Study of dense nuclear matter using parity doublet models

Masayasu Harada (Nagoya University)

@ Reimei Workshop “Hadrons in dense matter at J-PARC” (February 23, 2022)

Based on

- Y. Motohiro, Y. Kim, M. Harada, Phys. Rev. C 92, 025201 (2015); Erratum: Phys. Rev. C 95, 059903 (2017).
- Y. Takeda, Y. Kim and M. Harada, Phys. Rev. C 97, 065202 (2018).
- Y. Takeda, H. Abuki and M. Harada, Phys. Rev. D 97, 094032 (2018).
- T. Yamazaki and M. Harada, Phys. Rev. D 99, 034012 (2018).
- T. Yamazaki and M. Harada, Phys. Rev. C 100, 025205 (2019).
- 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).

Introduction

Origin of Mass ?

of Hadrons

Origin of Mass ?

of Hadrons

Origin of Mass ?

of Us

Origin of Mass ?

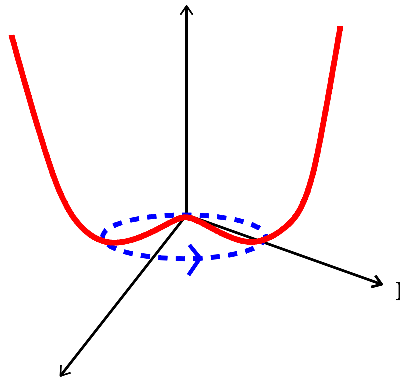
of Hadrons

of Us

=

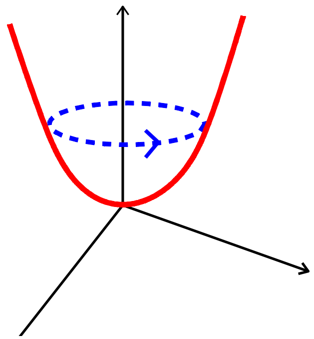
One of the Interesting problems of QCD

spontaneous chiral symmetry breaking



chiral symmetry broken phase at vacuum

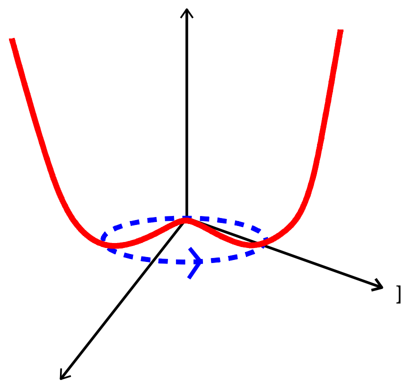
$\langle \bar{q}q \rangle \neq 0$ (chiral condensate)



chiral symmetric phase at high T and/or density

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

spontaneous chiral symmetry breaking



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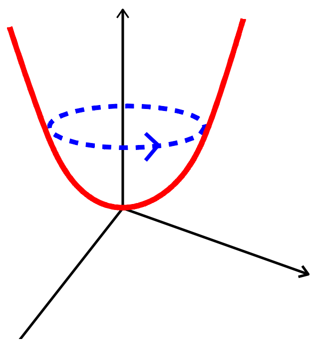


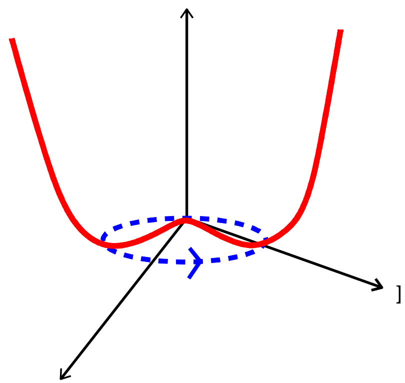
chiral symmetric phase at high T and/or density

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

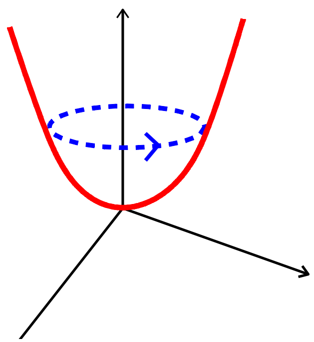
$\langle \bar{q}q \rangle = 0$

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

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)

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- 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.

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

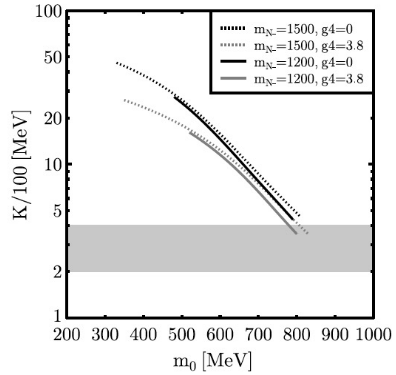
chiral invariant mass (m_0) spontaneous chiral symmetry breaking ($m_{\langle \bar{q} q \rangle}$)

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

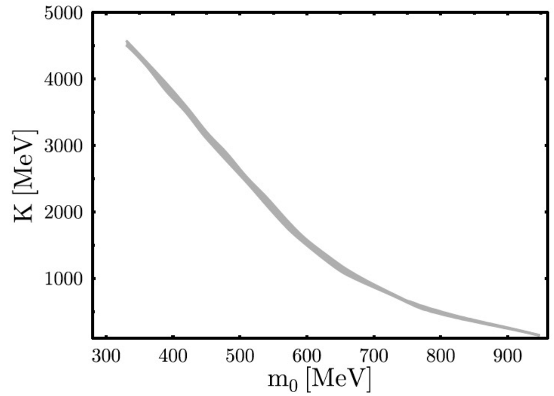
Nuclear matter in parity doublet models

- 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

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



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



Nuclear matter in parity doublet models

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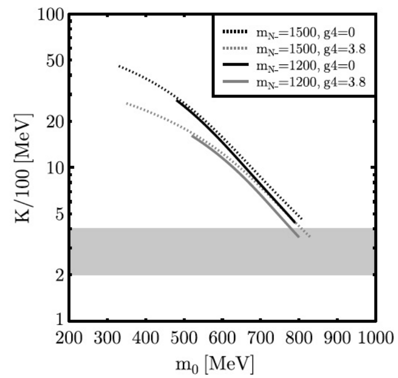
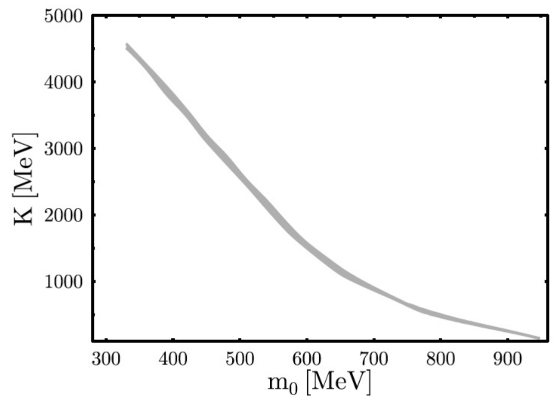
  - Large value of m_0 is needed to reproduce the incompressibility.
- Rho meson is further included with 4-point interaction.
  - $m_0 > 800$ MeV is needed to have $100 < K < 400$ MeV
- In our analysis [Y.Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015)], we constructed a model with a 6-point 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 (2008)



Study of dense nuclear matter using parity doublet models (PDMs)

- Construction of nuclear matter from a PDM
  - Y.Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015)
- 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).
- 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).
- 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).
- Construction of a unified EOS connecting a PDM and an NJL-type quark model
  - T. Minamikawa, T. Kojo and M. Harada, Phys. Rev. C 103, 045205 (2021).
- 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).

Outline

1. Introduction
2. Construction of nuclear matter from a PDM
3. Effect of $\Delta(1232)$ to nuclear matter based on parity doublet structure
4. A new Dual Chiral Density Wave (DCDW) in a PDM
5. A constraint to the chiral invariant mass in a PDM from the neutron star properties
6. A unified EOS for NS connecting a PDM and an NJL-type quark model
7. Summary

2. Construction of nuclear matter from a Parity Doublet Model (PDM)

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

chiral representation of baryons

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

- representation of quark under $SU(2)_R \times SU(2)_L$

$$q \sim q_r + q_l \sim (2,1) \oplus (1,2)$$

- representation of baryon under $SU(2)_R \times SU(2)_L$

$$\psi \sim q \otimes q \otimes q \sim \left[(2,1) \oplus (1,2)\right]^3$$

$$= 5\left[(2,1) \oplus (1,2)\right] \oplus 3\left[(3,2) \oplus (2,3)\right] \oplus \left[(4,1) \oplus (1,4)\right]$$

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$$= 5\left[(2,1) \oplus (1,2)\right] \oplus 3\left[(3,2) \oplus (2,3)\right] \oplus \left[(4,1) \oplus (1,4)\right]$$

Chiral symmetry is broken and the isospin symmetry remains

$I = \frac{1}{2}$ baryons

$I = \frac{3}{2}$ baryons

A Parity Doublet model

C.DeTar, T.Kunihiro, PRD39, 2805 (1989)
D.Jido, M.Oka, A.Hosaka, PTP106, 873 (2001)
Y.Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015)

- N(1535) = chiral partner to N(939)
- chiral transformations:
  - $\psi_{1l} \to g_L \psi_{1l}, \psi_{1r} \to g_R \psi_{1r}, \psi_{2l} \to g_R \psi_{2l}, \psi_{2r} \to g_L \psi_{2r}; g_L \in \mathrm{SU}(2)_L, g_R \in \mathrm{SU}(2)_R$
- A chiral invariant mass:
  - $m_0[\bar{\psi}_{1l}\psi_{2r} + \bar{\psi}_{2r}\psi_{1l} + \bar{\psi}_{1r}\psi_{2l} + \bar{\psi}_{2l}\psi_{1r}]$
- Yukawa interactions
  - $-g_1[\bar{\psi}_{1l} M \psi_{1r} + \bar{\psi}_{1r} M^\dagger \psi_{1l}] - g_2[\bar{\psi}_{2r} M \psi_{2l} + \bar{\psi}_{2l} M^\dagger \psi_{2r}]$

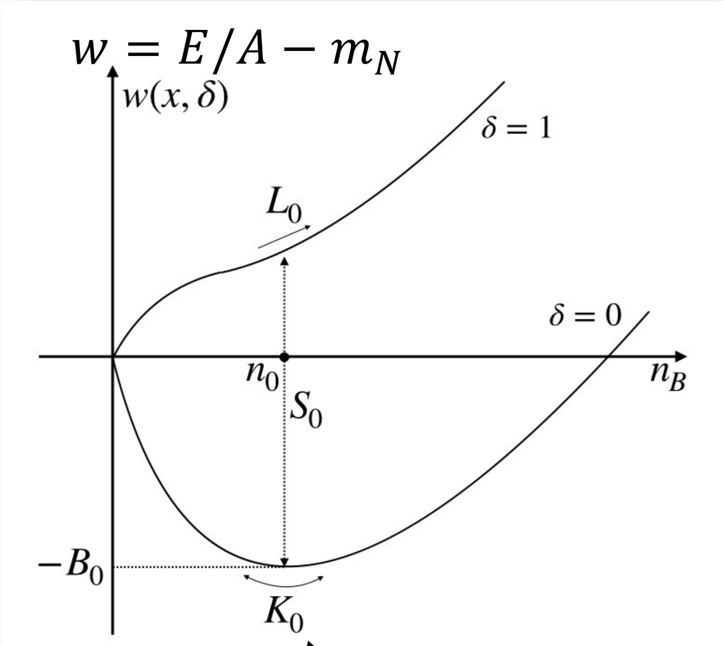
- $M = \sigma + i\,\vec{\tau}\cdot\vec{\pi}$ transforms $M \to g_L\, M\, g_R^\dagger$
- $\langle M \rangle = \bar{\sigma} \neq 0$ causes the spontaneous chiral symmetry breaking.

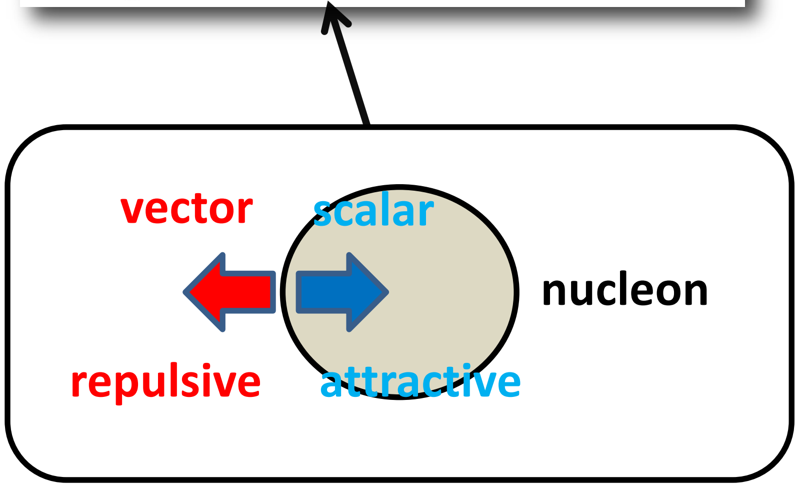
$$m_\pm = \frac{1}{2}\left[\sqrt{(g_1+g_2)^2\,\bar{\sigma}^2 + 4m_0^2} \mp (g_2 - g_1)\,\bar{\sigma}\right]$$

$m_+ = m(N(939))$
$m_- = m(N(1535))$

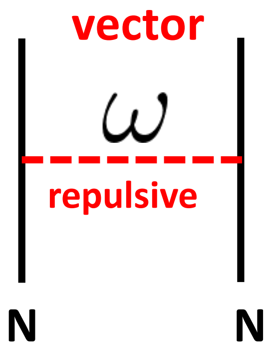
Nuclear Matter at normal nuclear density

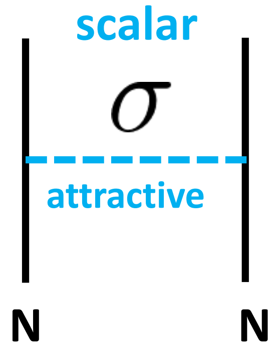
Y. Motohiro, Y. Kim, M. Harada, Phys. Rev. C 92, 025201 (2015); Erratum: Phys. Rev. C 95, 059903 (2017).





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





3. Effect of $\Delta(1232)$ to nuclear matter based on parity doublet structure

Y. Takeda, Y. Kim and M. Harada, Phys. Rev. C 97, no. 6, 065202 (2018).

Chiral Partner Structure of Delta Baryons

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

- Δ(1700) = chiral partner to Δ(1232)

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

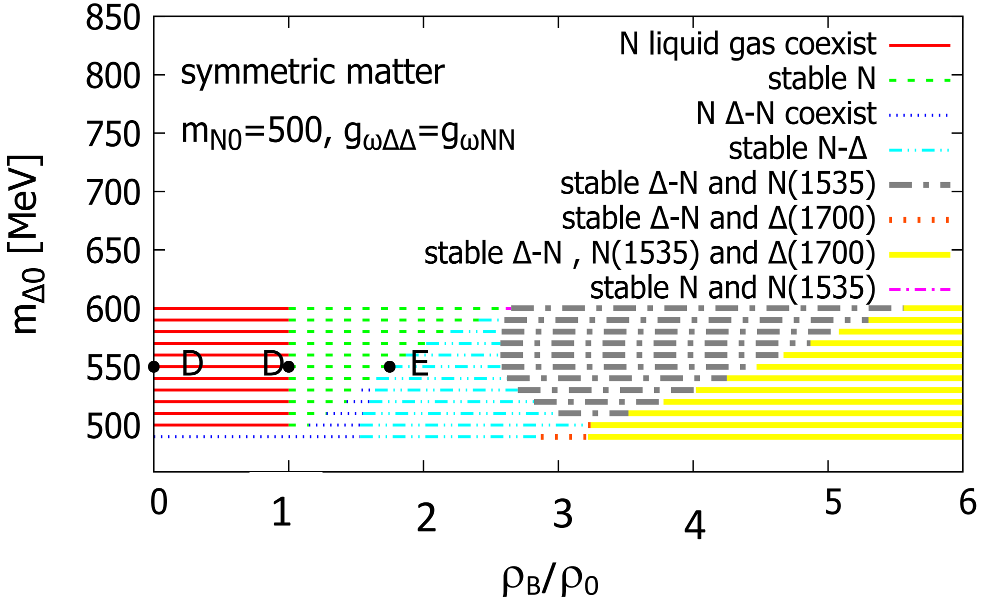
- $m_{\Delta 0}$ = chiral invariant mass for Δ.
- Masses of Δ(1232) and Δ(1700) = inputs

Phase structure & Density

m_{N0} = 500 MeV

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

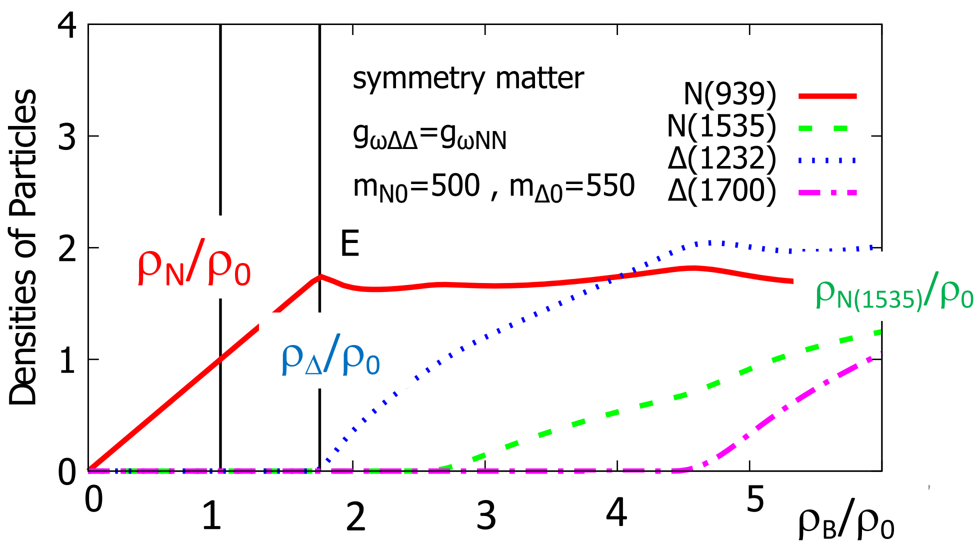
Phase structure



- N liquid-gas coexistence
- stable N phase
- coexistence of Delta-N matter and nuclear matter
- stable N-Delta matter
- stable N-Delta, N(1535) matter
- stable N-Delta, N(1535), Delta(1700) matter
- Stable N-N(1535) matter

$m_{\Delta 0}$ = 550 MeV

Baryon Density vs. ρ_B

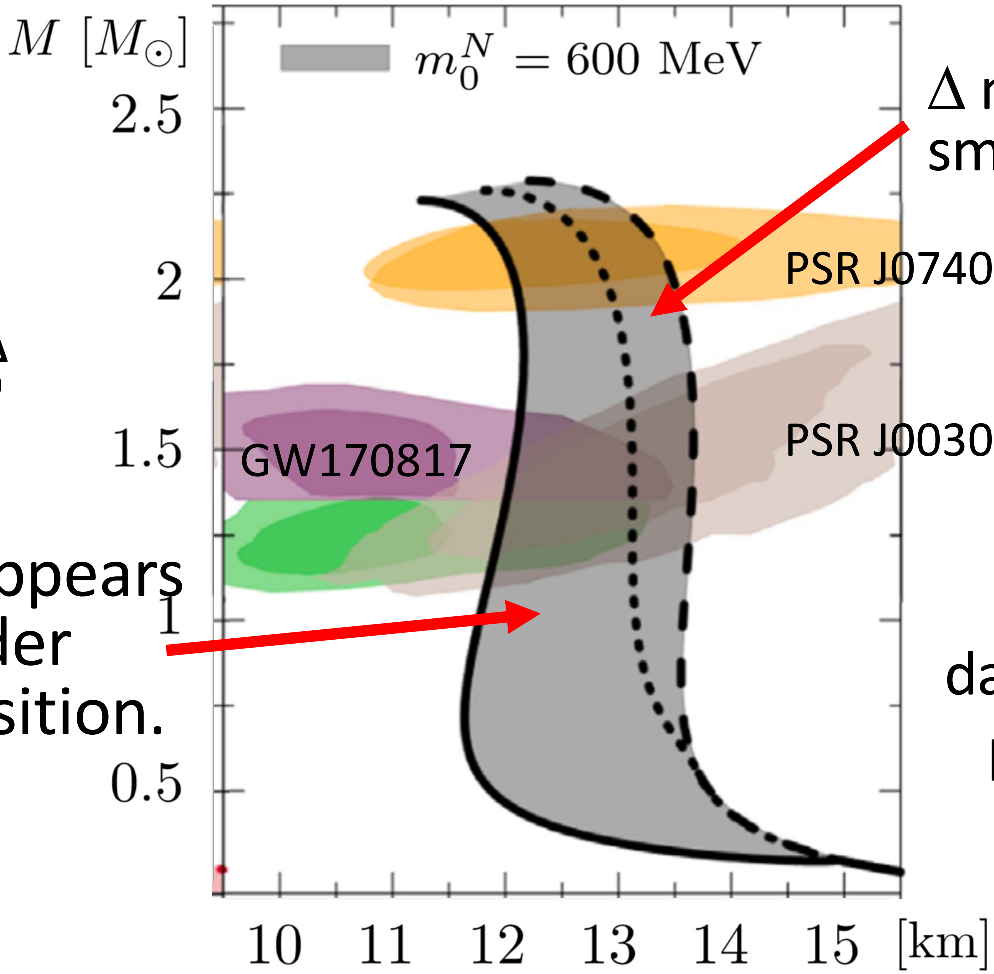


M-R relation of NS with Δ matter

M. Marczenko, K. Redlich and C. Sasaki, Astrophys. J. Lett. 925, L23 (2022).

solid curve:
$m_0^N = m_0^\Delta$

Δ matter appears via first-order phase transition.



Δ matter appears smoothly.

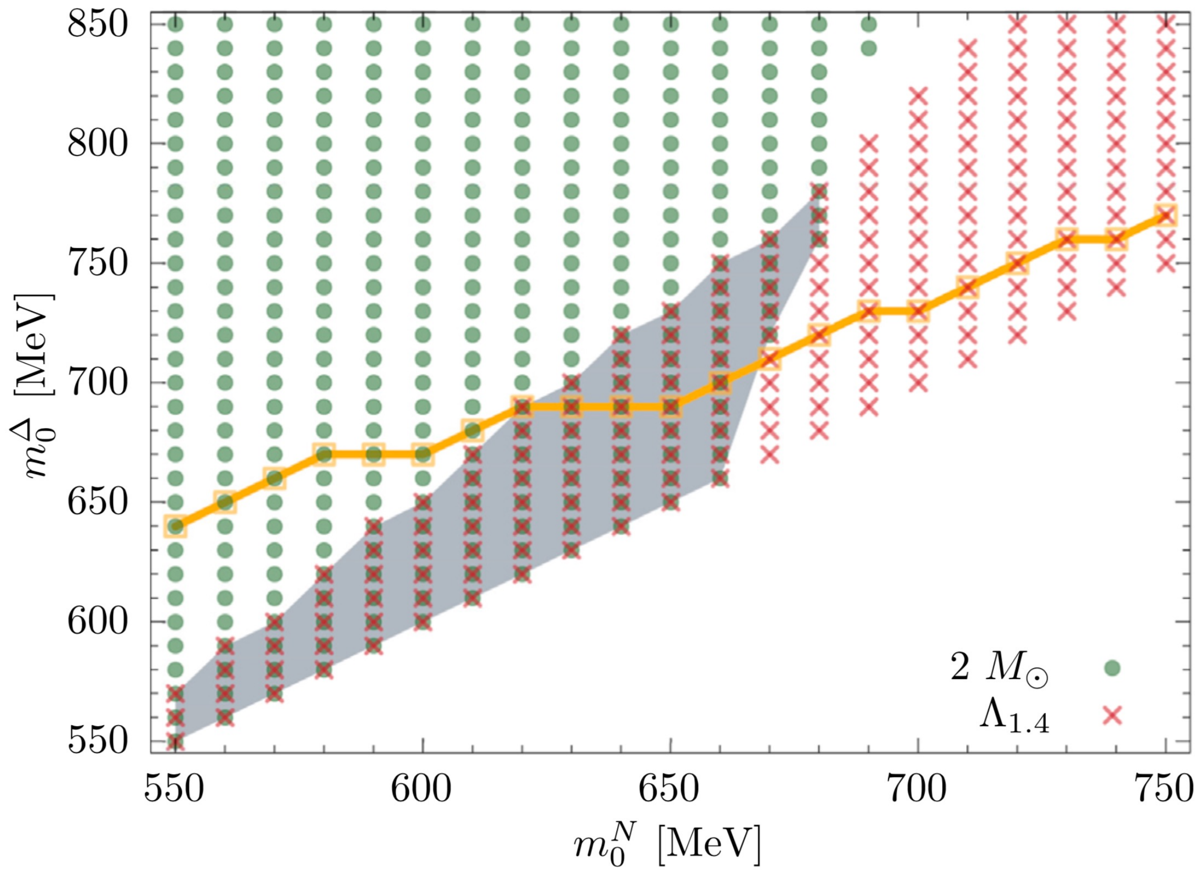
dashed curve:
pure nucleon matter

Δ matter softens the EOS, but pure hadronic matter can survive the observational constraints.

Constraint to chiral invariant masses from NS data

M. Marczenko, K. Redlich and C. Sasaki, Astrophys. J. Lett. 925, L23 (2022)

- allowed by PSR J0740+6620 $M_{\max} = (2.08 \pm 0.07)M_{\odot}$



× allowed by GW170817

Gray area: Δ matter is consistent with NS data.

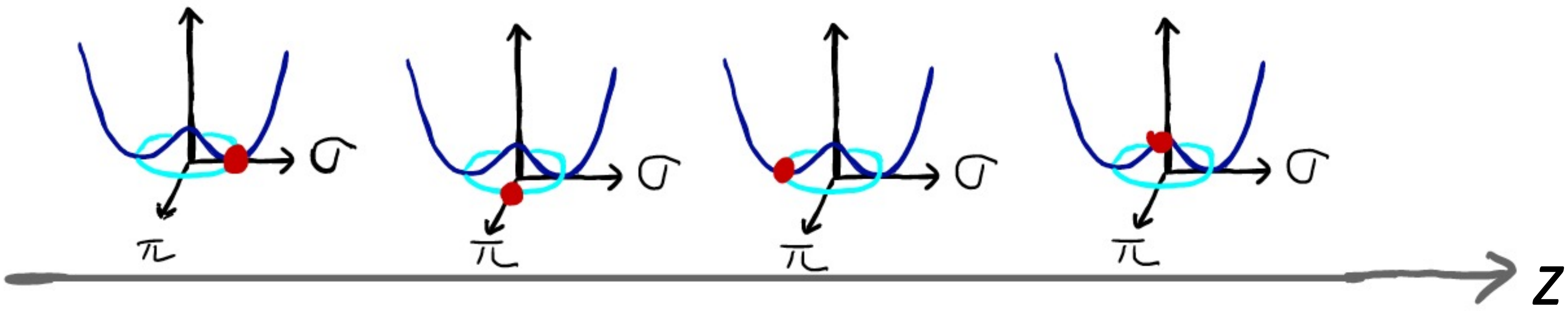
4. A new Dual Chiral Density Wave (DCDW) in a PDM

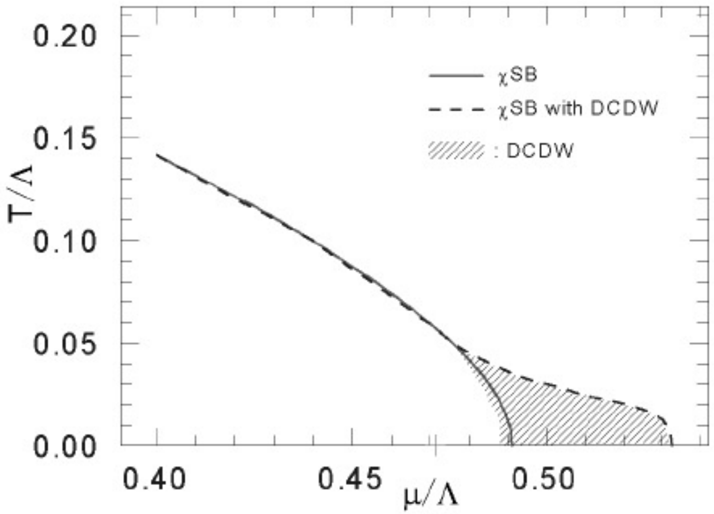
Y. Takeda, H. Abuki and M. Harada, Phys. Rev. D 97, no. 9, 094032 (2018).

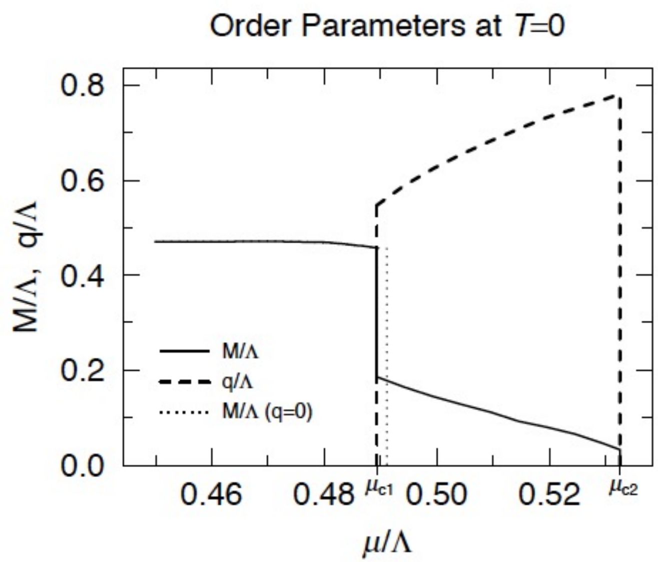
Dual Chiral Density Wave in NJL-type quark model

E.Nakano and T.Tatsumi, PRD71, 114006 (2005)

$$\langle M \rangle = \bar{\sigma} + i\tau_3 \bar{\pi}_3 = \sigma_0 (\cos 2fz + i\tau_3 \sin 2fz)$$



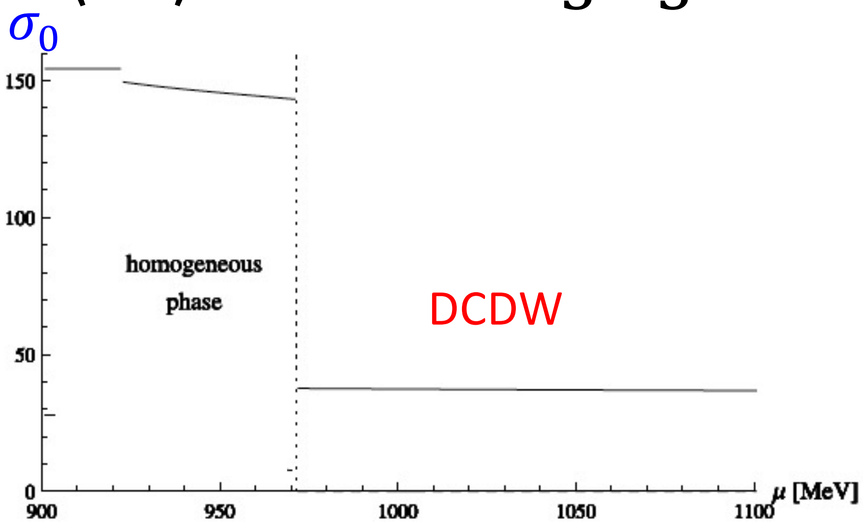


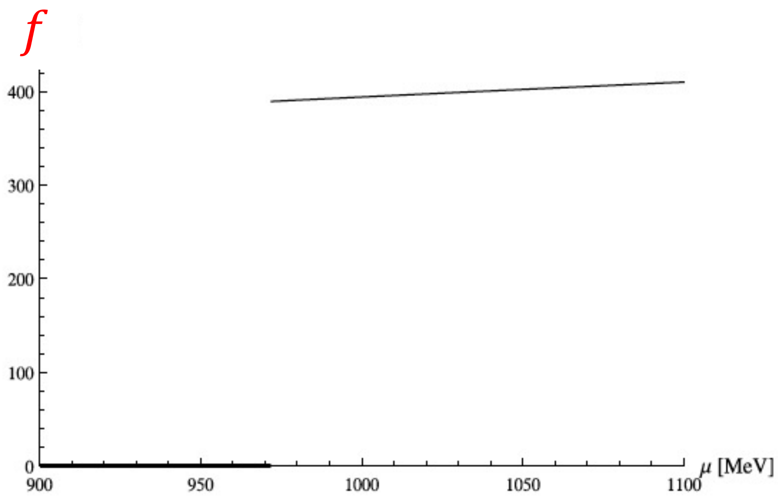


DCDW in a Parity Doublet Model

A.Heinz, F.Giacosa, D.H.Rischke, NPA933, 34 (2015)

$$\langle M \rangle = \bar{\sigma} + i\tau_3 \bar{\pi}_3 = \sigma_0 (\cos 2fz + i\tau_3 \sin 2fz)$$





- Phase transition to DCDW at $\mu_B = 973\text{MeV}$.
- Onset density : $\rho_B = 2.4\rho_0$

shifted DCDW (sDCDW)

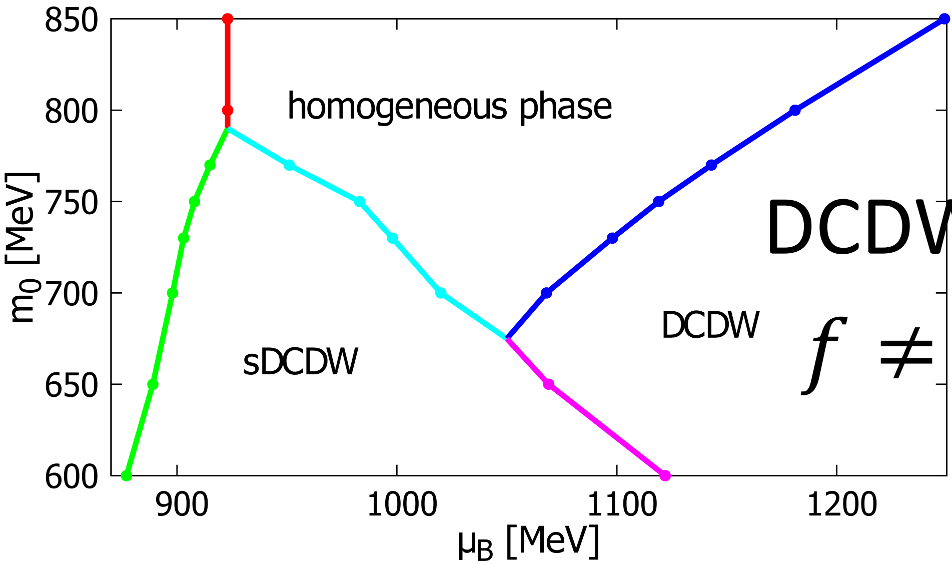
Y.Takeda, H.Abuki, M.Harada, PRD97, 094032 (2018)

$\langle M \rangle = \delta\sigma + \sigma_0(\cos 2fz + i\tau_3 \sin 2fz)$ note: $\int d^3x \, \langle M \rangle = \delta\sigma$

Homogeneous phase : $f = 0, \delta\sigma + \sigma_0 \neq 0$

sDCDW

$f \neq 0, \delta\sigma \neq 0$



DCDW

$f \neq 0, \delta\sigma = 0$

stability of normal nuclear matter $\Longrightarrow$ $m_0 \geq 780 \text{ MeV}$

5. A constraint to the chiral invariant mass in a PDM from the neutron star properties

T. Yamazaki and M. Harada, Phys. Rev. D 99, 034012 (2018)

T. Yamazaki and M. Harada, Phys. Rev. C 100, 025205 (2019)

A Parity doublet model with [(1,2)⊕(2,1)] and [(2,3)⊕(3,2)] representations

T. Yamazaki and M.Harada, Phys. Rev. D99, 034012 (2018)

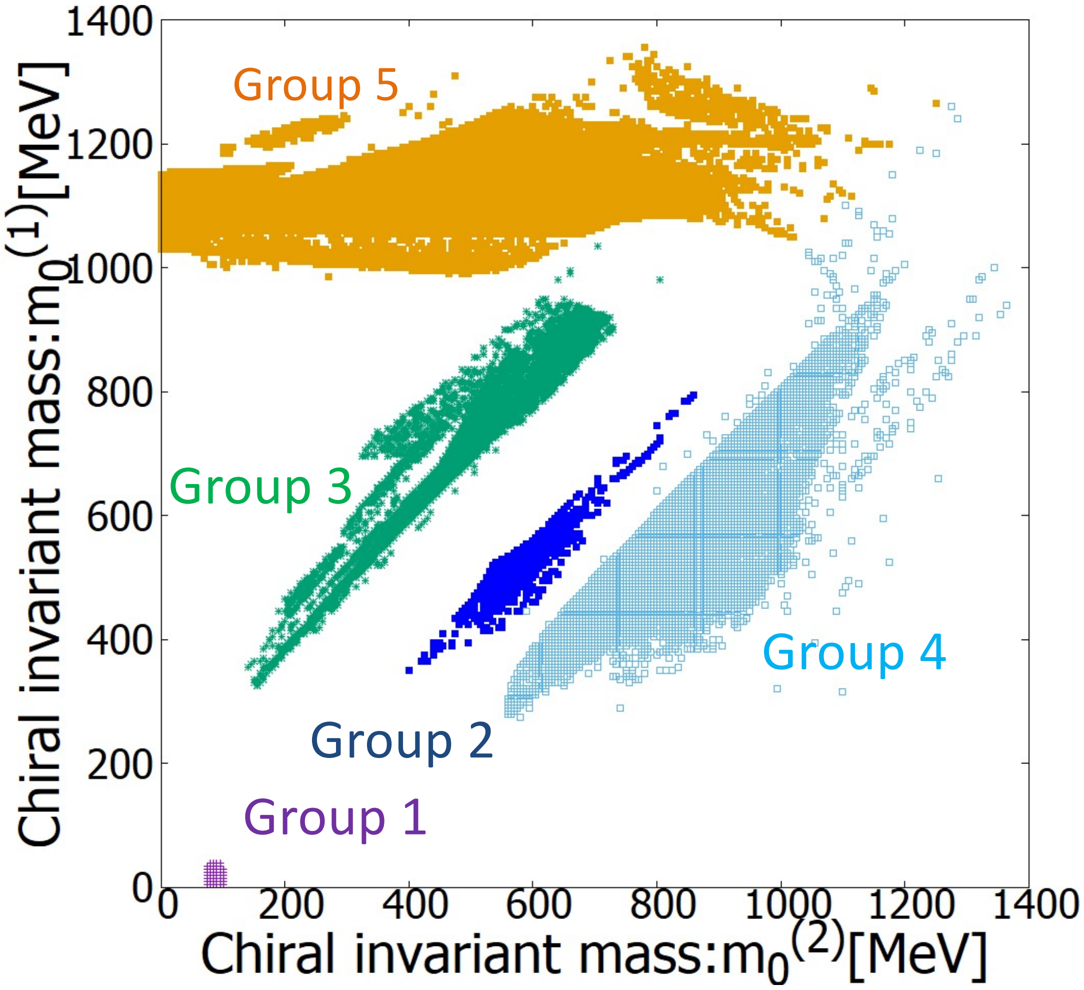
- 2 representations, [(1,2)⊕(2,1)] and [(2,3)⊕(3,2)] to study N(939), N(1440), N(1535), N(1650).
- 2 chiral invariant masses.
  - $-m_0^{(1)}[\bar{\psi}_1\gamma_5\psi_2 - \bar{\psi}_2\gamma_5\psi_1] - m_0^{(2)}[\bar{\Psi}_1\gamma_5\Psi_2 - \bar{\Psi}_2\gamma_5\Psi_1]$
- 6 Yukawa Interactions
  - $-g_1[\bar{\psi}_{1l}M\psi_{1r} + \bar{\psi}_{1r}M^\dagger\psi_{1l}] - g_2[\bar{\psi}_{2r}M\psi_{2l} + \bar{\psi}_{2l}M^\dagger\psi_{2r}]$ etc.
- We also have 4 terms with one derivative.
  - $a_1[\bar{\psi}_{1l}\gamma^\mu\partial_\mu M\psi_{2l} - \bar{\psi}_{1r}\gamma^\mu\partial_\mu M^\dagger\psi_{2r}]$ etc

Physical inputs

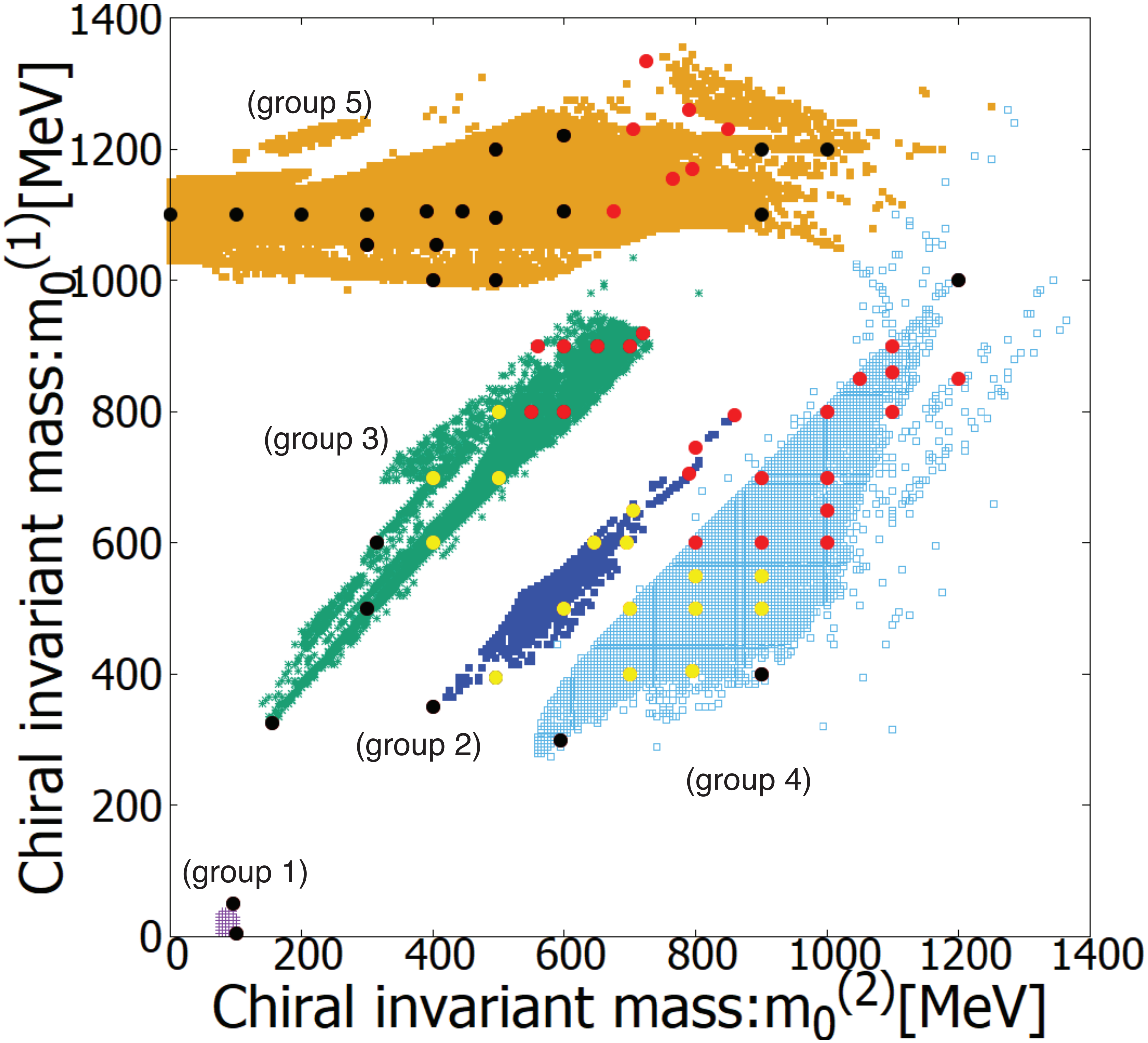
- Fix the values of $m_0^{(1)}$ and $m_0^{(2)}$.
- Use the following 10 physical inputs to determine 10 parameters (10 couplings).

	Mass (MeV)	Width$[\Gamma_{N^*\to N\pi}]$ (MeV)	axial charge
$N(939)$	939	-	1.272
$N(1440)$	1430	228	-
$N(1535)$	1535	68	$-0.25 \leq g_A \leq 0.25$
$N(1650)$	1655	84 $[\text{to } N(939)]$	0.55
		22 $[\text{to } N(1440)]$	

Constraint from vacuum properties



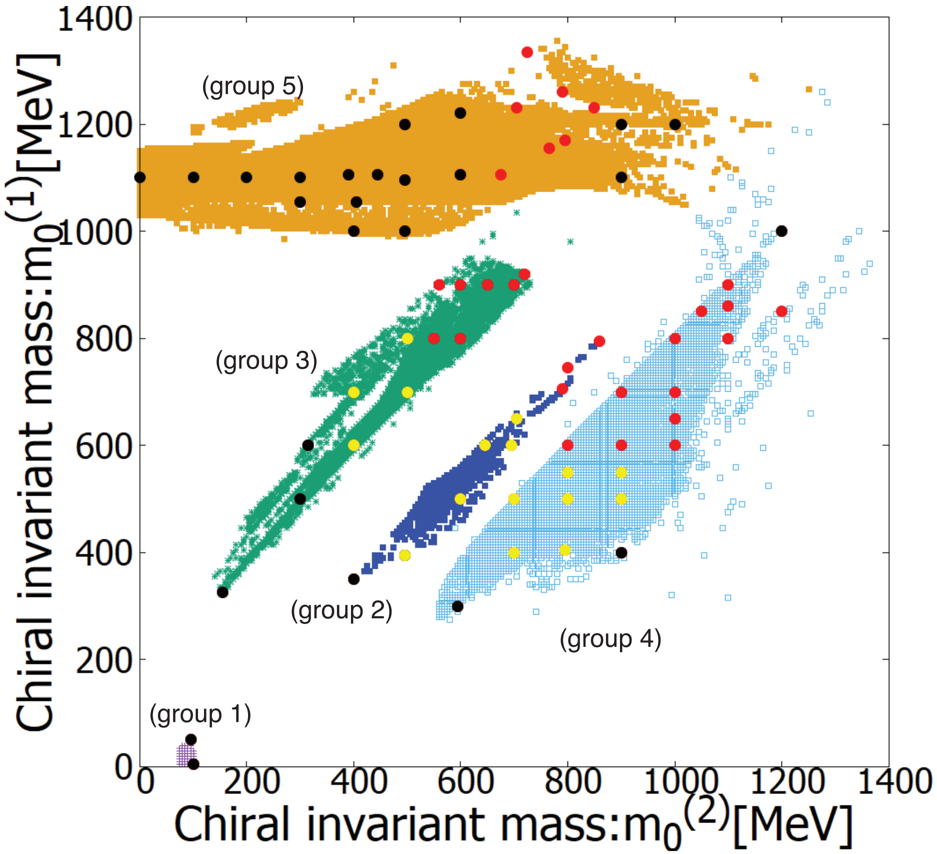
Constraint from saturation propeties



"• marks": the saturation properties are NOT satisfied.

Please note that the parameter choices in Group 1 are all excluded.

Constraint from Neutron Star Properties



Constraint from the tidal deformability:

$\tilde{\Lambda} \leq 800$ with $M_{\mathrm{chirp}} = 1.188\ M_{\odot}$

GW170817 (LIGO & Virgo)

- (yellow dots) are excluded
- (red dots) are allowed.

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

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

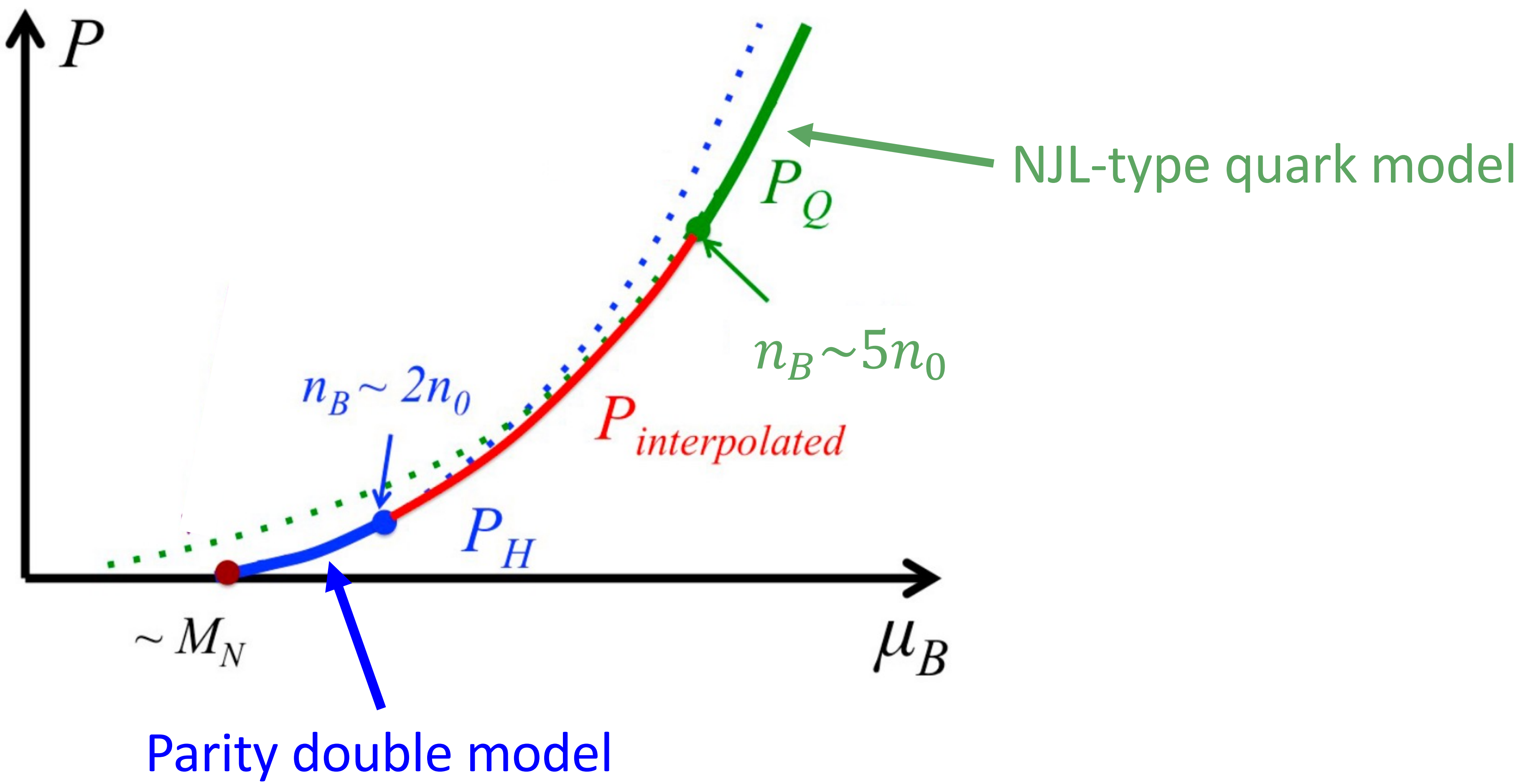
6. A unified EOS for NS connecting a PDM and an NJL-type quark model

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).

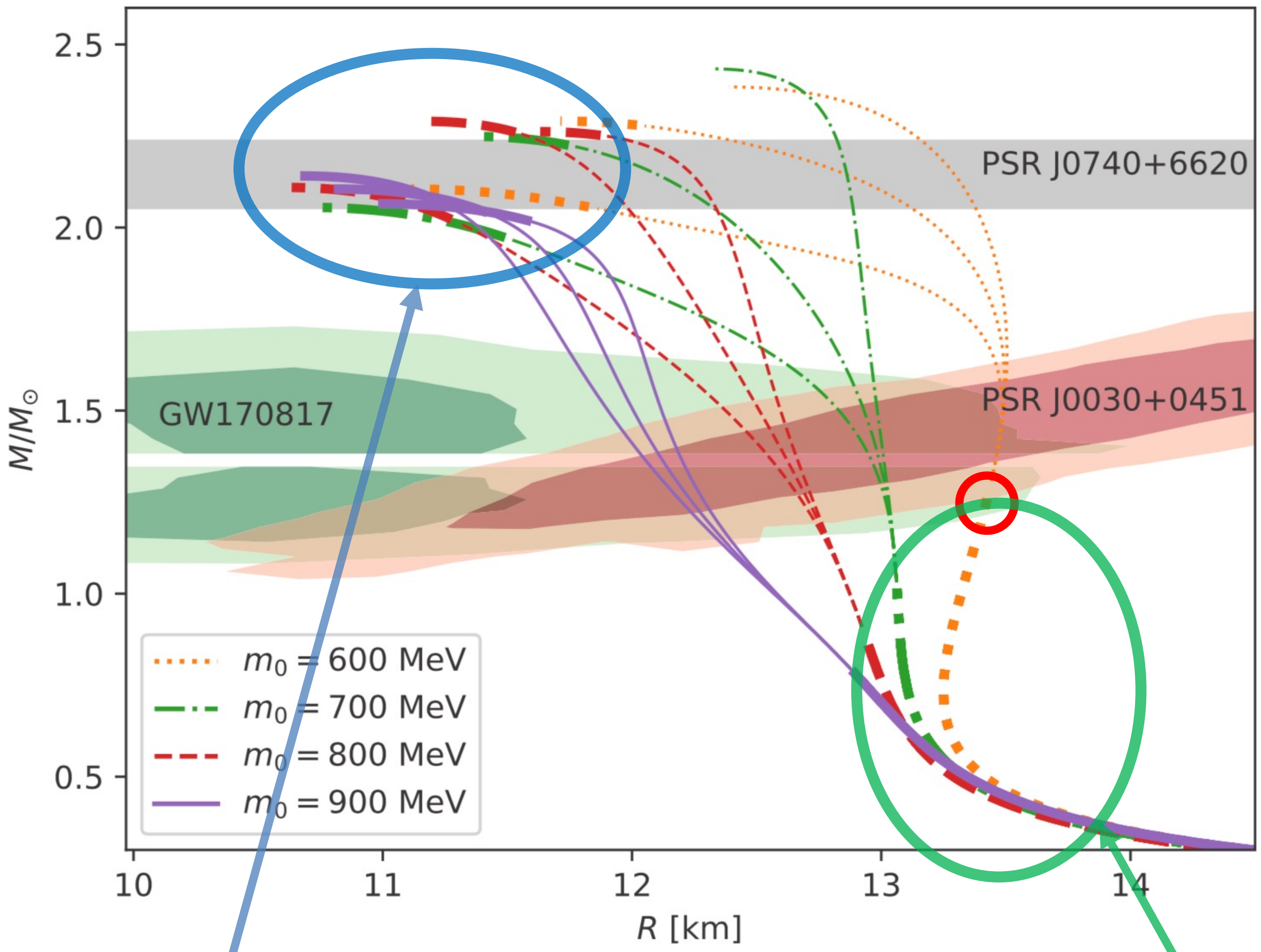
Unified EOS for NS in 3-window picture

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



M-R relation

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

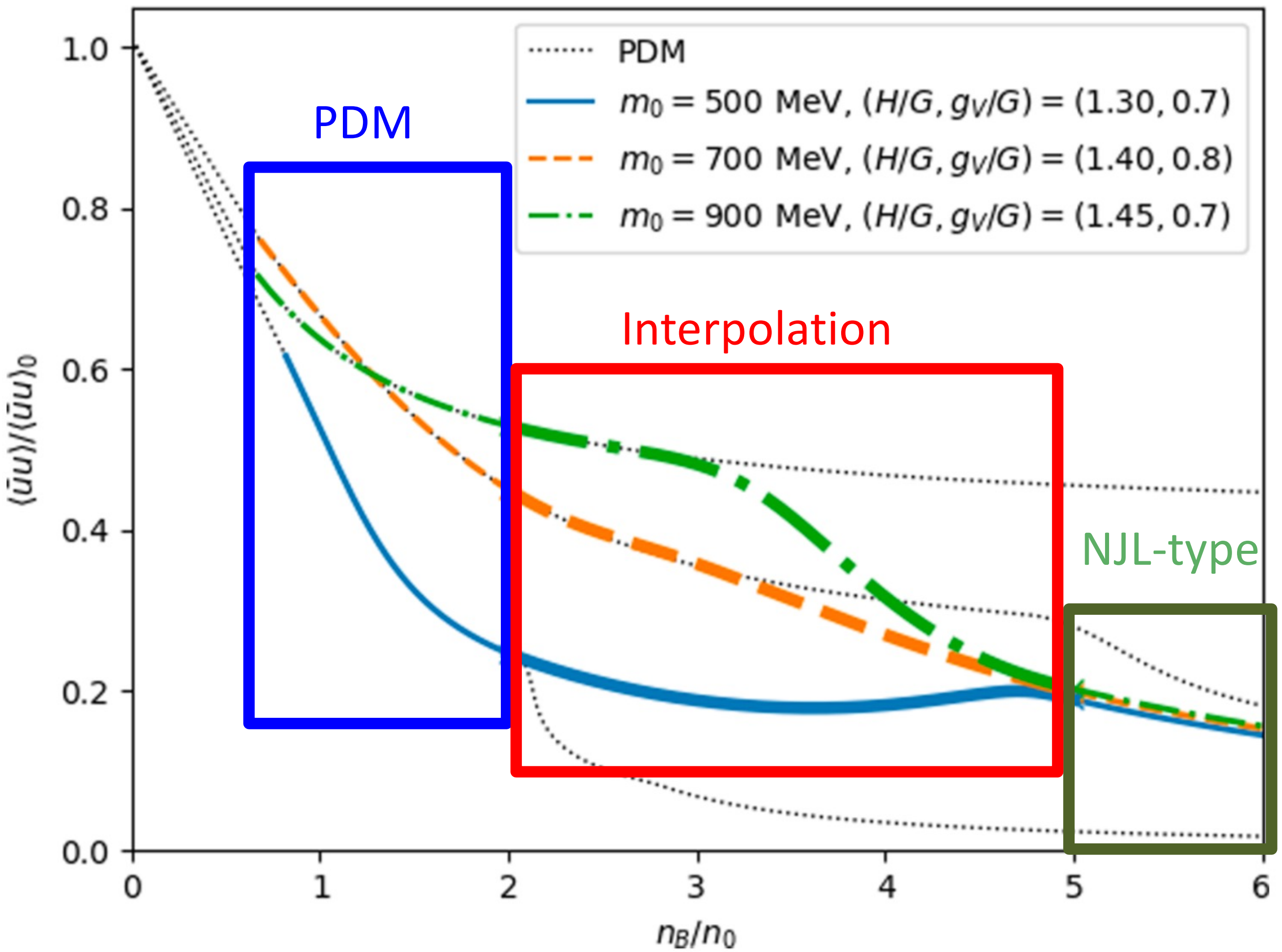


NS includes quark matter inside.

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).



See Minamikawa's talk

7. Summary

- I have introduced our study of dense matter based on parity doublet models.
- Although Δ baryon can enter the matter, the EOS still satisfy the constraints from NS.
- There could exist a new type of inhomogeneous condensate: shifted DCDW.
- Comparison of our EOS with constraints from NS implies that more than half of nucleon mass is the chiral invariant mass.
    - ➢ See Minamikawa's talk.

Origin of chiral invariant mass ?

- Dilaton (Gluon condensate and/or 4-quark condensate)
  - S. Gallas, F. Giacosa, G. Pagliara, Nucl. Phys. A 872, 13 (2011).
  - W. G. Paeng, H. K. Lee, M. Rho and C. Sasaki, Phys. Rev. D 85, 054022 (2012).
  - Y. L. Ma, H. K. Lee, W. G. Paeng and M. Rho, Sci. China Phys. Mech. Astron. 62, 112011 (2019).
- Gluon background in vacuum
  - Y. Kim, I. A. Mazur, M. Harada and H. K. Lee, arXiv:2009.02839 [hep-ph].
- Chiral Scalar density
  - T. Minamikawa, T. Kojo and M. Harada, Phys. Rev. C 104, 065201 (2021).
    - ➢ See Minamikawa's talk

The End