Origin of mass from neutron star observations

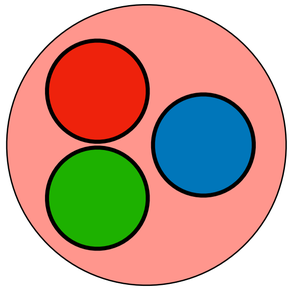
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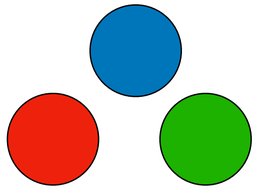
RCNP
大阪大学 核物理研究センター

Origin of nucleon mass?

Nucleons (proton & neutron)



Three quarks



Mass of a proton:

$$\sim 1000\,\mathrm{MeV}$$

$\gg$

Mass of three quarks:

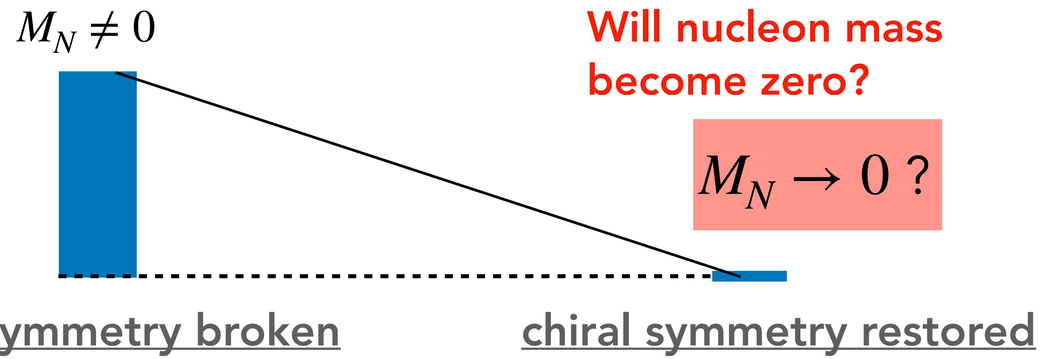
$$\sim 10\,\mathrm{MeV}$$

Where is the actual origin of nucleon mass?

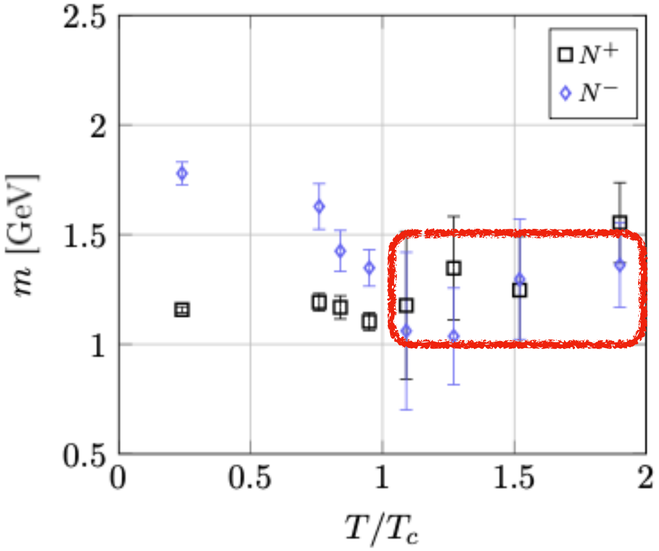
Origin of nucleon mass?

- **Mass from spontaneous breaking of chiral symmetry** $M_{\chi SB}$ σ: order parameter of chiral symmetry

Density/Temperature ↑ $M_{\chi SB}$ ↓



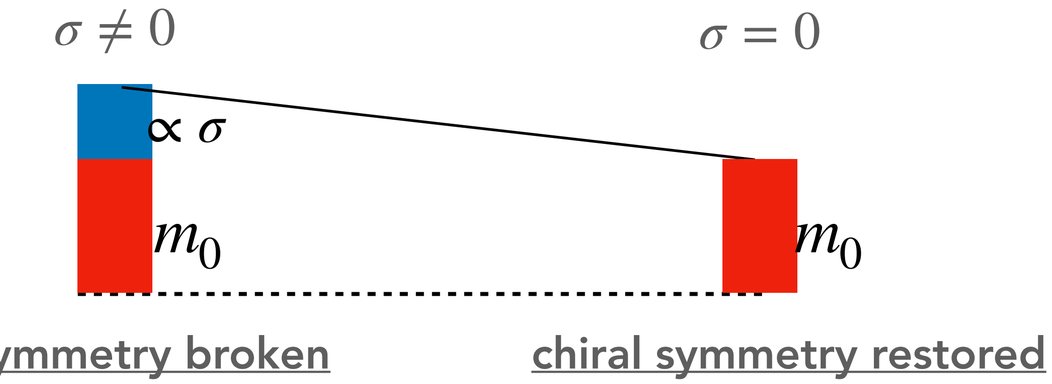
On the other hand, result from **lattice QCD at finite T** (e.g. Aarts+'15,'18):



Other contribution:

Chiral invariant mass m_0

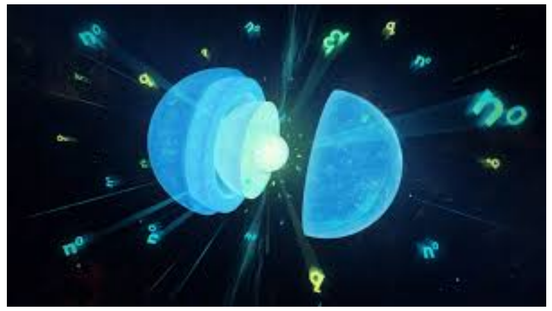
$$M_N = M_{\chi\mathrm{SB}} + m_0$$



How large is m_0 ?

Methodology

Neutron star as the natural laboratory



Mass: $M \sim 1 - 2\, M_\odot$

Radius: $R \sim 10 - 12$ Km

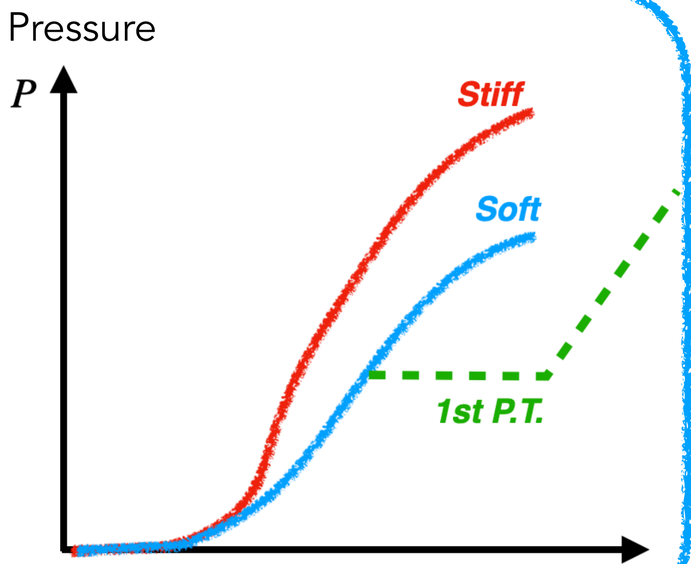
Density: ~ 10^{14-15} g/cm^3

Normal nuclear density: $\sim 3 \times 10^{14}$ g/cm^3

Extract microscopic information from macroscopic object NS

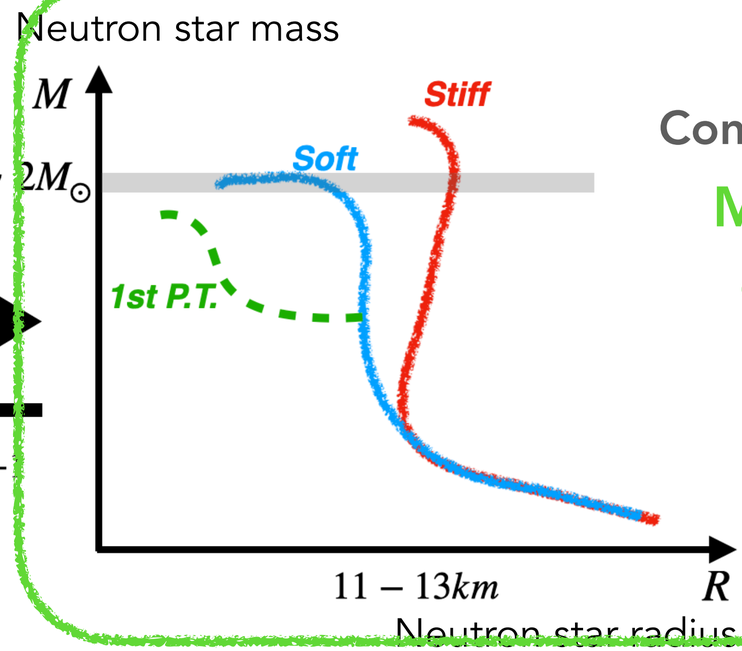
Microscopic model

(Infor. m_0)



TOV

TOV^{-1}



Confront with:

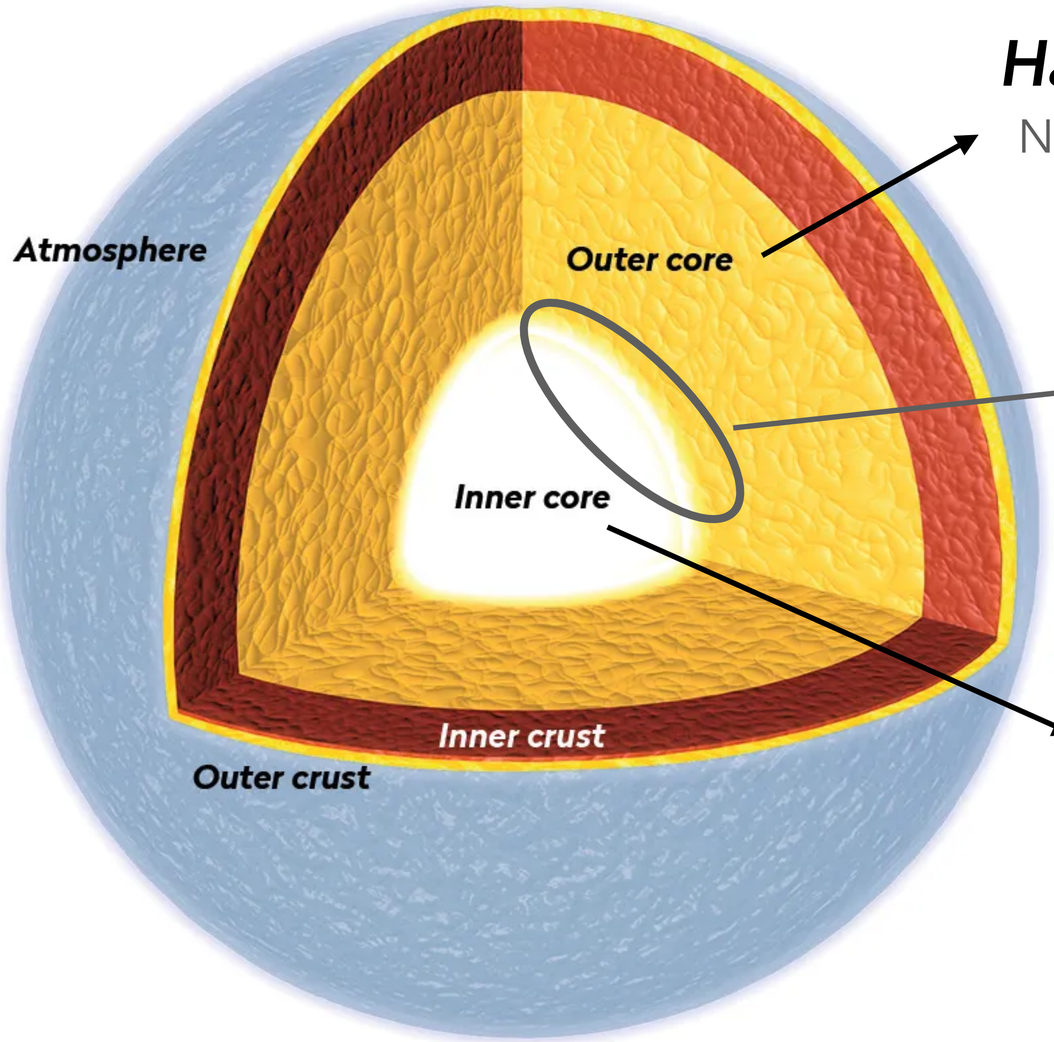
More and more observations!

(GW, NICER…)

Insights into chiral invariant mass!

Phases inside Neutron Star

Phases inside NS



Low density

Hadronic matter $\lesssim 2n_0$ (n_0: normal nuclear density)

Neutrons, protons, electrons ..

Quark-hadron phase transition

$2n_0 \lesssim n_B \lesssim 5n_0$

Crossover / First-order phase transition?

Quark matter $\gtrsim 5n_0$

Deconfined quarks ..

High density

Phases inside Neutron Star: Hadronic matter

DeTar, Kunihiro, 1989; Jido, Oka, Hosaka, 2001

Parity Doublet Model(PDM)

Hadronic matter

$$\mathscr{L}_{\mathrm{PDM}} = \mathscr{L}_{\mathrm{Nucleon}}(\psi_1, \psi_2, \dots) \quad + \mathscr{L}_{\mathrm{Meson}}(\sigma, \pi, \omega, \rho, \dots)$$

ordinal dirac mass term:

$$m\bar{\psi}\psi = m(\bar{\psi}^L\psi^R + \bar{\psi}^R\psi^L)$$

$$\rightarrow \underline{\quad m(\bar{\psi}^L L^\dagger R\psi^R + \bar{\psi}^R R^\dagger L\psi^L) \quad}$$

chiral variant

in PDM:

$$m_0(\bar{\psi}_1\gamma_5\psi_2 - \bar{\psi}_2\gamma_5\psi_1) = m_0(\bar{\psi}_1^L\psi_2^R + \bar{\psi}_1^R\psi_2^L + \mathrm{h.c.})$$

$$\rightarrow \quad m_0(\bar{\psi}_1^L \cancel{L^\dagger L}\psi_2^R + \bar{\psi}_1^R \cancel{R^\dagger R}\psi_2^L + \mathrm{h.c.})$$

chiral invariant

	$L \in \mathrm{SU}(2)_L$ left-handed	$R \in \mathrm{SU}(2)_R$ right-handed
nucleon ψ_1	$\psi_1^L \rightarrow L\psi_1^L$	$\psi_1^R \rightarrow R\psi_1^R$
nucleon ψ_2	$\psi_2^L \rightarrow R\psi_2^L$	$\psi_2^R \rightarrow L\psi_2^R$

Mirror assignment

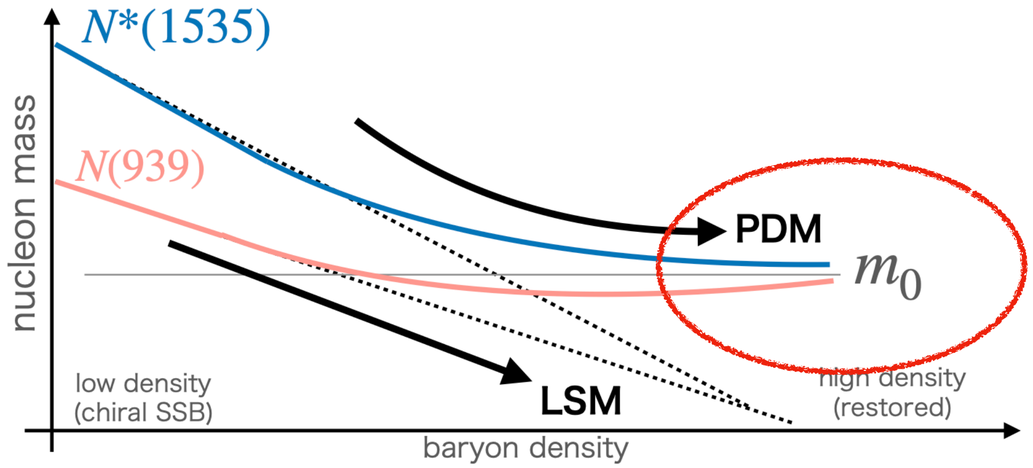
Phases inside Neutron Star: Hadronic matter

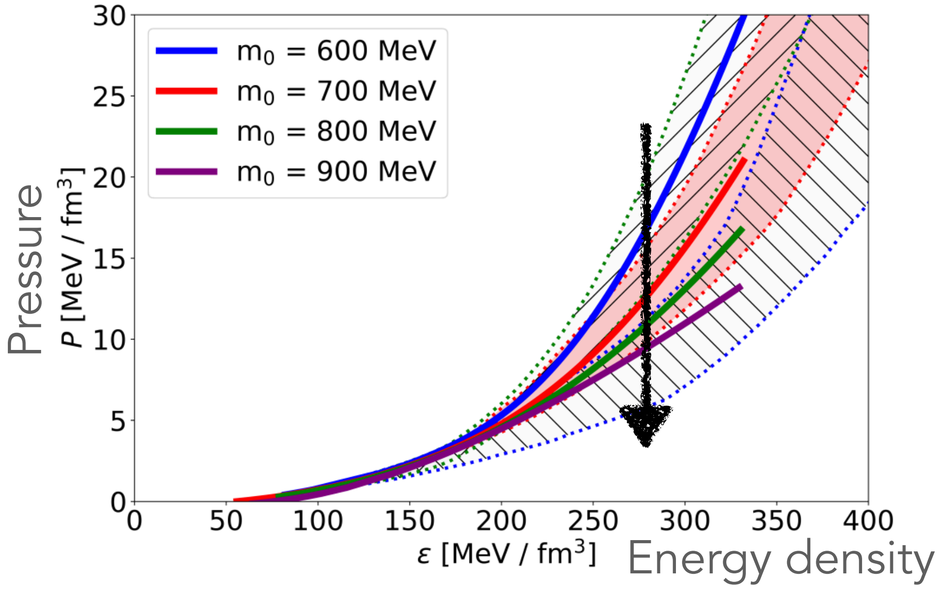
$$\mathscr{L}_{\mathrm{PDM}} = \mathscr{L}_{\mathrm{Nucleon}}(\psi_1, \psi_2, \dots) + \mathscr{L}_{\mathrm{Meson}}(\sigma, \pi, \omega, \rho, \dots)$$

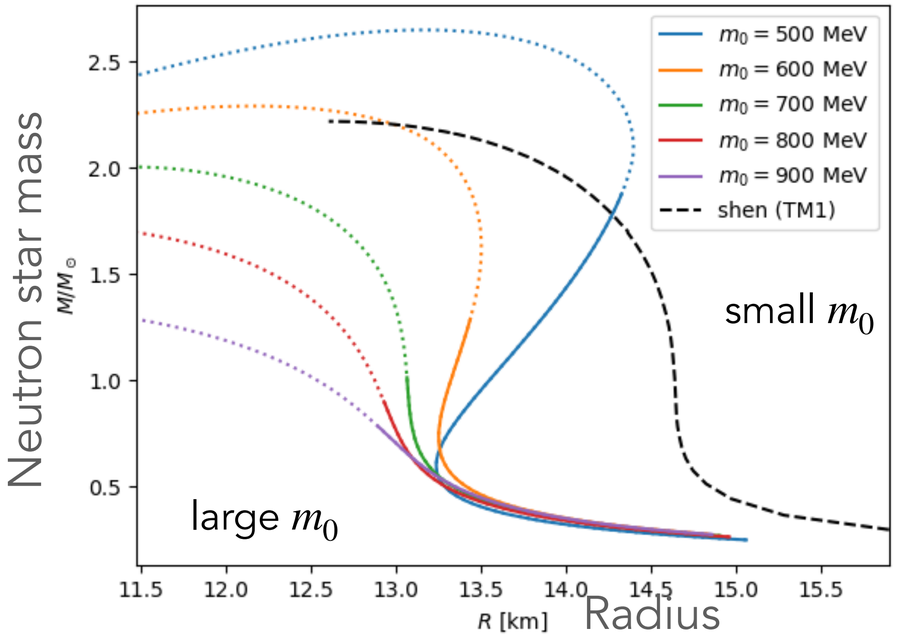
$$g_1(\bar{\psi}_{1L}\sigma\psi_{1R} + \dots) + g_2(\bar{\psi}_{2R}\sigma\psi_{2L} + \dots)$$
$$+ m_0(\psi_{1L}\psi_{2R} + \dots)$$

Mass formula of nucleons N(939) and N*(1535)

$$M_{N\pm} = \sqrt{m_0^2 + g_+^2\sigma^2} \mp g_-\sigma \overset{\sigma \to 0}{\rightarrow} m_0$$







Phases inside Neutron Star: Quark matter

$$\mathscr{L} = \mathscr{L}_{\mathrm{NJL}} - H(q^T \Gamma_A q)(\bar{q}\Gamma^A \bar{q}^T) + g_V(\bar{q}\gamma^0 q)^2$$

Quark matter

- Original NJL-type model(Hatsuda and Kunihiro) includes four point interaction

$$+G(\bar{\psi}\psi)^2$$

- U(1) axial anomaly

$$-K\det(\bar{\psi}\psi)$$

$$G\Lambda^2 = 1.835, \quad K\Lambda^5 = 9.29 \qquad \Lambda = 631.4\mathrm{MeV}$$

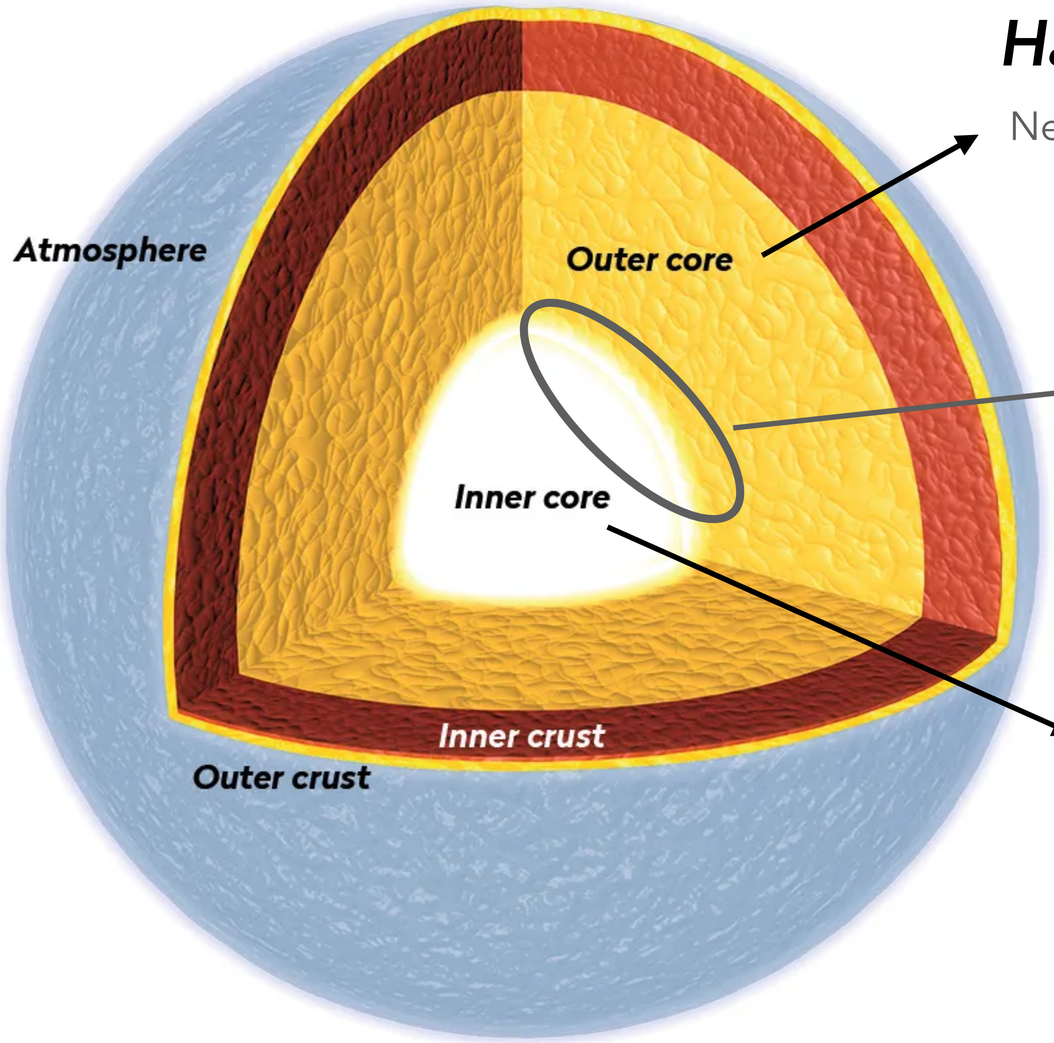
H: coupling for diquark condensates

g_V: coupling for vector (repulsive) interaction

H and g_V two parameters are remained

Phases inside Neutron Star

Phases inside NS



Low density

Hadronic matter $\lesssim 2n_0$ (n_0: normal nuclear density)

Neutrons, protons, electrons ..

- Described by the parity doublet model

(parameter: m_0)

Quark-hadron phase transition

$2n_0 \lesssim n_B \lesssim 5n_0$

Crossover / First-order phase transition?

Quark matter $\gtrsim 5n_0$

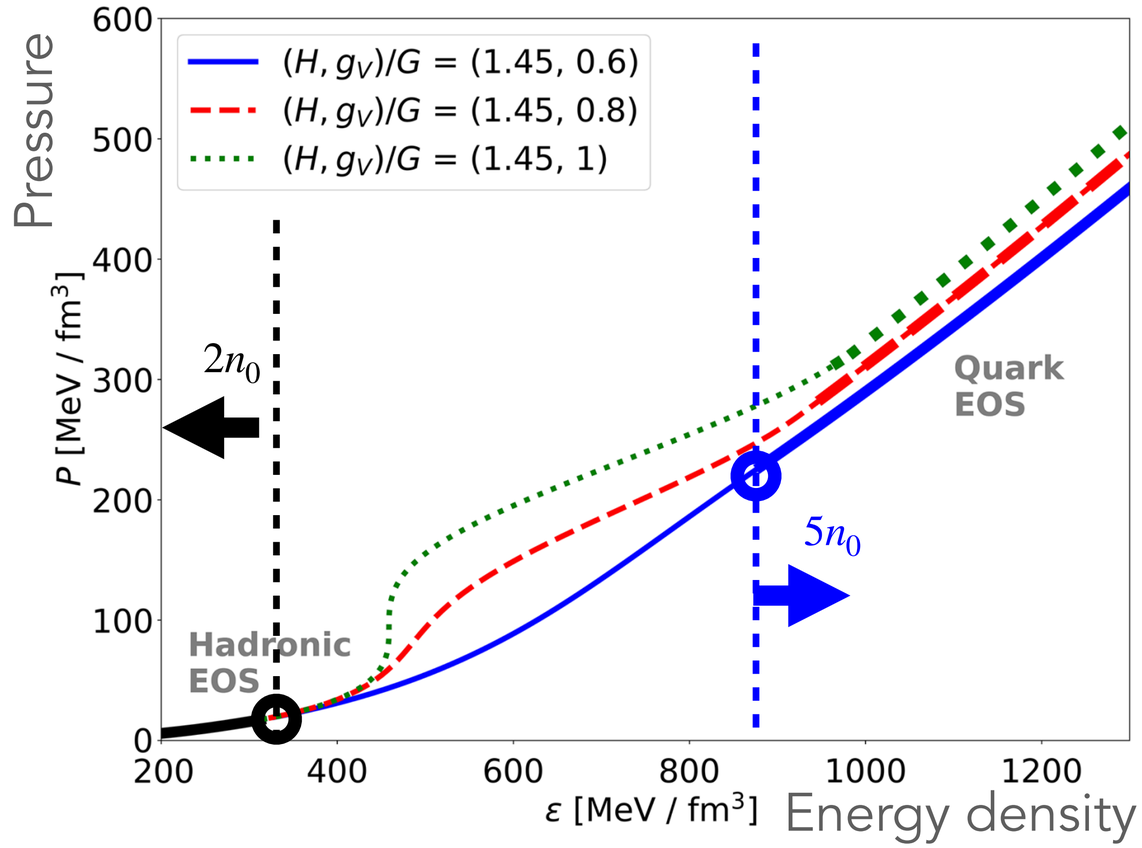
Deconfined quarks ..

- Described by the NJL-type quark model

(parameter: H, g_V)

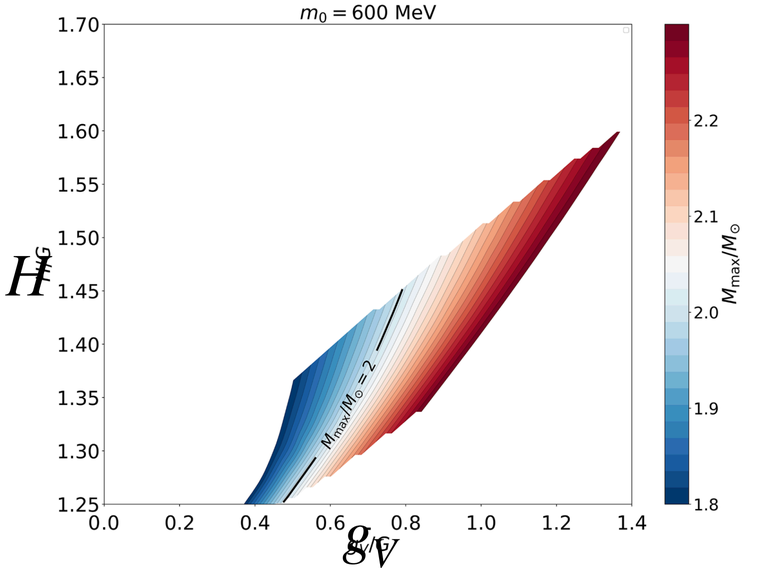
High density

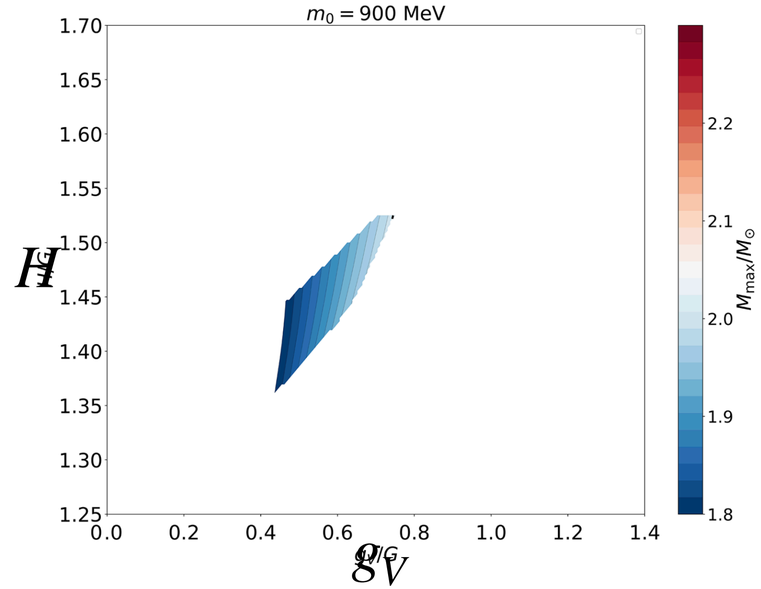
Quark-hadron phase transition



Causality condition:

$$c_s^2 = \frac{dp}{d\varepsilon} \leq 1$$





interpolate w/ polynomial: $P = \sum_{n=0}^{5} c_n \mu_B^n$

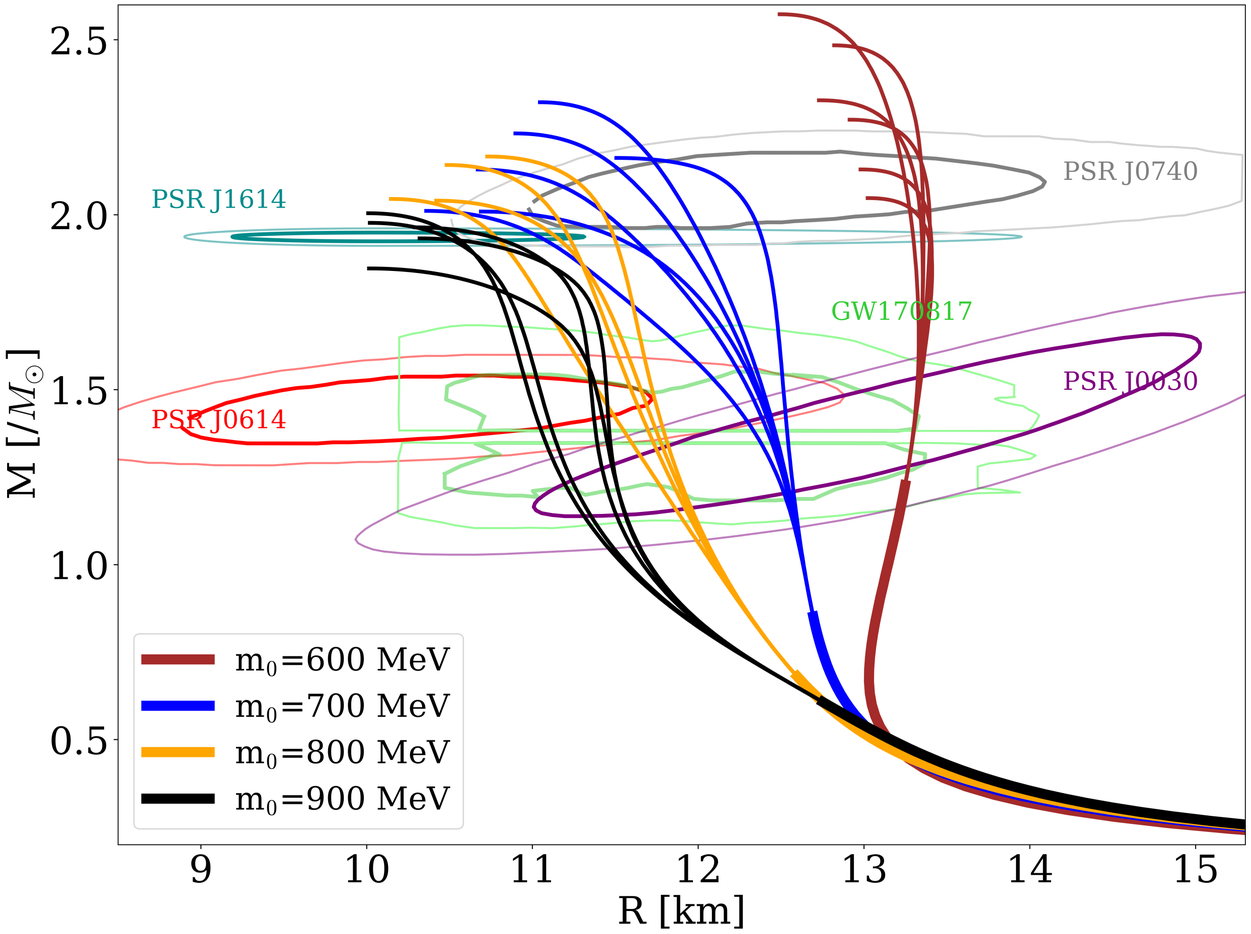
(six) Boundary Conditions =>

(six) coefficients c_n

Hadronic & Quark EOS are fixed; no other parameter in the interpolate region

Confront with neutron star observations

B. Gao, M. Harada, A. Hosaka, T. Kunihiro. (2026, in preparation)



Thick curves: PDM

- GW 170817 (B. P. Abbott 2017)

- NICER project (Neutron star Interior Composition ExploreR)

PSR J0030 (T. E. Riley et al, 2019)

PSR J0740 (M. C. Miller et al, 2021)

PSR J0437 (D. Choudhury et al, 2024)

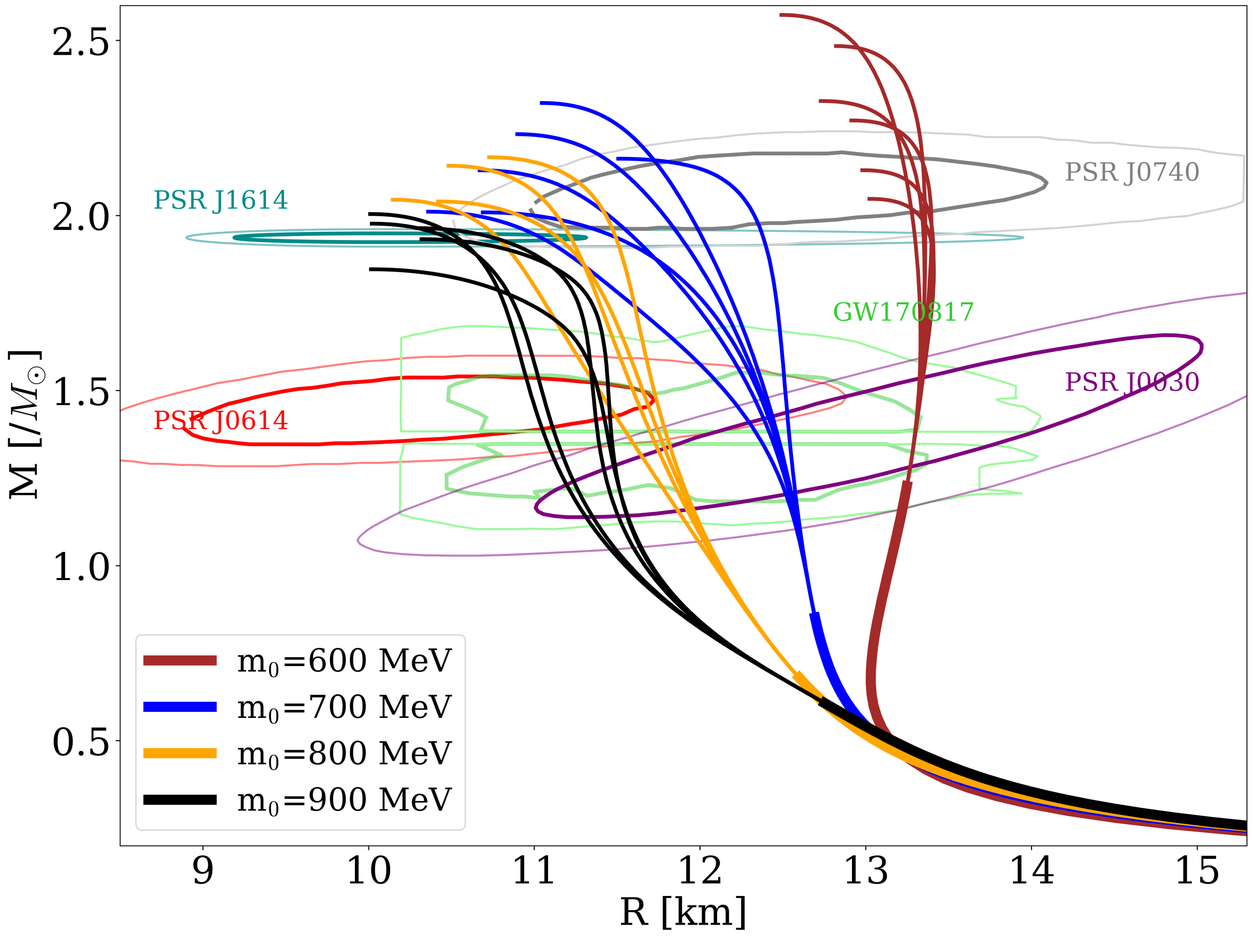
PSR J0614 (L. Mauviard et al, 2025)

PSR J1614 (L. Mauviard et al, 2026)

……..

Confront with neutron star observations

B. Gao, M. Harada, A. Hosaka, T. Kunihiro. (2026, in preparation)



Thick curves: PDM

- GW + PSR J0030 + PSR J0740

$$580 \leq m_0 \leq 860 \text{ MeV}$$

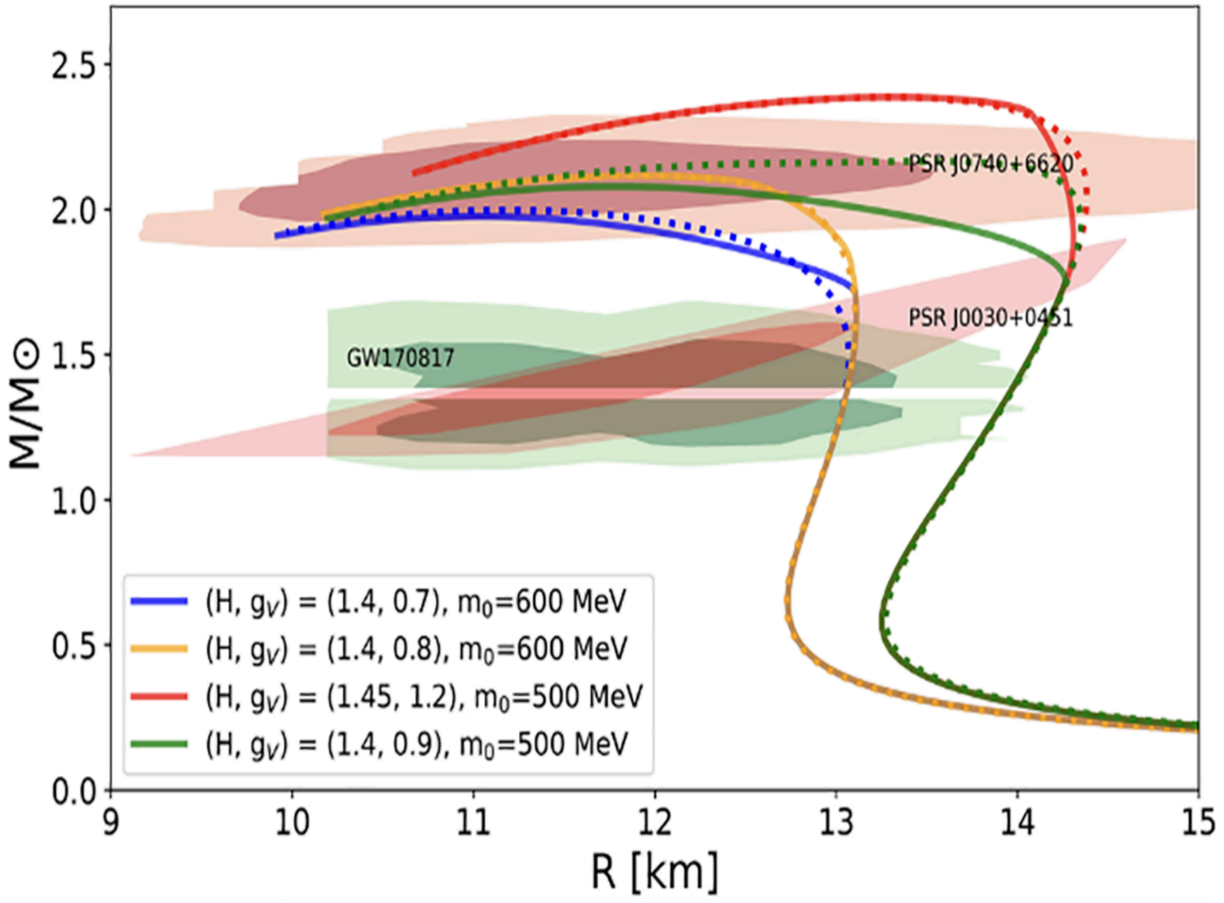
- GW + PSR J0030 + PSR J0740 + PSR J0614

$$800 \leq m_0 \leq 860 \text{ MeV}$$

Lower boundary is largely shifted!

Compare with quark-hadron 1st-order P.T

Quark-hadron first-order phase transition



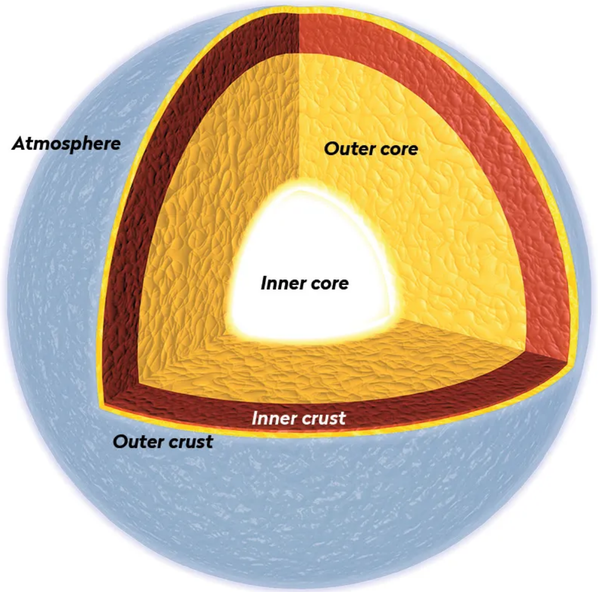
The results do not change too much !

NS observations favor relatively large chiral invariant mass m_0

More than half of the nucleon mass is from m_0 instead of $M_{\chi SB}$

Summary

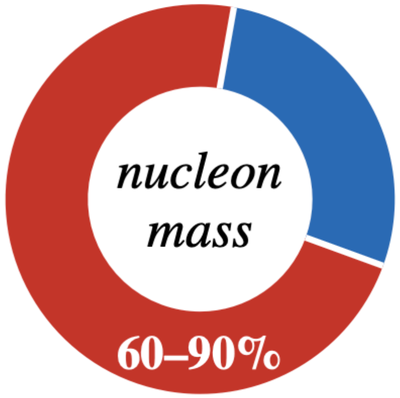
Nucleon mass $M_N = m_{\chi\mathrm{SB}} + m_0$



By using the parity doublet model together with NJL-type quark model

with quark-hadron crossover & 1st-order phase transition

NS observation favor large chiral invariant mass



$m_N = m_0 + m_{\chi\mathrm{SB}}(\sigma)$

- **chiral invariant mass m_0**: survives chiral restoration
- **chiral symmetry breaking mass $m_{\chi\mathrm{SB}}(\sigma)$**: vanishes as $\sigma \to 0$ at high density or temperature

More than half of the nucleon mass originates from the source beyond the chiral condensate independent of the quark-hadron phase transition property!

Thanks for your attention!