# Study of neutron star property based on the parity doublet model

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Based on

Y. Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015);
Erratum: Phys. Rev. C 95, 059903 (2017).
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).
B. Gao, Y. Yan and M. Harada, Phys. Rev. C 109, 065807 (2024).
Y.-K. Kong, T. Minamikawa and M. Harada, Phys. Rev. C 108, 055206 (2023).
Y.-K. Kong and M. Harada, Nuclear Physics Review, 2024, 41(3): 787-793.
B. Gao, W.L.Yuan, M. Harada and Y.L. Ma, Phys. Rev. C 110, 045802 (2024).

# Theoretical Nuclear Physics in Japan - Topics in Japan Physical Society Meeting -

- Nuclear Forces and Few-Body Systems
- Nuclear Fission and Fusion
- Structure and Reactions of Light Nuclei
- Hypernuclei and Strangeness
- Hypernuclei and Meson Production
- Nuclear Meson Systems
- Hadron Structure and Interactions
- Mean Field and Many-Body Fundamentals
- Exotic Hadrons
- Nuclear Matter and Quark Matter
- High-Energy Heavy Ion Reactions
- High-Energy QCD and Nucleon Structure
- Nuclear Matter and Neutron Stars
- Astro-Nuclear Physics

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# 1. Introduction

**Origin of Mass ?**

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of Hadrons

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of Us

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of Hadrons

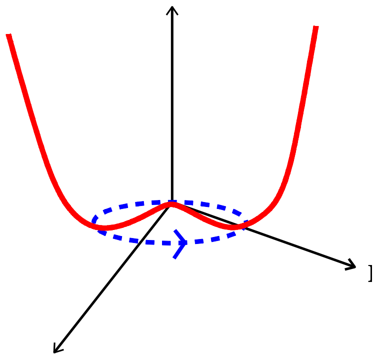
**Origin of Mass ?**

of Us

II

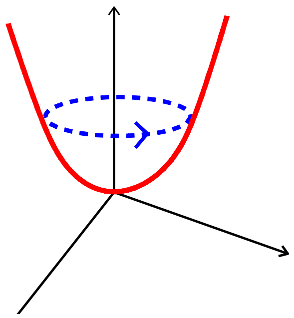
**One of the Interesting problems of QCD**

# Spontaneous chiral symmetry breaking



chiral symmetry broken phase at vacuum

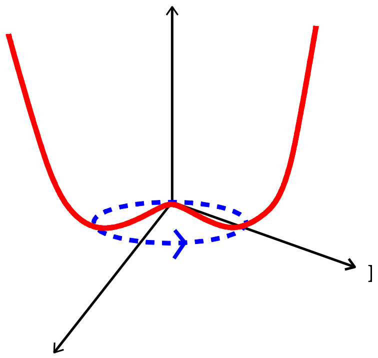
$\langle \bar{q}q \rangle \neq 0$ (chiral condensate)



chiral symmetric phase at high T and/or density

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

# Spontaneous chiral symmetry breaking



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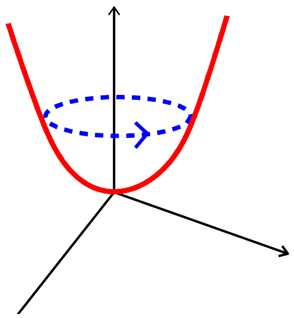

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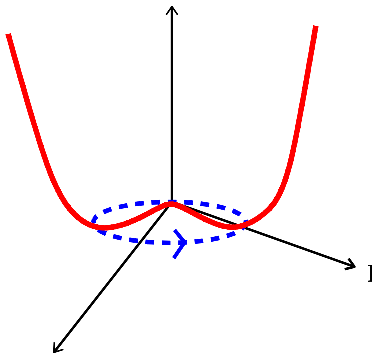
- The spontaneous chiral symmetry breaking is expected to generate a part of hadron masses.
- It causes mass difference between chiral partners.

# Spontaneous chiral symmetry breaking



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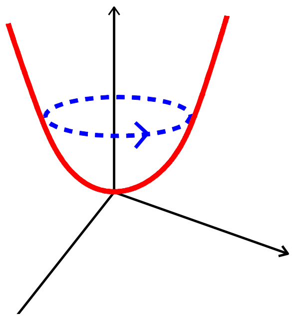

chiral symmetric phase at high T and/or density

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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 ?**

- 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.

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

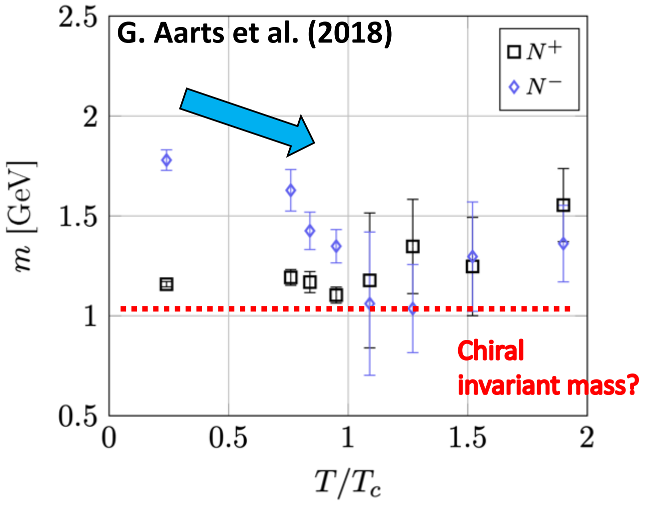
← spontaneous chiral symmetry breaking

↑ chiral invariant mass

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

⇨ Constraint to $m_0$ from phenomenological analysis ?

e.g. Finite-T lattice calculation



# Constraint to $m_0$ at vacuum

- analysis based on a simple linear sigma model

  C.DeTar, T.Kunihiro, PRD39, 2805 (1989)

  D.Jido, M.Oka, A.Hosaka, PTP106, 873 (2001)

  - $N(1535)$ is regarded as the chiral partner to $N(939)$.
  - use $\Gamma_{N^*\to\pi N}$ as an input to determine $m_0 = 270\ \mathrm{MeV}$
- Inclusion of derivative interactions in an extended model

  T. Yamazaki and M. Harada, PRD99, 034012 (2019)

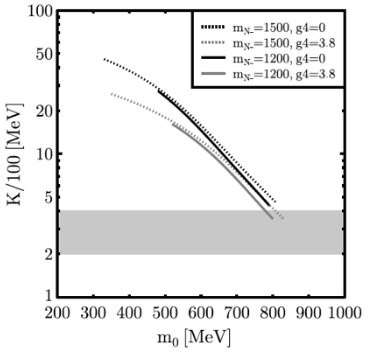
  - $g_A = 1.26$ and $\Gamma_{N^*\to\pi N}$ can be explained for $300 \lesssim m_0 \lesssim 1000\ \mathrm{MeV}$ .

# Constraint to $m_0$ in dense matter

- a simple linear sigma model with $\sigma^4 \ln \sigma^2$ term, $\omega$ & $\rho$ mesons

  T.Hatsuda & M.Prakash, PLB224, 11 (1989)

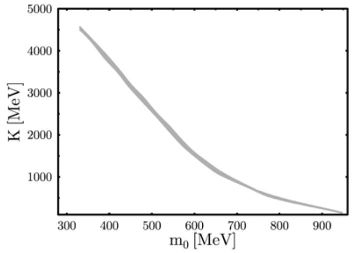
  - ➢ use $m_0 = 270$ MeV (De Tar-Kunihiro, Jido et al.) as an input
  - ➢ obtain $K_0$(incompressibility) $\approx 143$ MeV




- add $\omega^4$ term, no $\sigma^4 \ln \sigma^2$ term

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

  - ➢ use $K_0 \lesssim 400$ MeV to obtain $m_0 \gtrsim 800$ MeV




- add $\omega^4, \rho^4, \omega^2\rho^2$ terms, no $\sigma^4 \ln \sigma^2$ term

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

  - ➢ use $K_0 \lesssim 400$ MeV to obtain $m_0 \gtrsim 800$ MeV

- add $\sigma^6$ term, no $\omega^4, \rho^4, \omega^2\rho^2$, $\sigma^4 \ln \sigma^2$ terms

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

  - $K_0 \approx 240$ MeV for $500 \lesssim m_0 \lesssim 900$ MeV

# Constraint to $m_0$ from Neutron Star observation

- PDM with $\sigma^6$ term
  T. Yamazaki and M. Harada, Phys. Rev. C 100, 025205 (2019)
  - use binary dimensionless tidal deformability $\tilde{\Lambda} < 800$ from GW170817
  - obtain $m_0 > 500$ MeV

- PDM (low density) - NJL (high density) crossover model
  T. Minamikawa, T. Kojo and M.H., Phys. Rev. C 103, 045205 (2021).
  - use $M_{max} \gtrsim 2M_\odot$ & GW170817 & NICER
  - obtain $600 \lesssim m_0 \lesssim 900$ MeV

- PDM - NJL crossover model with iso-triplet $a_0$ meson
  Y.-K. Kong, T. Minamikawa and M. Harada, Phys. Rev. C 108, 055206 (2023).
  - use $M_{max} \gtrsim 2M_\odot$ & GW170817 & NICER
  - obtain $560 \lesssim m_0 \lesssim 840$ MeV

- PDM - NJL 1st-order model
  B. Gao, W. L. Yuan, M.H. and Y.L. Ma, Phys. Rev. C 110, 045802 (2024).
  - Constraint to $m_0$ is not affected very much.

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# Outline

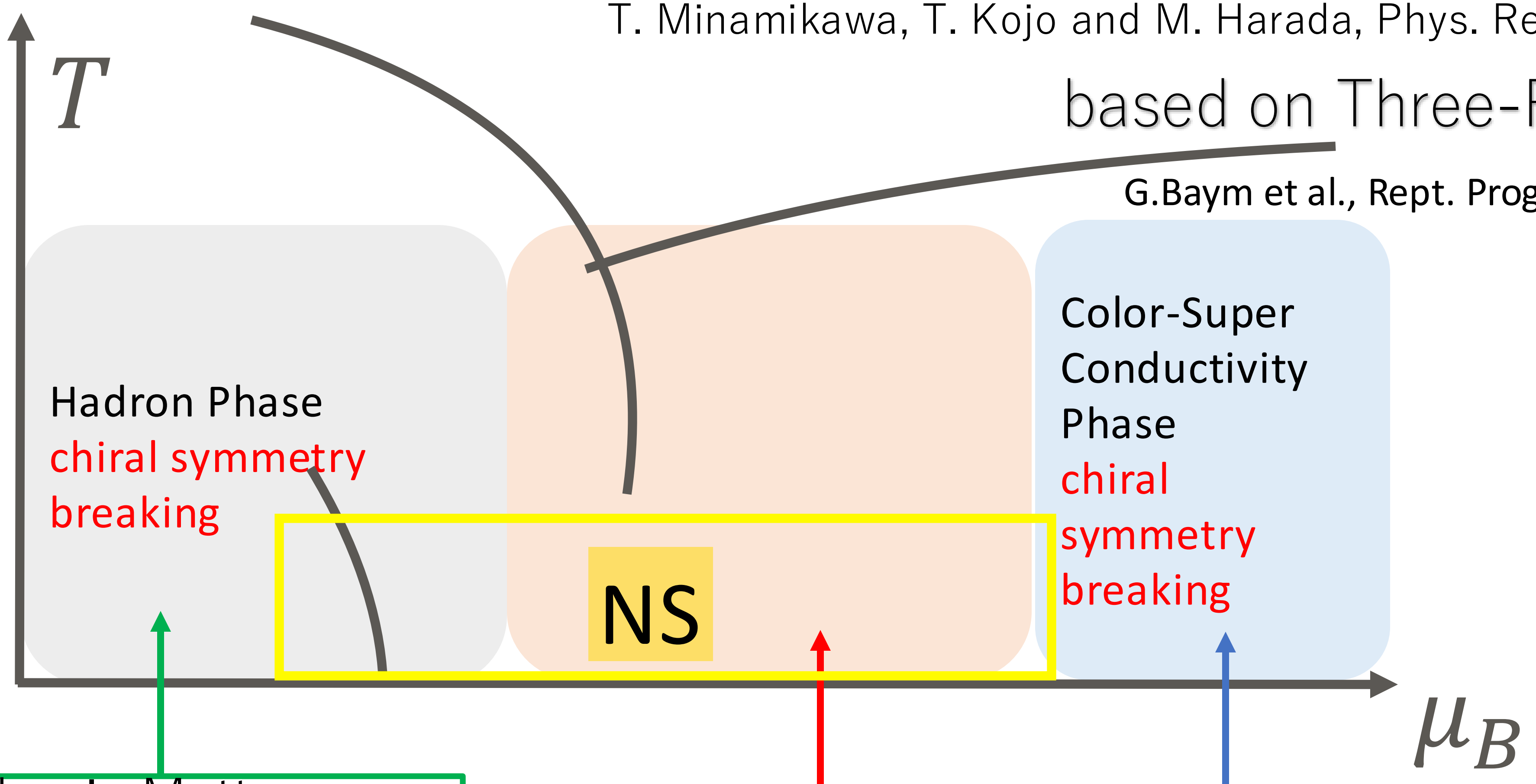
1. Introduction
2. PDM-NJL crossover model & Constraints to $m_0$ from neutron star observation
3. Constraints from the supernova remnant HESS J1731-347
4. Study of 1st order phase transition
5. Effect of iso-triplet scalar $a_0(980)$ meson
6. Summary

# 2. PDM-NJL crossover model & Constraints to $m_0$ from neutron star observation

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

based on Three-Region Structure

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



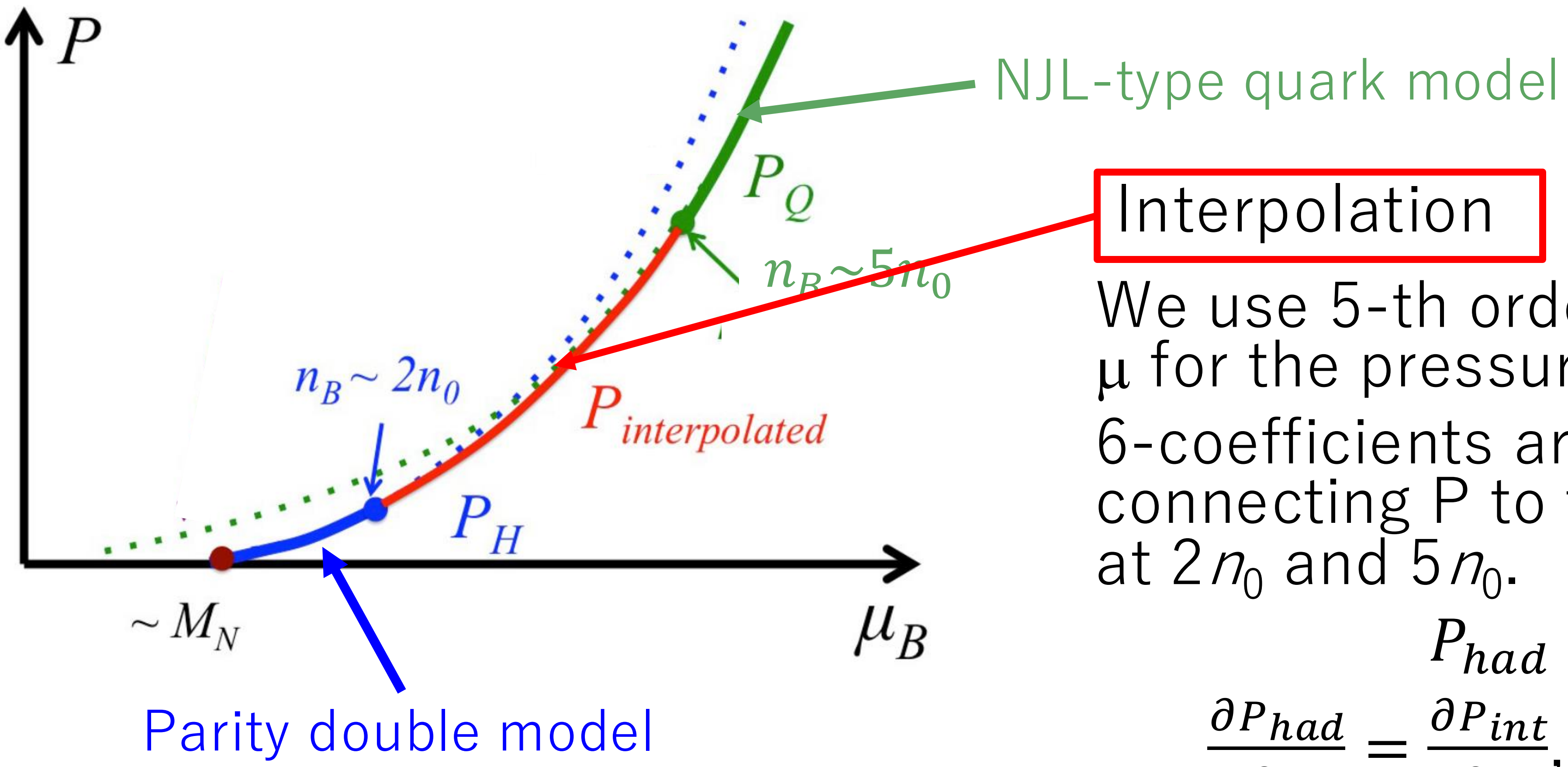

Hadronic Matter
(Parity doublet model)

Interpolation

Quark Matter
(NJL-type quark model)

# Unified EOS for NS in the PDM-NJL crosssover model

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




**Interpolation**

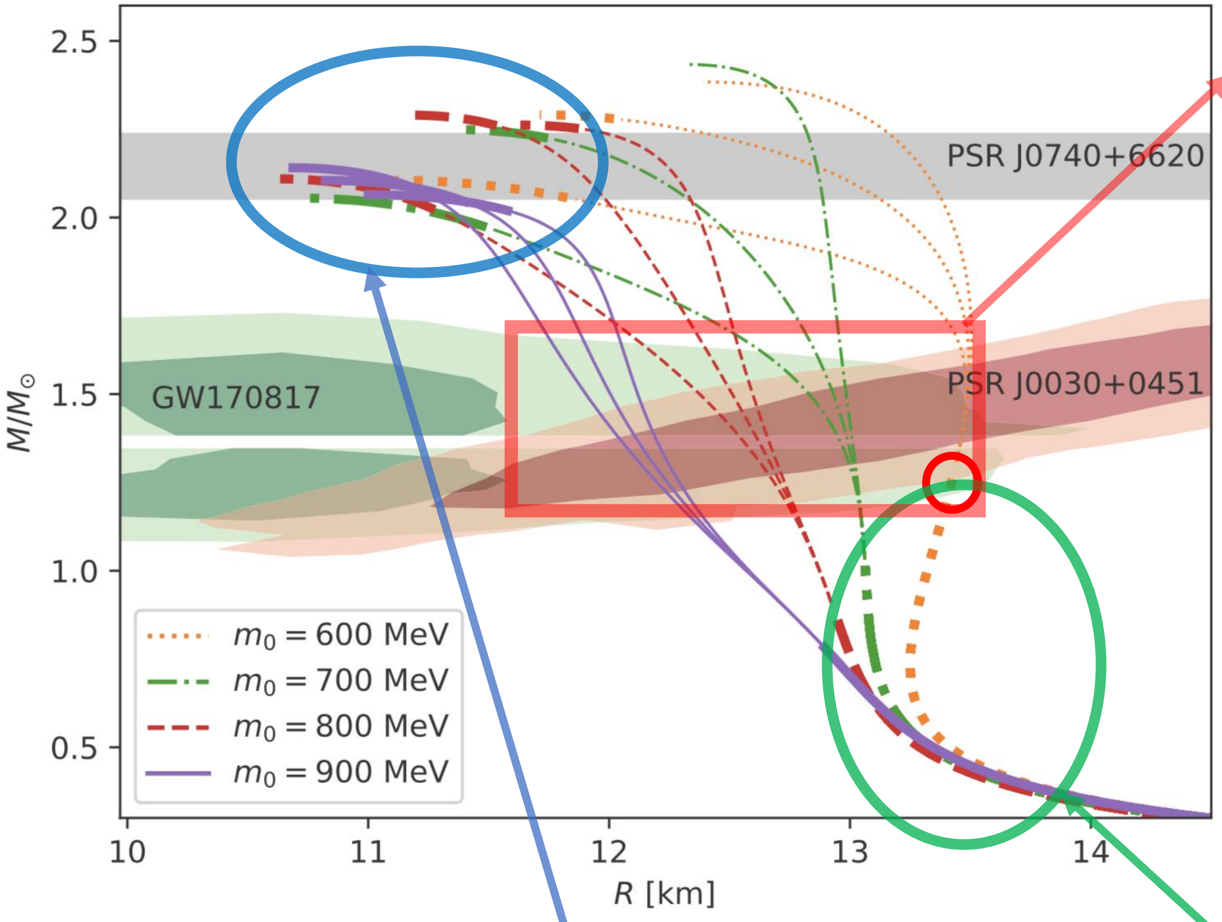
We use 5-th order polynomial of μ for the pressure *P*.
6-coefficients are determined by connecting P to the second order at 2$n_0$ and 5$n_0$.

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

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

# 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 |

NSs include quark matter inside.

NSs are made from only hadronic matter.

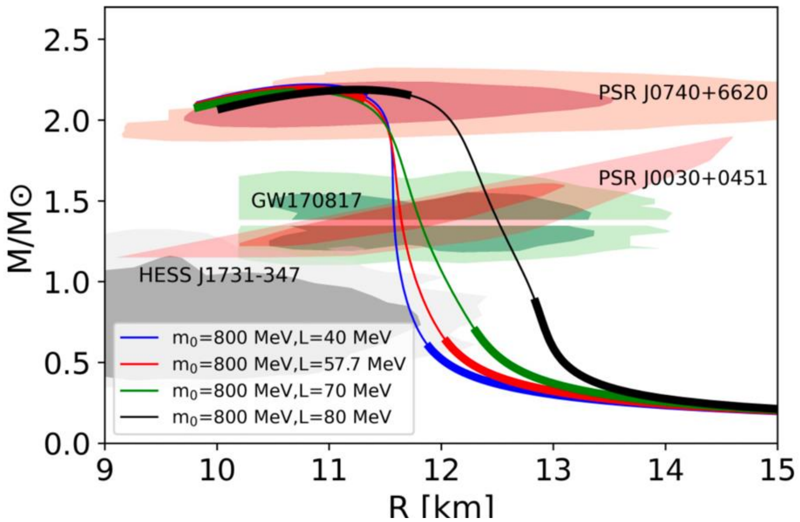
# 3. Constraints from supernova remnant HESS J1731-347

B. Gao, Y. Yan and M. Harada, Phys. Rev. C 109, 065807 (2024)

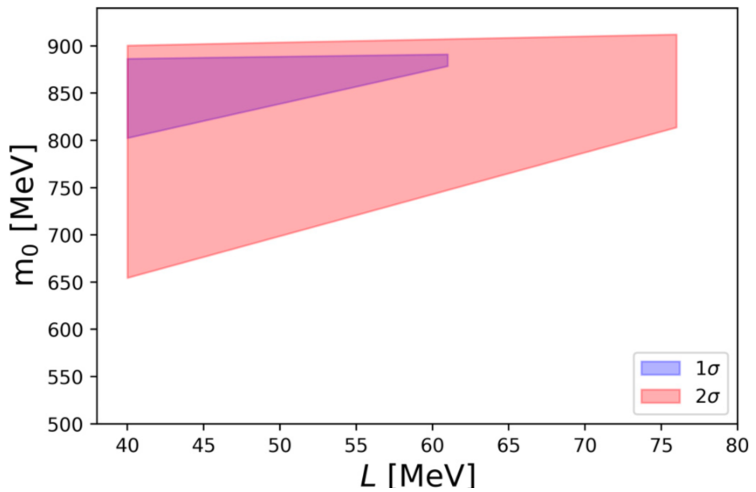
- We added the $\omega - \rho$ mixing term to the model for controlling the slope parameter $L_0$.

$$-\lambda_{\omega\rho}(g_\omega \omega)^2 (g_\rho \rho)^2$$

$m_0 = 800\text{MeV}$ and
$L_0 = 40, 57.7, 60, 80\text{MeV}$




Constraints to $m_0$ for given $L_0$.

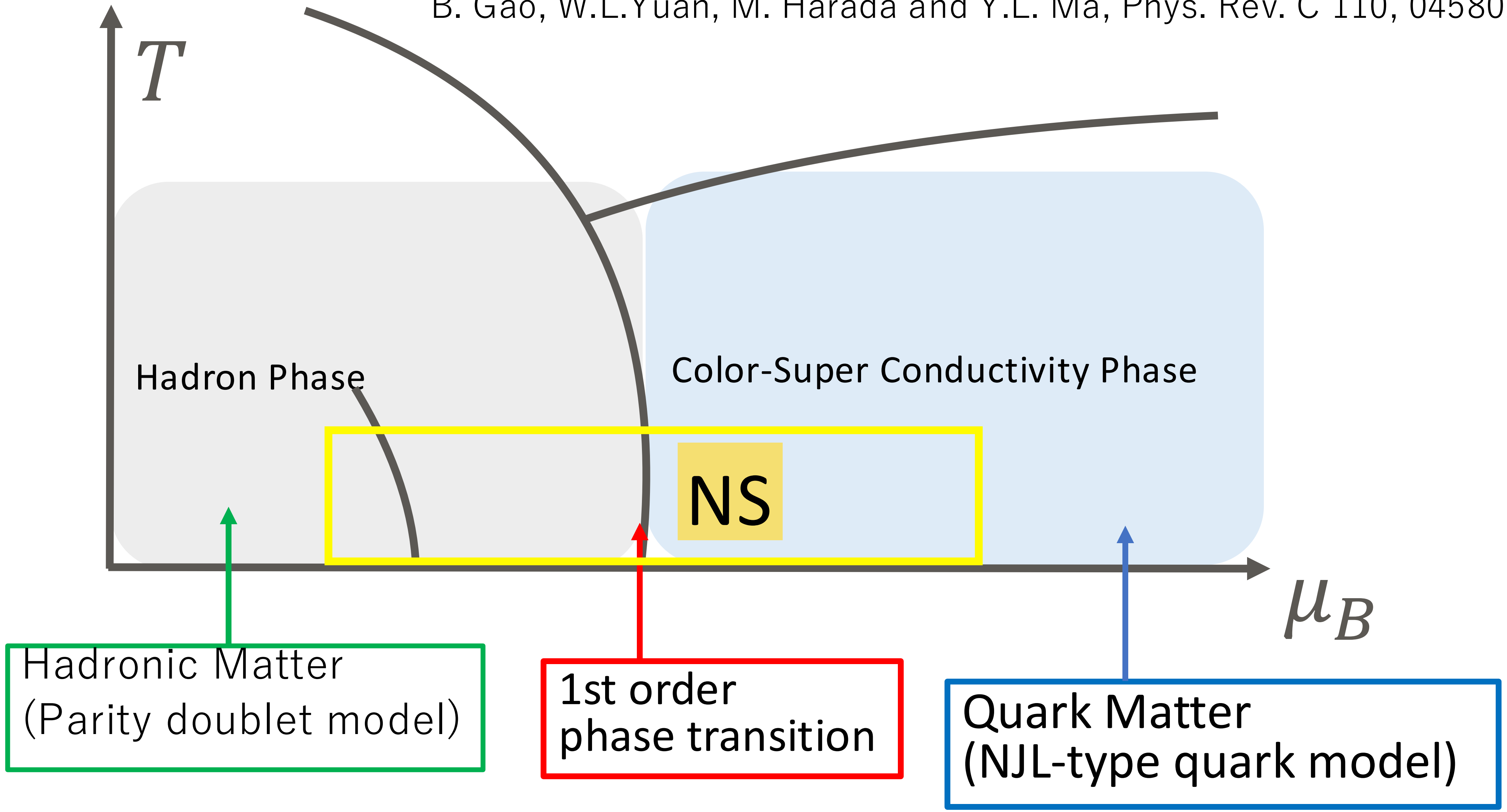



- For $m_0 = 800\text{MeV}$ and $L_0 = 40\text{MeV}$ (blue curve), it is possible to explain the HESS as a neutron star with satisfying constraints from LIGO/VIRGO and NICER.
- If HESS is a neutron star, HESS data is used to obtain constraint to $m_0$:

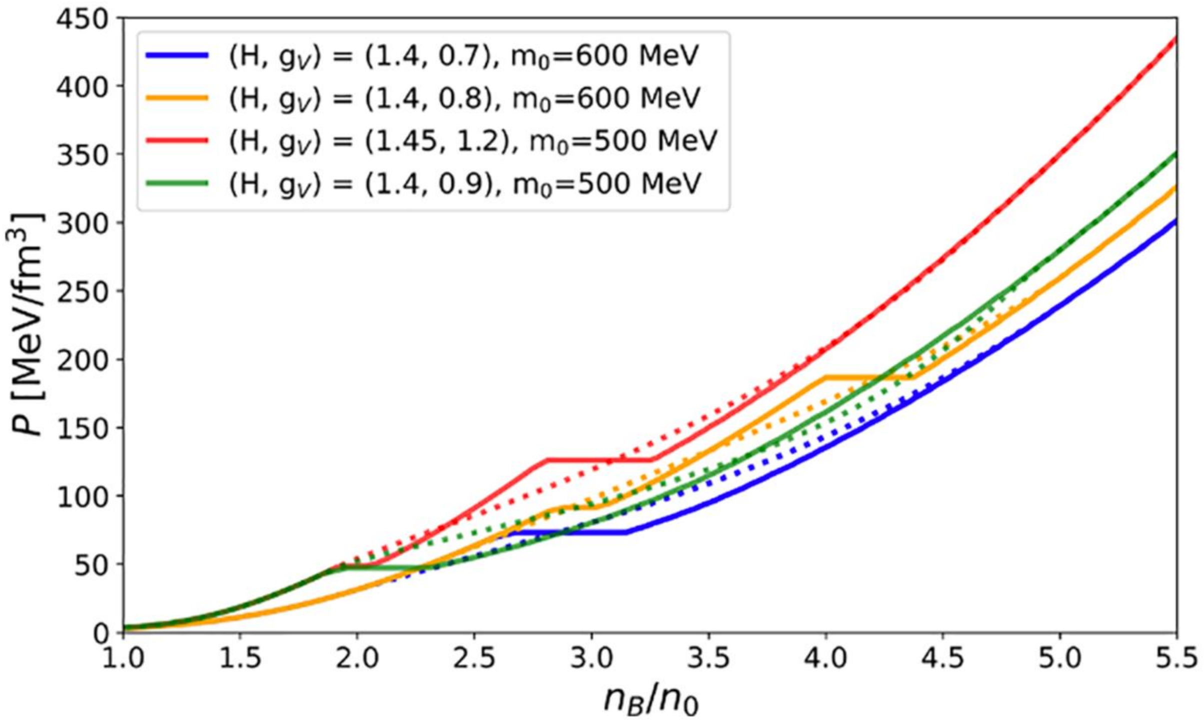
  e.g. $m_0 \gtrsim 850$ MeV for $L_0 = 57.7$ MeV

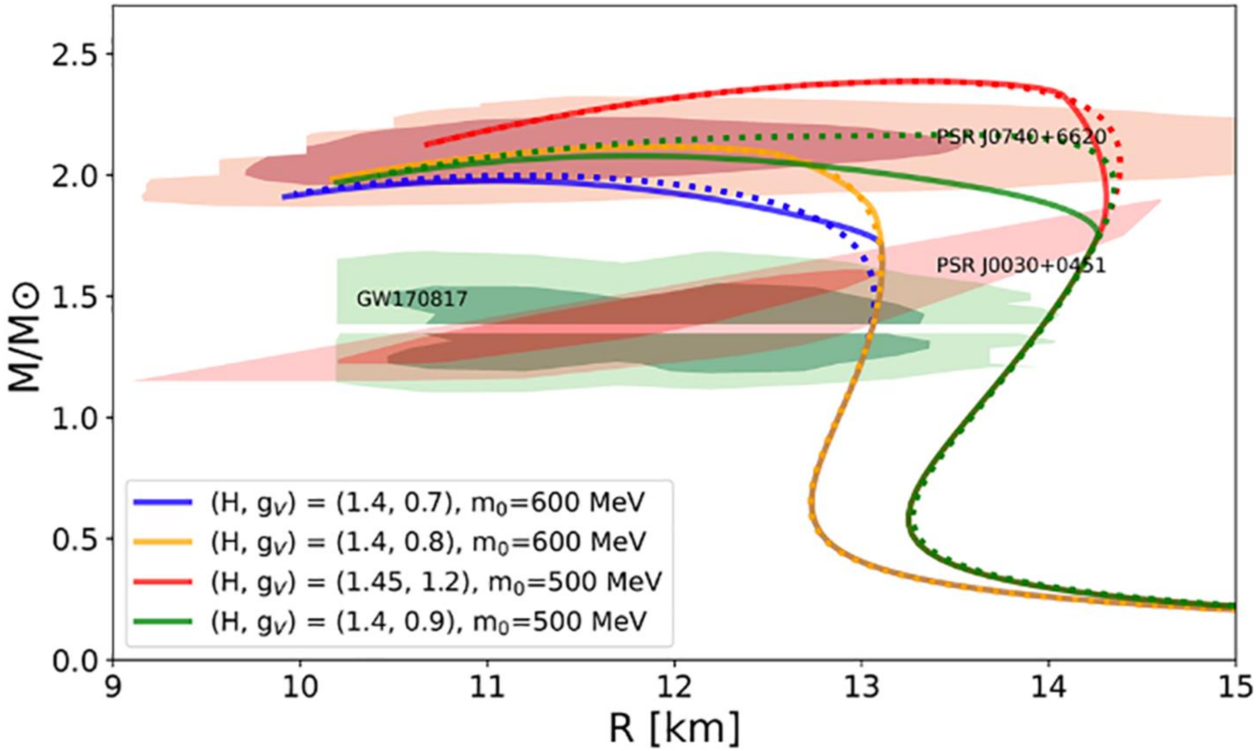
# 4. Study of 1st order phase transition from PDM to NJL

B. Gao, W.L.Yuan, M. Harada and Y.L. Ma, Phys. Rev. C 110, 045802 (2024).



# Comparison with crossover




- Difference
  - ➢ M-R relation: sudden change for 1st order
  - ➢ maximum mass of NS: smaller for 1st order

➢ Constraint to $m_0$ is not affected.

# 5. Effect of iso-triplet scalar $a_0(980)$ meson

Y.-K. Kong, T. Minamikawa and M. Harada, Phys. Rev. C 108, 055206 (2023).

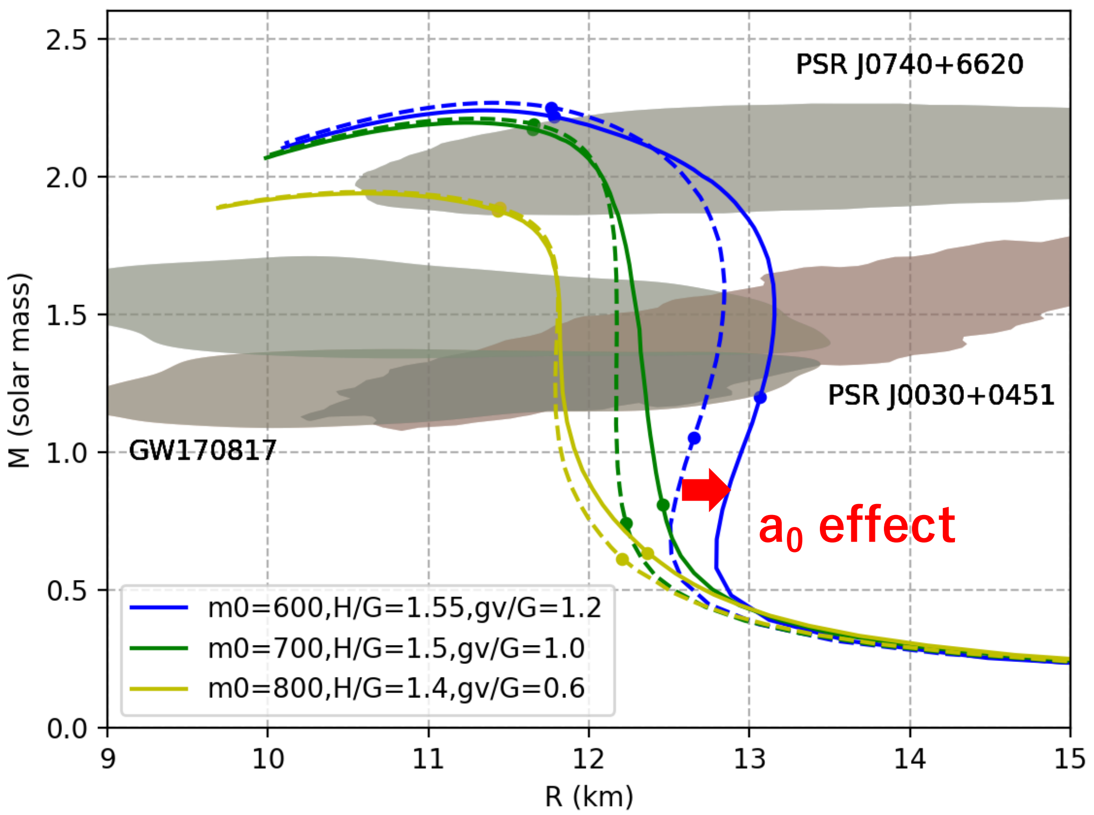
- We construct a PDM with a0(980) meson and study its effects in neutron stars.

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

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

$a_0(980)$

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

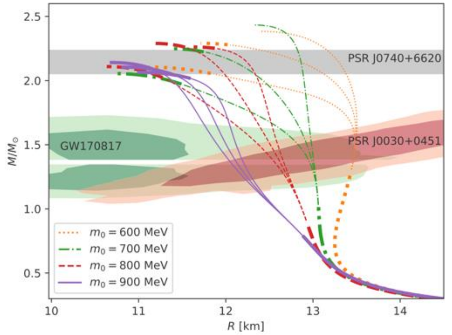


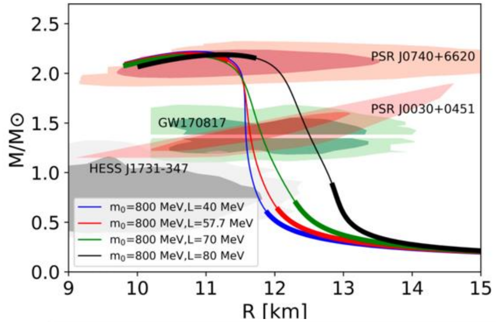

— PDM with $a_0$
--- PDM without $a_0$

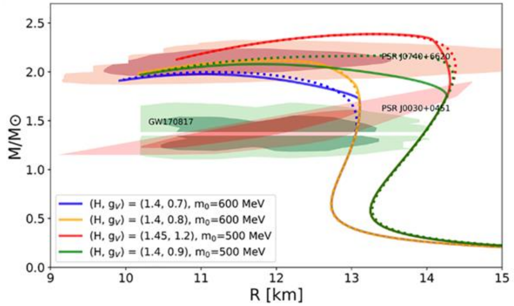
$L_0 = 50$ MeV

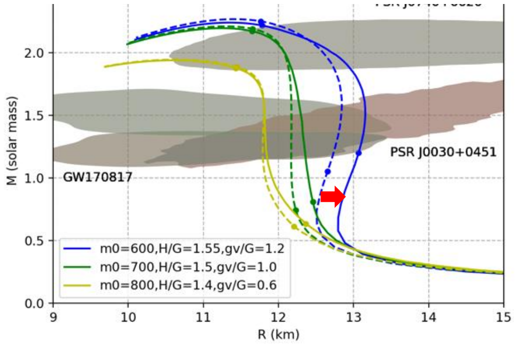
# 6. Summary

- Chiral invariant mass (microscopic information) in the PDM is constrained by NS observational data (macroscopic information):
  - $600 \leq m_0 \leq 900 MeV$
  - (roughly more than 50% of nucleon mass)
- If HESS is a neutron star, $m_0$ is strongly constrained:
  - e.g. $m_0 \gtrsim 850$ MeV for $L_0 = 57.7$ MeV
- 1st order phase transition instead of crossover
  - constraint to $m_0$ is not affected very much.
- Effect of iso-triplet
  - $a_0(980)$ meson slightly modifies the constraint



Thank you very much for your attention !