Building relativistic mean-field models for neutron stars in light of the PREX-2 and CREX results

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Soongsil University

OMEG
Origin of Matter and Evolution of Galaxies
우주 물질 중점연구소

Several constraints on nuclear equation of state (EoS)

from nuclear experiments and astrophysical observations

1 Low-density region ($\rho_B \leq \rho_0$)

- Characteristics of finite nuclei: binding energies, B/A, and charge radius, R_{ch}
- The accurate measurement of neutron skin thickness from the parity-violating electron scattering: PREX-2 (^{208}Pb) and CREX (^{48}Ca) — "slope parameter discrepancy"

PREX collaboration, Phys. Rev. Lett., 126, (2021) 172502 and CREX collaboration, Phys. Rev. Lett. 129 (2022) 042501.

2 Intermediate-density region ($\rho_B \simeq (1.5 - 2.5)\rho_0$)

— Astrophysical data of a canonical 1.4 $M_\odot$ neutron star —

- Neutron-star radius, $R_{1.4}$: PSR J0030+0451 (NICER)
  $1.44^{+0.15}_{-0.14}$ $M_\odot$ and $13.02^{+1.24}_{-1.06}$ km, and $1.34^{+0.15}_{-0.16}$ $M_\odot$ and $12.71^{+1.14}_{-1.19}$ km

M. C. Miller, *et al.*, Astrophys. J. Lett. 887 (2019) L24, T. E. Riley, *et al.*, Astrophys. J. Lett. 887 (2019) L21.

- Dimensionless tidal deformability, $\Lambda_{1.4}$: GW170817
  $\Lambda_{1.4} = 190^{+390}_{-120}$

LIGO Scientific Collaboration and Virgo Collaboration, Phys. Rev. Lett. 119 (2018) 161101.

3 High-density region

- Particle flow data in heavy-ion collisions (HICs)
- Maximum mass of a neutron star: $M_{\mathrm{NS}}^{\mathrm{max}} > 2M_\odot$

To clarify the properties of isospin-asymmetric nuclear matter

Relativistic mean-field (RMF) models

with isoscalar- and isovector-meson mixing

- The interacting Lagrangian density including the isoscalar (σ and ω^μ) and isovector ($\vec{\delta}$ and $\vec{\rho}^{\,\mu}$) mesons as well as nucleons ($N = p, n$) is given by

$$\mathcal{L}_{\rm int} = \sum_N \bar{\psi}_N \left[g_\sigma \sigma - g_\omega \gamma_\mu \omega^\mu + g_\delta \vec{\delta} \cdot \vec{\tau}_N - g_\rho \gamma_\mu \vec{\rho}^{\,\mu} \cdot \vec{\tau}_N \right] \psi_N - U_{\rm NL}(\sigma, \omega, \vec{\delta}, \vec{\rho}).$$

- The nonlinear potential is here supplemented as

$$U_{\rm NL}(\sigma, \omega, \vec{\delta}, \vec{\rho}) = \underbrace{\frac{1}{3} g_2 \sigma^3 + \frac{1}{4} g_3 \sigma^4 - \frac{1}{4} c_3 (\omega_\mu \omega^\mu)^2}_{\text{isospin-symmetric properties}} \underbrace{- \frac{1}{4} e_3 (\vec{\rho}_\mu \cdot \vec{\rho}^{\,\mu})^2 - \Lambda_{\sigma\delta} \sigma^2 \vec{\delta}^{\,2} - \Lambda_{\omega\rho} (\omega_\mu \omega^\mu)(\vec{\rho}_\nu \cdot \vec{\rho}^{\,\nu})}_{\text{isospin-asymmetric properties}}.$$

isospin-symmetric properties: $E_0(\rho_0)$, K_0, J_0, $\cdots$

isospin-asymmetric properties: $E_{\rm sym}(\rho_0)$, L, $K_{\rm sym}$, $J_{\rm sym}$, $\cdots$

	isoscalar	isovector	mixing
Lorentz-scalar	σ ($\sim$500 MeV)	$\vec{\delta}$ (990 MeV)	σ-δ mixing
vector	ω^μ (780 MeV)	$\vec{\rho}^{\,\mu}$ (775 MeV)	ω-ρ mixing

— Theoretical approaches —

1. The strength of δ-N coupling, g_δ^2

   It has been reported that the CREX and PREX-2 results can be explained simultaneously.

   B. T. Reed, F. J. Fattoyev, C. J. Horowitz, and J. Piekarewicz, arXiv:2305.19376 [nucl-th].

2. RMF models with σ-δ mixing, $\Lambda_{\sigma\delta}\sigma^2\vec{\boldsymbol{\delta}}^2$, as well as ω-ρ mixing, $\Lambda_{\omega\rho}\left(\omega_\mu\omega^\mu\right)\left(\vec{\boldsymbol{\rho}}_\nu\cdot\vec{\boldsymbol{\rho}}^\nu\right)$

   Neutron-star properties at the canonical-mass point ($M_{\mathrm{NS}} = 1.4\ M_\odot$):

   - Radius, $R_{1.4}$
   - Dimensionless tidal deformability, $\Lambda_{1.4}$

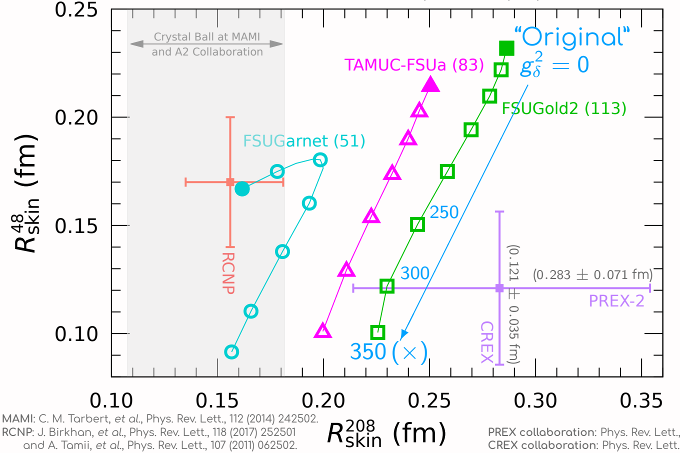
   T. Miyatsu, M.-K. Cheoun, and, K. Saito, Astrophys. J. 929 (2022) 82,
   T. Miyatsu, M.-K. Cheoun, K. S. Kim, and, K. Saito, Phys. Lett. B 843 (2023) 138013.

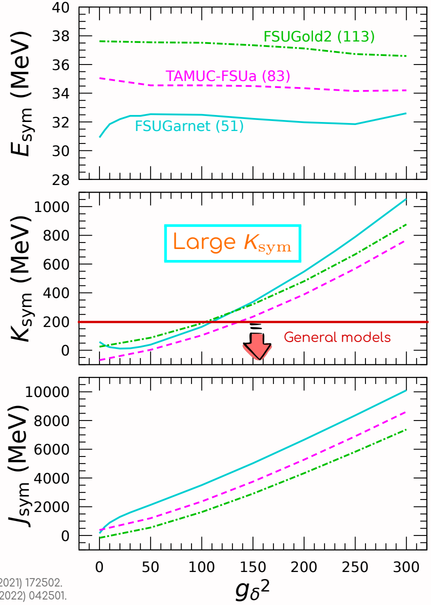
Effect of the δ-N interaction

Acceptable limit of the δ-N coupling, g_δ^2

$0 \leq g_\delta^2 \leq 300$

RMF models—FSUGold2 and FSUGarnet: W.-C. Chen and J. Piekarewicz, Phys. Rev. C 90 (2014) 04430 and Phys. Lett. B 748 (2015) 284, TAMUC-FSUa: F. J. Fattoyev and J. Piekarewicz, Phys. Rev. C 82 (2010) 025810.

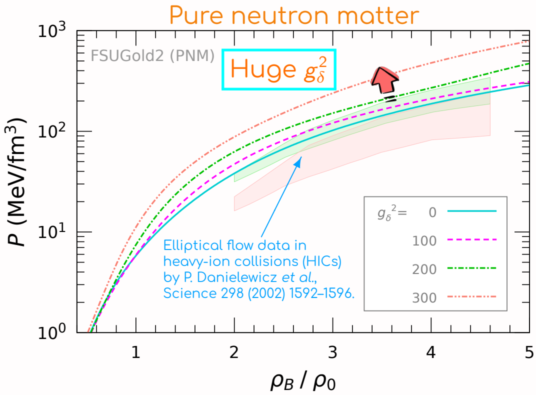


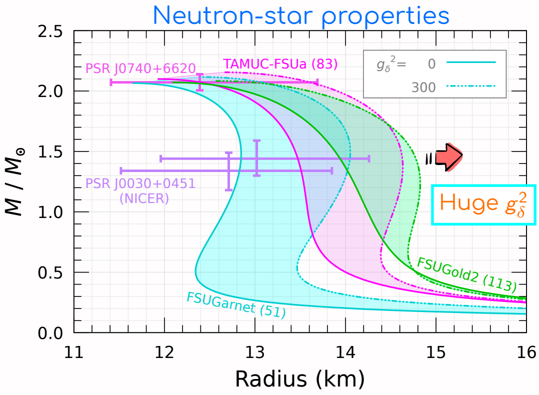


MAMI: C. M. Tarbert, *et al.*, Phys. Rev. Lett., 112 (2014) 242502.
RCNP: J. Birkhan, *et al.*, Phys. Rev. Lett., 118 (2017) 252501 and A. Tamii, *et al.*, Phys. Rev. Lett., 107 (2011) 062502.
PREX collaboration: Phys. Rev. Lett., 126 (2021) 172502.
CREX collaboration: Phys. Rev. Lett., 129 (2022) 042501.

Effect of the δ-N interaction

On dense nuclear matter and neutron stars





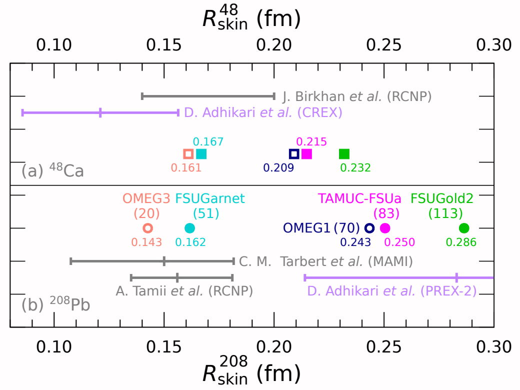
- ✓ The δ meson affects only the isospin-asymmetric matter properties.
- ✓ The large g_δ^2 (CREX and PREX-2) $\Rightarrow$ too stiff P at high densities in PNM and too large $R_{1.4}$ and $\Lambda_{1.4}$.

Isoscalar- and isovector-meson mixing

To understand the terrestrial experiments and astrophysical observations

- Introducing the isoscalar-mixing, $\Lambda_{\sigma\delta}\sigma^2\vec{\delta}^2$, with the relatively small g_δ^2 as well as the isovector-mixing, $\Lambda_{\omega\rho}(\omega_\mu\omega^\mu)(\vec{\rho}_\nu\cdot\vec{\rho}^\nu)$.
- Focusing on the astrophysical observations: NICER and GW170817—$R_{1.4}$ and $\Lambda_{1.4}$

Models	g_δ^2	g_ρ^2	$\Lambda_{\sigma\delta}$	$\Lambda_{\omega\rho}$
FSUGold2	0	20.5	0	12.3
FSUGold2	300.0	214.6	0	196.0
OMEG1	30.0	44.6	95.0	75.7
OMEG3	15.0	57.6	70.0	909.8

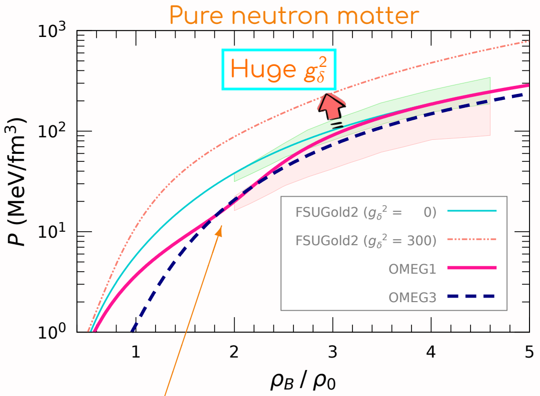


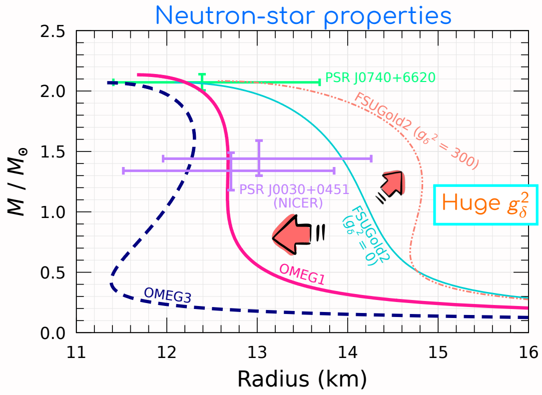
✓ The large $R_{\rm skin}^{208}$ with the smaller L than the general RMF models due to the σ-δ mixing.

✓ However, it is preferable to adopt the small value of $L = 20$ MeV to explain the CREX data.

Isoscalar- and isovector-meson mixing

On dense nuclear matter and neutron stars



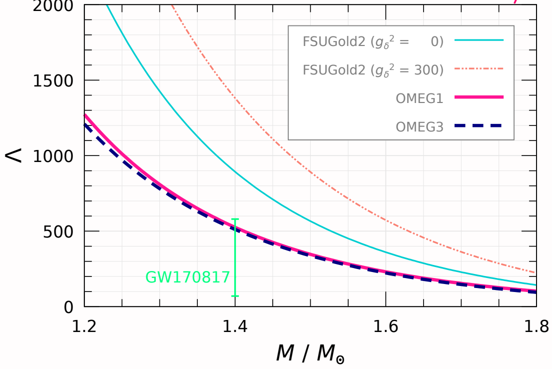


✓ The σ-δ mixing affects P of isospin-asymmetric nuclear matter around $2\rho_0$.
✓ The neutron-star radius becomes small.

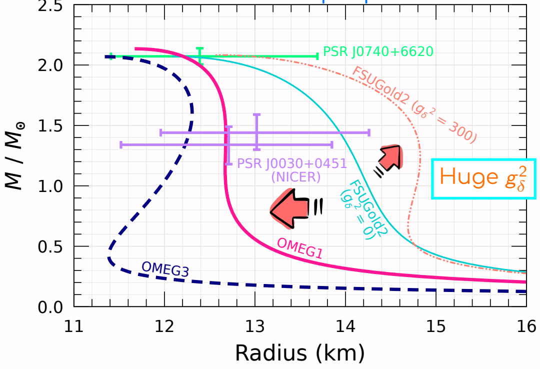
Isoscalar- and isovector-meson mixing

On dense nuclear matter and neutron stars

Dimensionless tidal deformability



Neutron-star properties



✓ The σ-δ mixing affects P of isospin-asymmetric nuclear matter around $2\rho_0$.

✓ The neutron-star radius becomes small. ⇒ The $R_{1.4}$ and $\Lambda_{1.4}$ satisfy the observations.

Summary

- Taking into account the terrestrial experiments and astrophysical observations of neutron stars, we have constructed new EoSs for neutron stars using the RMF model with nonlinear couplings between the isoscalar and isovector mesons.
- We have introduced the δ-N coupling and σ-δ mixing in the conventional RMF model.

Models	g_δ^2	$\Lambda_{\sigma\delta}$	$R_{\rm skin}^{48}$	$R_{\rm skin}^{208}$	flow data (HICs) SNM	flow data (HICs) PNM	$R_{1.4}$ NICER	$\Lambda_{1.4}$ GW170817	$M_{\rm NS}^{\rm max}$ ($M_\odot$)
FSUGold2	0	0	×	PREX-2	✓	✓	✓	×	2.07
	300	0	CREX	PREX-2	✓	×	×	×	2.08
OMEG1	30	95	×	PREX-2	✓	✓	✓	✓	2.13
OMEG3	15	70	RCNP	RCNP	✓	✓	✓	✓	2.07
DINOa*	279	0	CREX	PREX-2	✓	×	×	×	2.17
DINOb*	313	0	CREX	PREX-2	✓	×	×	×	2.15
DINOc*	336	0	CREX	PREX-2	✓	×	×	×	2.14

* B. T. Reed, F. J. Fattoyev, C. J. Horowitz, and J. Piekarewicz, arXiv:2305.19376 [nucl-th].

Thank You for Your Attention.

— Appendix —

Understanding nuclear and neutron-star physics

Purpose:

- Understanding the properties of nuclear matter and neutron stars in the same framework.
- Taking into account the results from nuclear experiments and astrophysical observations of neutron stars.

Nuclear equation of state (EoS)

- Isospin-asymmetric nuclear EoS: $E(\rho_B, \alpha) = E_0(\rho_B) + E_{\rm sym}(\rho_B)\alpha^2 + \mathcal{O}(\alpha^4)$,

  with the baryon density, $\rho_B = \rho_p + \rho_n$, and the isospin asymmetry, $\alpha = (\rho_n - \rho_p)/\rho_B$.
- The bulk properties of nuclear matter are given by the coefficients based on the expansion of $E(\rho_B, \alpha)$ around the saturation density ρ_0,

$$E_0(\rho_B) = E_0(\rho_0) + P(=0)\chi + \frac{K_0}{2!}\chi^2 + \mathcal{O}(\chi^3), \quad E_{\rm sym}(\rho_B) = E_{\rm sym}(\rho_0) + L\chi + \frac{K_{\rm sym}}{2!}\chi^2 + \mathcal{O}(\chi^3),$$

isospin-symmetric matter properties — isospin-asymmetric matter properties

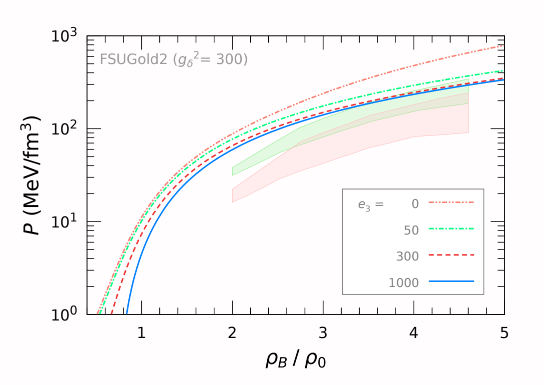
where $\chi = (\rho_B - \rho_0)/3\rho_0$.

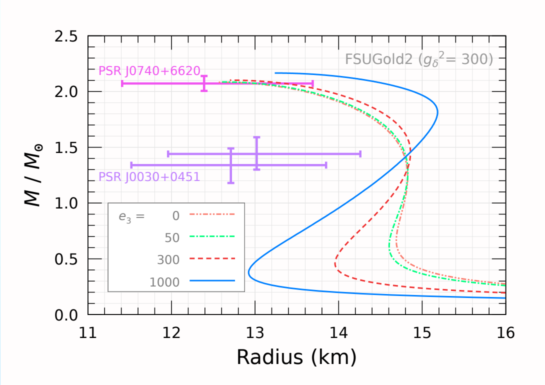
Abstract

- We construct new effective interactions using the relativistic mean-field model with the isoscalar- and isovector-meson mixing.
- Taking into account the results of neutron skin thickness of ^{208}Pb and ^{48}Ca by the PREX-2 and CREX experiments as well as the particle flow data in heavy-ion collisions, the observed mass of PSR J0740+6620, and the tidal deformability of a neutron star from binary merger events, we study the ground-state properties of finite nuclei and the characteristics of nuclear matter and neutron stars.
- It is found that the σ-δ mixing is very important to understand the terrestrial experiments and astrophysical observations of neutron stars self-consistently.
- Especially, we present that the equation of state for neutron stars exhibits the rapid stiffening around twice the nuclear saturation density, which is caused by the soft nuclear symmetry energy due to the σ-δ mixing.
- It is also noticeable that the small dimensionless tidal deformability of a canonical neutron star observed from GW170817 can be explained within the current relativistic mean-field models.

Role of the ρ-meson self-interaction

FSUGold2 with $g_\delta^2 = 300$





Role of the ρ-meson self-interaction

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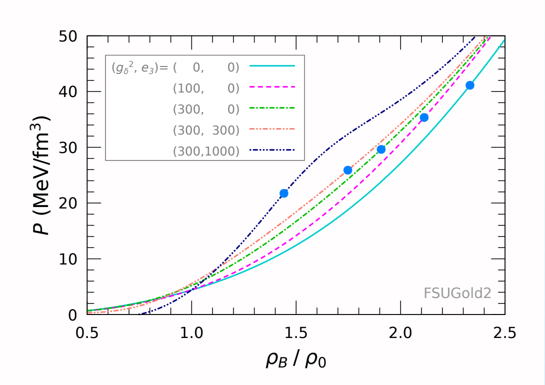

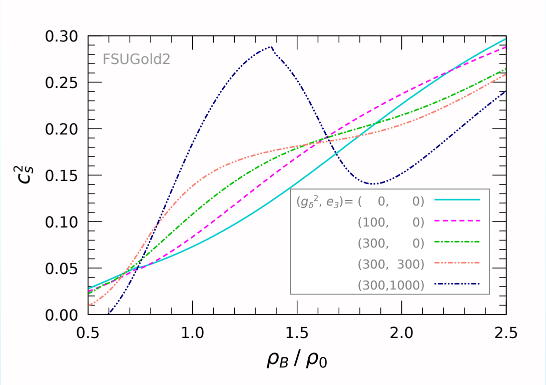

Nuclear symmetry energy

$$E_{\rm sym} = E_{\rm sym}^{\rm kin} + E_{\rm sym}^{\rm pot}$$
$$= E_{\rm sym}^{\rm kin} + E_{\rm sym}^{\rho} + E_{\rm sym}^{\delta}$$