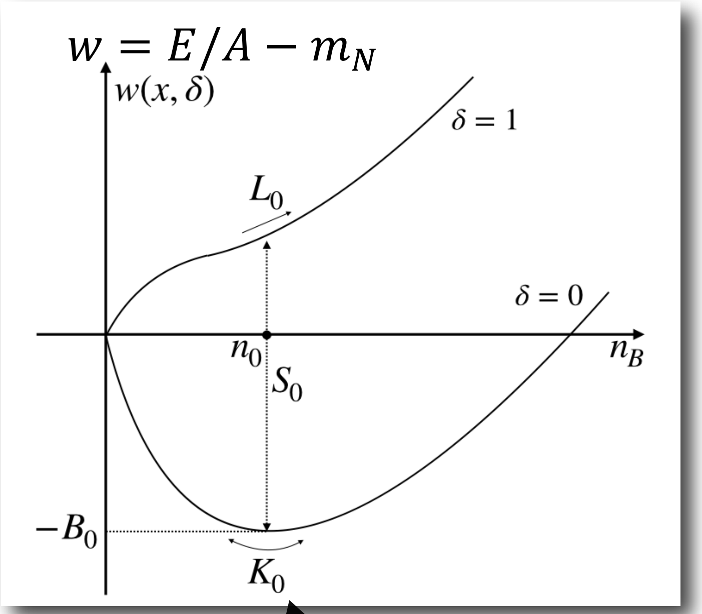
2. Nuclear matter from PDM

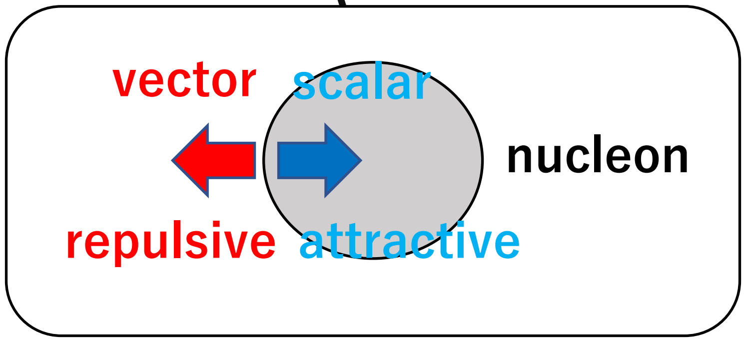
A relativistic mean field (RMF) approach based on the parity doublet model

- N(939), N*(1535) as chiral partners
  - $m_\pm = \frac{1}{2}\left[\sqrt{(g_1+g_2)^2\sigma^2 + 4m_0^2} \mp (g_1-g_2)\sigma\right]$
  - $m_+ = m(N(939))$, $m_- = m(N^*(1535))$
  - 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

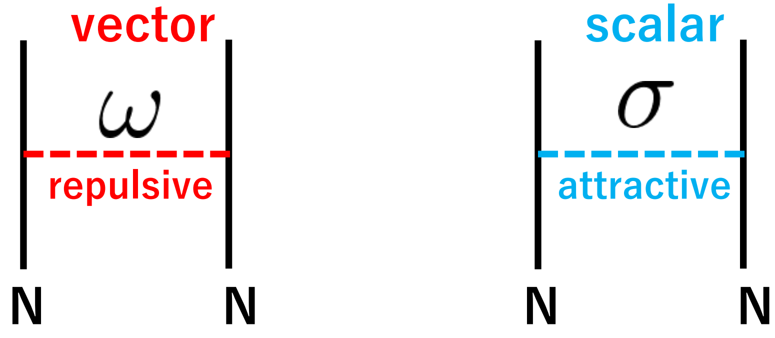
Nuclear Matter at normal nuclear density

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





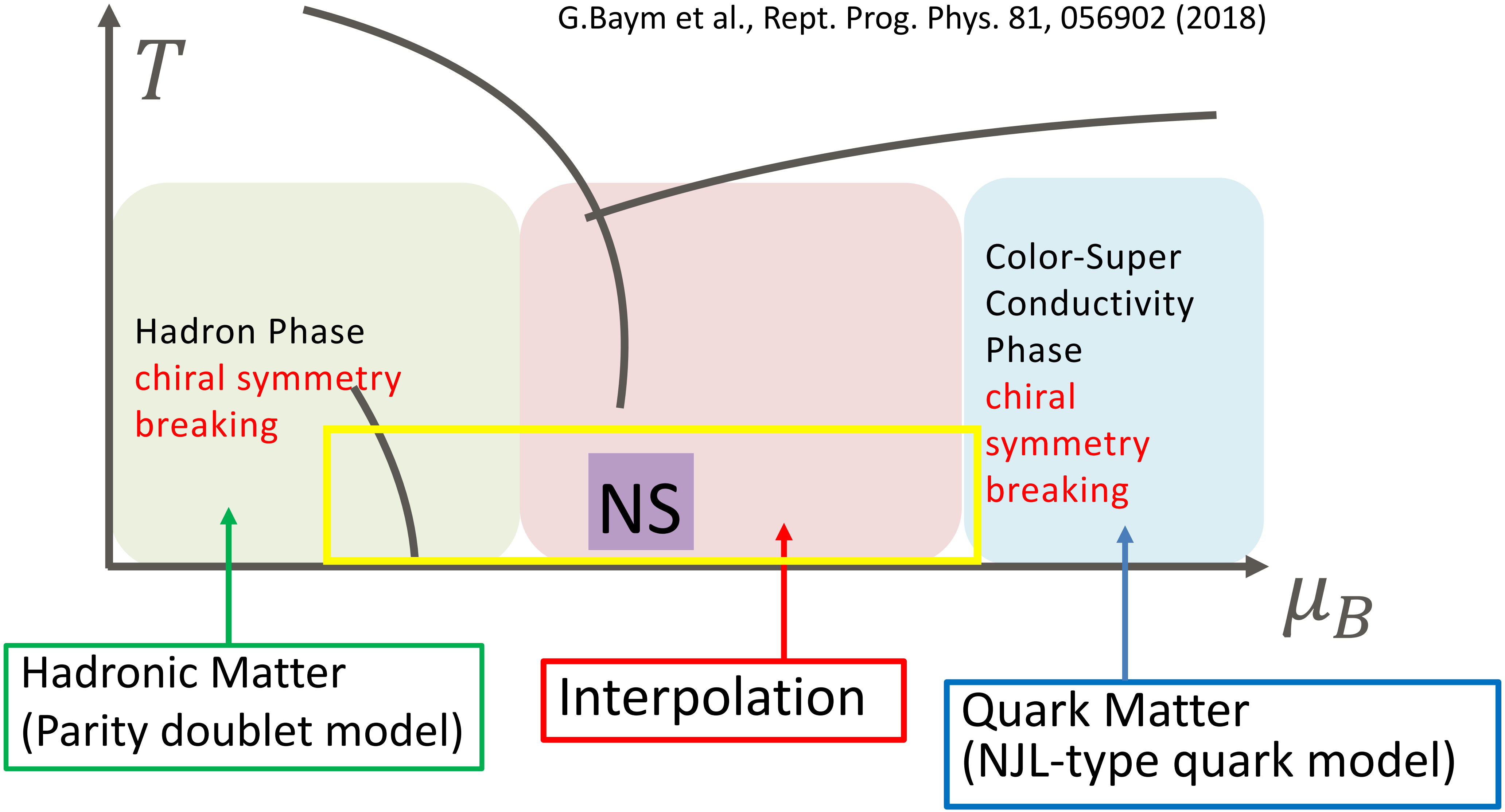
- Nuclear saturation density
  - $\rho(\mu_B^* = 923\text{MeV}) = n_0 = 0.16\text{fm}^{-3}$
- Binding energy at normal nuclear density
  - $w = \left[\frac{E}{A} - m(939)\right]_{n_0} = -16\text{MeV}$
- Incompressibility
  - $K_0 = 9\rho_0^2 \left.\frac{\partial^2(E/A)}{\partial\rho^2}\right|_{n_0} =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



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

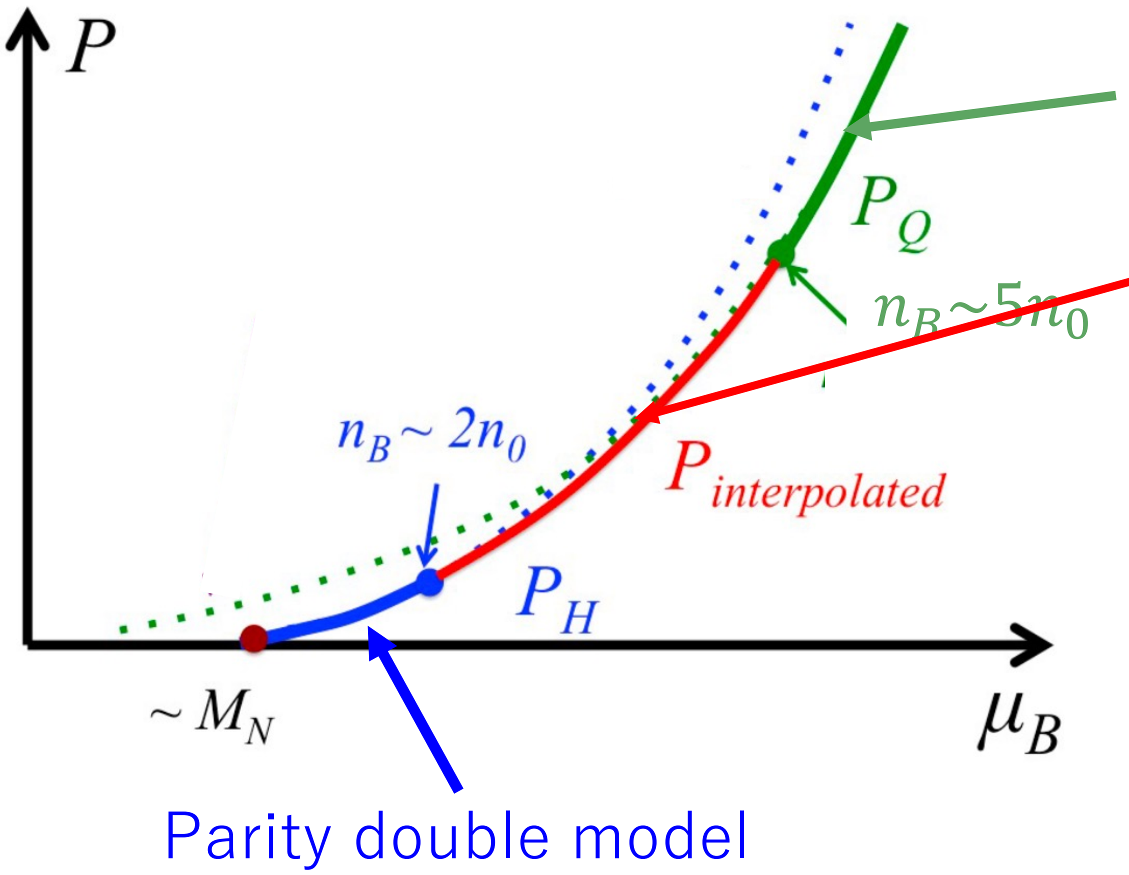
$$H \sum_{A,A'=2,5,7} \left[\left(\bar{q} i\gamma_5 \tau_A \lambda_{A'} C \bar{q}^T\right) \left(q^T C i\gamma_5 \tau_A \lambda_{A'} q\right) + \left(\bar{q} \tau_A \lambda_{A'} C \bar{q}^T\right) \left(q^T C \tau_A \lambda_{A'} q\right) \right]$$

  - 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*.

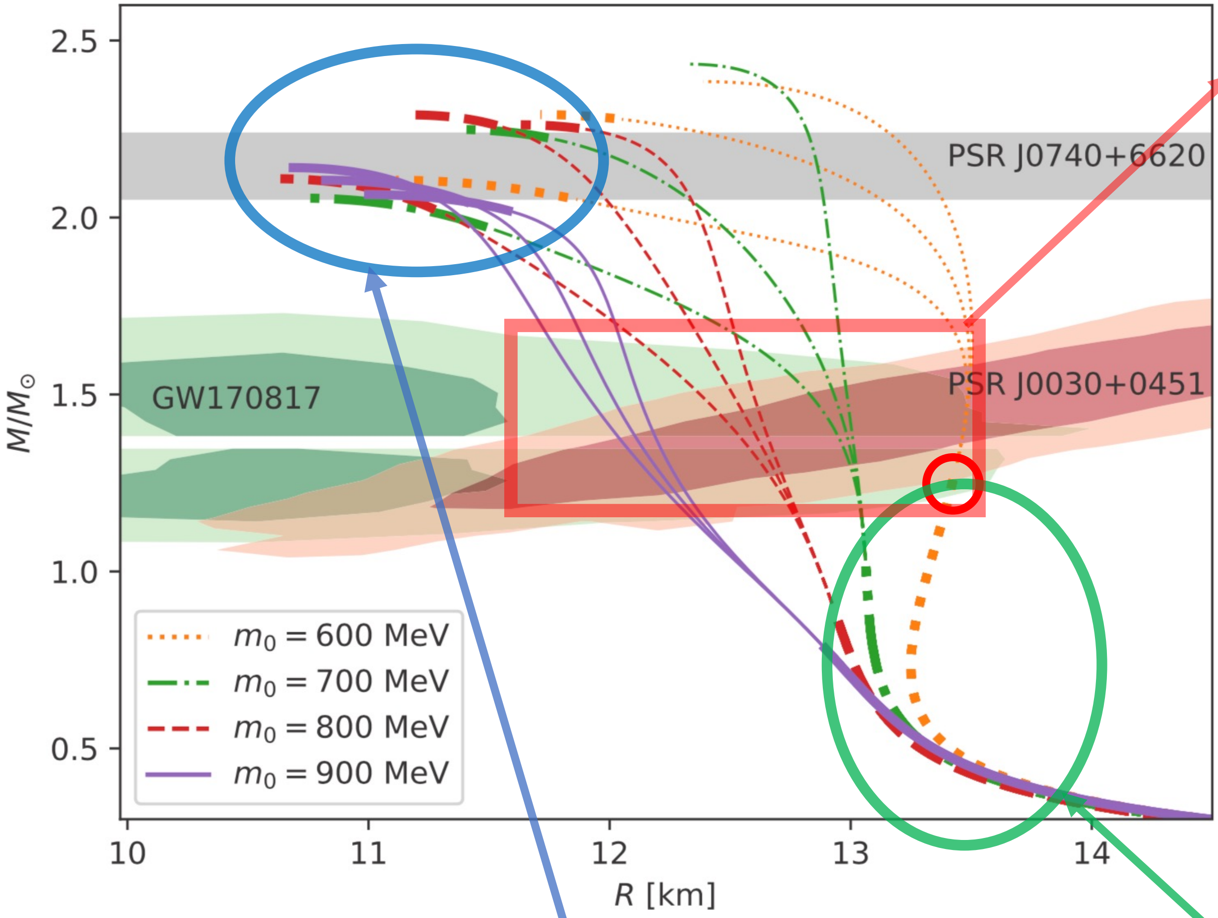
6-coefficients are determined by connecting P to the second order at 2n_0 and 5n_0.

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

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

M-R relation

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



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

Mass formula

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

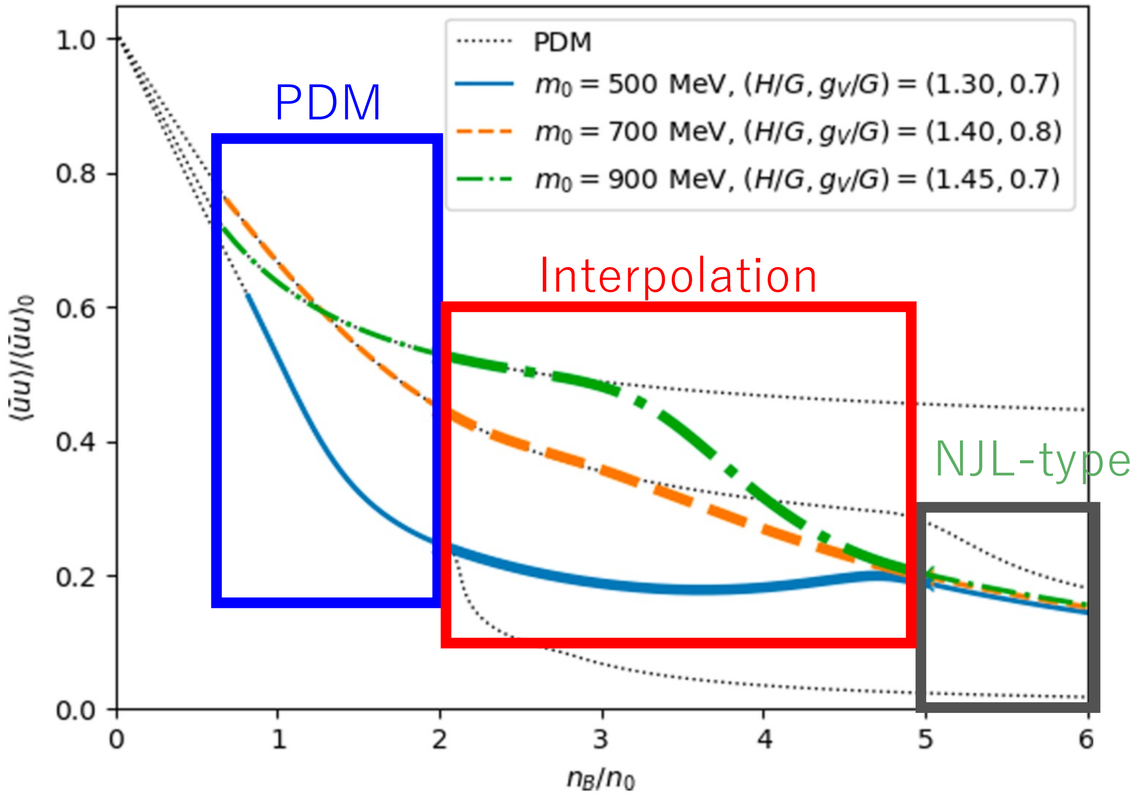
m_0	interaction	Attractive force by σ	Repulsive force by ω	EOS
small	strong	strong	strong	stiff
large	weak	weak	weak	soft

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 $M \sim 1.4 M_\odot$

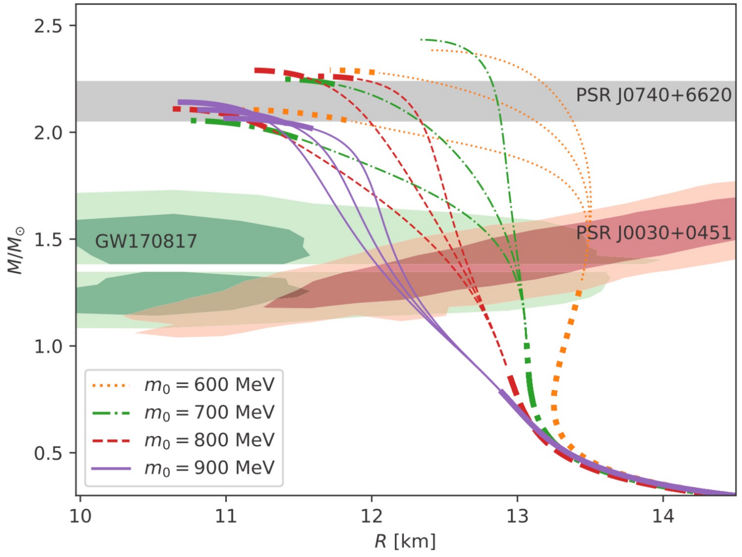
$m_0 \gtrsim 600 MeV$

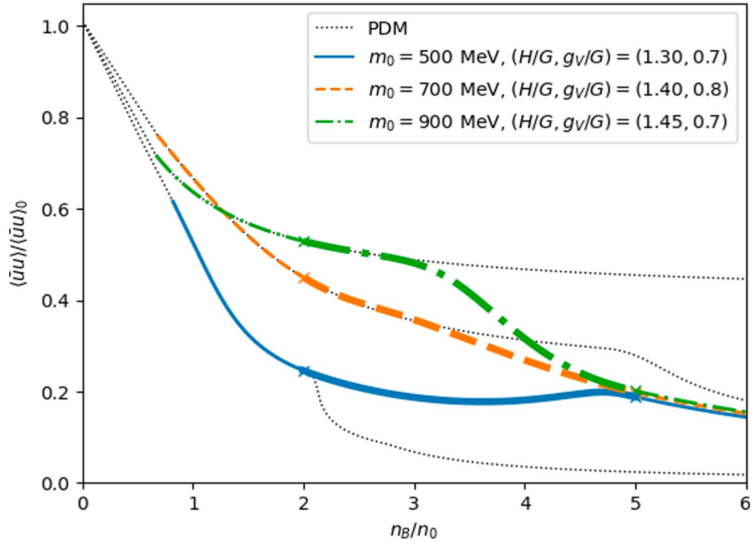
Constraint to Chiral condensate at high density (Microscopic information)

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

Summary

- NS properties such as M-R relation (macroscopic information) gives constraint to the chiral invariant mass and chiral condensate (microscopic information).
  - $R \lesssim 13.5\ km$ for $M \sim 1.4 M_{\odot}$
  - $600 \lesssim m_0 \lesssim 900 MeV$
  - $\langle \bar{q}q \rangle_{n_B} / \langle \bar{q}q \rangle_0 \gtrsim 0.4\ at\ n_B = 2n_0$
- Future works:
  - Inclusion of hyperons or Δ baryon





Thank you very much for your attention !