Nuclear equation of state from terrestrial experiments and astrophysical observations

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Soongsil University

OMEG
Origin of Matter and Evolution of Galaxies
우주 물질 중점연구소

Table of contents

Studying nuclear and neutron-star physics

The aim of this study:

- To understand 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.

⇒ "Unified" 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,

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

isospin-symmetric matter properties | isospin-asymmetric matter properties

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

Constraints on the nuclear 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, $R_{\rm ch}$
   - The accurate measurement of neutron skin thickness from the parity-violating electron scattering: PREX-2 (^{208}Pb) and CREX (^{48}Ca)

   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 (gravitational-wave signals)
     $\Lambda_{1.4} = 190^{+390}_{-120}$

     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: $M_{\rm NS}^{\rm max} > 2M_\odot$

To clarify the properties of isospin-asymmetric nuclear matter

Discrepancy between between R_{skin} and $\Lambda_{1.4}$

Characteristics of isospin-asymmetric nuclear matter

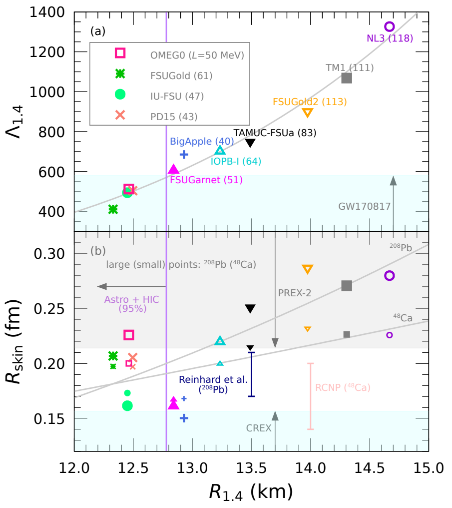
Isospin-asymmetric matter properties

$$E_{\mathrm{sym}}(\rho_B) = E_{\mathrm{sym}}(\rho_0) + L\chi + \frac{K_{\mathrm{sym}}}{2!}\chi^2 + \mathcal{O}(\chi^3)$$

Density-dependence of $E_{\mathrm{sym}}(\rho_B) \Rightarrow$ focusing on L

- Astrophysical constraint: **small L**
  Dimensionless tidal deformability (GW170817)
  $\Lambda_{1.4} = 190^{+390}_{-120}$ B. P. Abbott, *et al.*, Phys. Rev. Lett. 121, 161101.
- Terrestrial experiment: **large L**
  Parity-violating electron scattering, PREX-2 (^{208}Pb)
  $R^{208}_{\mathrm{skin}} = 0.283 \pm 0.071$ fm PREX Collaboration, Phys. Rev. Lett. 126, 172502.

To solve this discrepancy, we construct **new effective interactions:** “OMEG family”



Neutron skin puzzle ?

- Due to less information on parity-violating electron scattering, further research is needed:
  - Dispersive corrections in elastic electron-nucleus scattering — P. Gueye *et al.*, Eur. Phys. J. A 56, 126.
  - γZ-exchange contributions to the parity-violating asymmetry, A_{pv} — Qian-Qian Guo and Hai-Qing Zhou, Phys. Rev. C 108 (2023) 035501.

Two aspects of neutron skin puzzle

1. Difficulty of reconciling the PREX-2 and CREX results simultaneously:

   While ^{208}Pb is estimated to have a relatively thick neutron skin of around 0.28 fm (PREX-2), ^{48}Ca is estimated to have a significantly smaller skin of around 0.12 fm (CREX).

   At present, there is no "theoretical" calculation...

2. Discrepancy between the PREX-2 experiment and the neutron-star observations:

   Large $R_{\rm skin}^{208}$ (large L) versus small $R_{\rm NS}$ and $\Lambda_{1.4}$ (small L)

We have to directly focus on the density profiles of $\rho_{\rm ch}$ (ρ_p) and ρ_W (ρ_n), not $R_{\rm skin} = R_n - R_p$.

Parity-violating electron scattering

Lead Radius Experiment (PREX)

PREX Collaboration, Phys. Rev. Lett. 126 (2021) 172502.

- The parity-violating asymmetry A_{pv} in longitudinally polarized elastic electron scattering off ^{208}Pb nuclei:

$$A_{pv}(Q^2) = \frac{d\sigma_R/d\Omega - d\sigma_L/d\Omega}{d\sigma_R/d\Omega + d\sigma_L/d\Omega} \simeq \frac{G_F Q^2 |Q_W|}{4\sqrt{2}\pi\alpha Z} \frac{F_W(Q^2)}{F_{\rm ch}(Q^2)}, \quad F_W(Q^2) = \frac{1}{Q_W}\int d\boldsymbol{r}\, \rho_W(\boldsymbol{r}) e^{i\boldsymbol{Q}\cdot\boldsymbol{r}},$$

where $d\sigma_{L(R)}/d\Omega$ is the differential cross section for the scattering of left (right) handed electrons from ^{208}Pb, G_F is the Fermi coupling constant, $F_{W(\rm ch)}$ is the neutral *weak* (charge) form factor, and Q_W is the *weak* charge of ^{208}Pb.

Electromagnetic (EM) charge

1. EM charge densities in nuclei have been very well measured for years.
   De Vries, *et al.*, Atom. Data Nucl. Data Tabl. 36 (1987) 495–536.
2. EM charge is coupled to photon: a positive electric charge of $+1e$
3. Very good probe of the proton density.

Weak (W) charge

1. The Z^0 boson couples to the weak charge, Q_W.
2. Neutrons strongly linked to weak charge of nucleus because of the small Q_W^p and large Q_W^n:
   $$Q_W^n \simeq -1 \text{ and } Q_W^p = 1 - 4\sin^2\Theta_W \simeq 0.08.$$

Theoretical analyses of (weak) charge density

- Charge density with a dipole-type (Sachs) form factor: elastic electron scattering

$$\rho_{\rm ch}(\boldsymbol{r}) = \int d\boldsymbol{r}' \, \rho_{\rm sn}\left(\boldsymbol{r}-\boldsymbol{r}'\right) \rho_p(\boldsymbol{r}'), \quad \rho_{\rm sn}\left(\boldsymbol{r}-\boldsymbol{r}'\right) = \frac{\mu^3}{8\pi} \exp\left(-\mu\left|\boldsymbol{r}-\boldsymbol{r}'\right|\right),$$

where the cut off parameter is given by $\mu = 0.71$ GeV.

- Weak charge density (a spin-zero nucleus): Parity-violating electron scattering

Z. Lin, and C. J. Horowitz, Phys. Rev. C. 92 (2015) 014313.

$$\rho_W\left(\boldsymbol{r}\right) = 4 \int d\boldsymbol{r}' \left[G_p^z\left(\left|\boldsymbol{r}-\boldsymbol{r}'\right|\right) \rho_p\left(\boldsymbol{r}'\right) + G_n^z\left(\left|\boldsymbol{r}-\boldsymbol{r}'\right|\right) \rho_n\left(\boldsymbol{r}'\right)\right],$$

where G_p^z and G_n^z are the Fourier transformations of weak from factors for the coupling of a Z^0 to proton or neutron:

$$G_p^z = \frac{1}{4}\left(G_p^E - G_n^E\right) - \sin^2\Theta_W G_p^E - \frac{1}{4}G_s^E, \quad G_n^z = \frac{1}{4}\left(G_n^E - G_p^E\right) - \sin^2\Theta_W G_n^E - \frac{1}{4}G_s^E.$$

If the contribution of strange quarks is ignored, then

$$\rho_W\left(\boldsymbol{r}\right) \simeq Q_W^p \rho_{\rm ch}\left(\boldsymbol{r}\right) + Q_W^n \int d\boldsymbol{r}' \left[G_p^E\left(\left|\boldsymbol{r}-\boldsymbol{r}'\right|\right)\rho_n + G_n^E\left(\left|\boldsymbol{r}-\boldsymbol{r}'\right|\right)\rho_p\right].$$

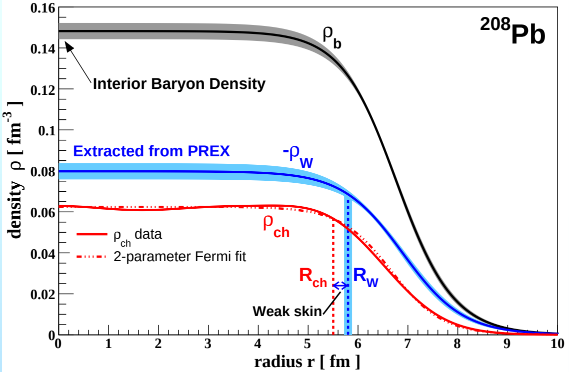
PREX-2 experiment

Large neutron skin thickness, $R_{\rm skin} = R_n - R_p = 0.283$ fm

PREX Collaboration, Phys. Rev. Lett. 126 (2021) 172502.

- Weak radius:

$$R_W^2 = \frac{1}{Q_W} \int d\boldsymbol{r}\, r^2 \rho_W(\boldsymbol{r}), \quad Q_W = \int d\boldsymbol{r}\, \rho_W(\boldsymbol{r}) = ZQ_W^p + NQ_W^n.$$



The ρ_b^0 is approximately calculated using a symmetrized two-parameter Fermi function:

$$\rho_W(r, c, a) = \rho_b^0 \frac{\sinh(c/a)}{\cosh(r/a) + \cosh(c/a)}.$$

TABLE III. PREX-1 and -2 combined experimental results for ^{208}Pb. Uncertainties include both experimental and theoretical contributions.

^{208}Pb Parameter	Value
Weak radius (R_W)	5.800 ± 0.075 fm
Interior weak density (ρ_W^0)	-0.0796 ± 0.0038 fm^{-3}
Interior baryon density (ρ_b^0)	0.1480 ± 0.0038 fm^{-3}
Neutron skin ($R_n - R_p$)	0.283 ± 0.071 fm

— Theoretical framework —

Relativistic mean-field (RMF) models with isoscalar- and isovector-meson mixing

RMF models with isoscalar- and isovector-meson mixing

T. Miyatsu, M.-K. Cheoun and, K. Saito, Astrophys. J. 929, 82 (2022).

- 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, $\cdots$

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	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

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— Numerical results —

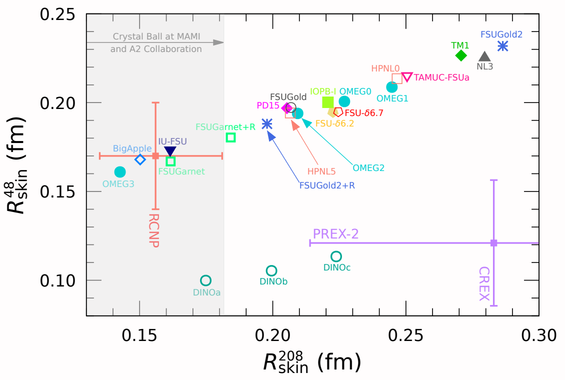
1. Neutron skin thickness of ^{48}Ca and ^{208}Pb
2. Neutron star properties
   - Mass-radius relation of a neutron star
   - Neutron-star tidal deformability, Λ
3. Discussion: nuclear symmetry energy

Neutron skin thickness of ^{208}Pb and ^{48}Ca

Using the effective interactions based on RMF models

Models (L)	g_δ^2	g_ρ^2	$\Lambda_{\sigma\delta}$	$\Lambda_{\omega\rho}$
NL3 (118)	—	19.9	—	—
FSUGold2 (113)	—	20.1	—	12.3
FSUGarnet (51)	—	48.0	—	1555.7
OMEG0 (50)	37.7	51.7	87.0	102.6
OMEG1 (70)	30.0	44.6	95.0	75.7
OMEG2 (45)	20.0	44.4	85.0	288.9
OMEG3 (20)	15.0	57.6	70.0	909.8
DINOc (90)	335.8	230.7	—	171.6

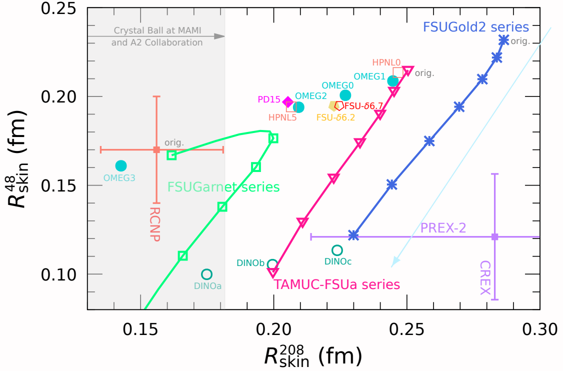
- **The OMEG family** is constructed so as to reproduce the characteristics of finite nuclei and nuclear matter as well as neutron stars.



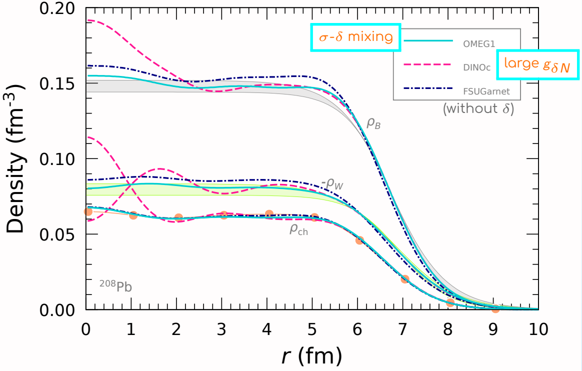
Neutron skin thickness of ^{208}Pb and ^{48}Ca

The effect of $K_{\rm sym}$ due to the δ-N coupling

Introducing the large δ-N coupling



Density profiles



The $K_{\rm sym}$ becomes large as $g_{\delta N}$ increases.
$K_{\rm sym}$ = 25 MeV ($g^2_{\delta N}$ = 0) → $K_{\rm sym}$ = 877 MeV ($g^2_{\delta N}$ = 300)

The experimental data of $\rho_{\rm ch}$ is not supported.
Neutron skin puzzle !?

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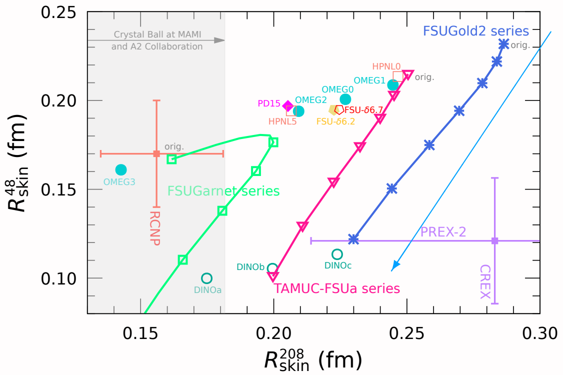

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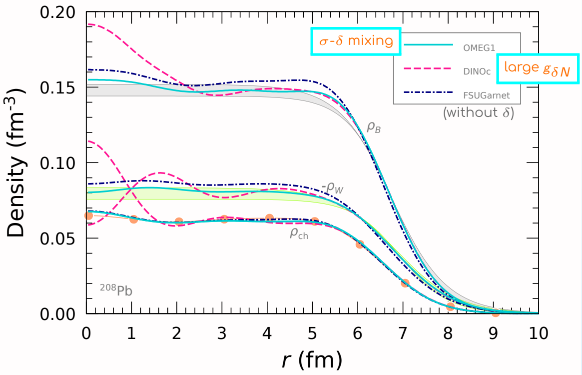

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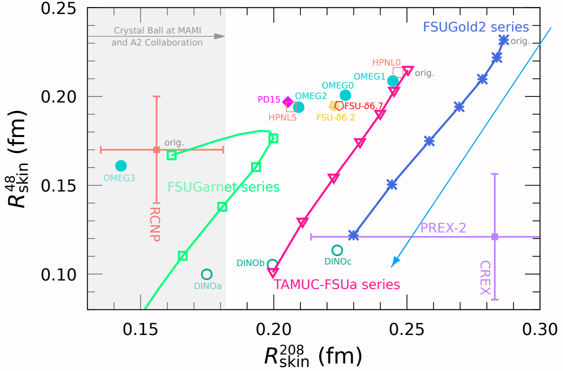

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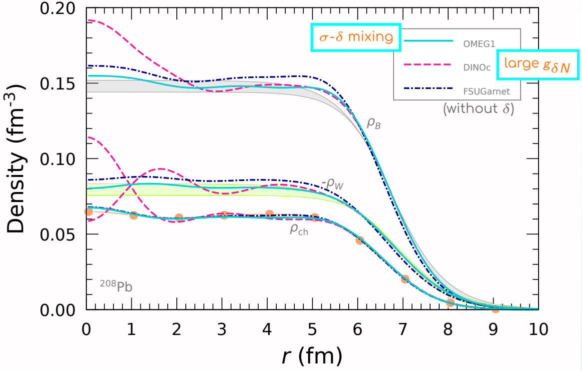

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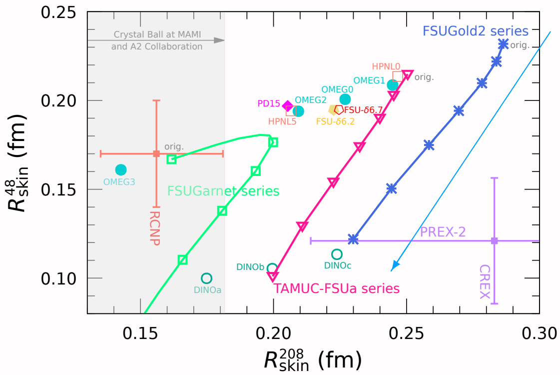

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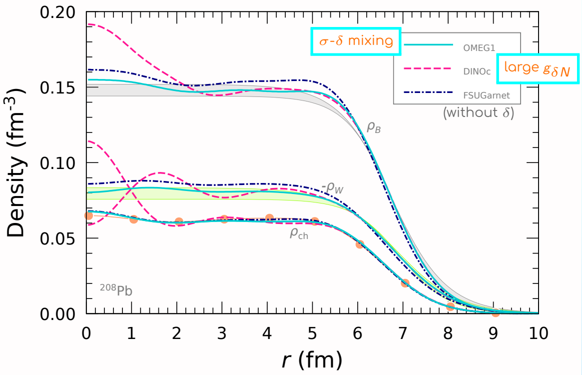

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Neutron skin puzzle (1)

Properties of neutron stars

Solving the Tolman–Oppenheimer–Volkoff (TOV) equation

$$\frac{dP(R)}{dR} = -\frac{G[P(R)+\epsilon(R)][M(R)+4\pi R^3 P(R)]}{R[R-2GM(R)]},$$

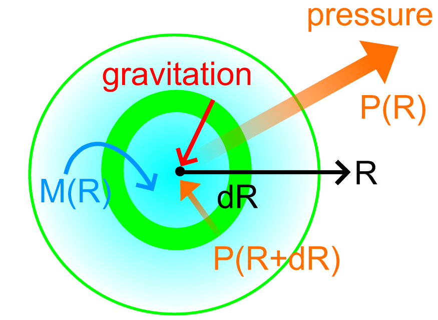
$$M(R) = \int_0^R 4\pi r^2 \epsilon(r) dr,$$

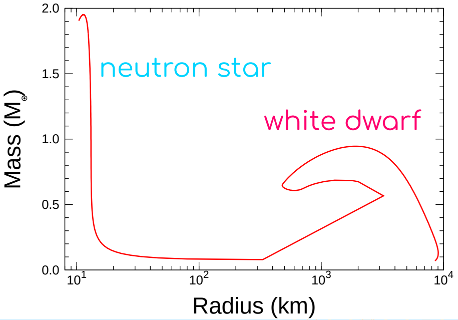
- ϵ: energy density
- P: pressure
- G: gravitational constant

Neutron-star EoS

The charge neutrality and β equilibrium conditions are imposed with leptons (e^- and μ^-).

$$\mu = \mu_n - \mu_p = \mu_e = \mu_\mu,$$
$$q = Y_p - Y_L = \rho_p/\rho_B - \sum_{\ell=e,\mu} \rho_\ell/\rho_B = 0.$$

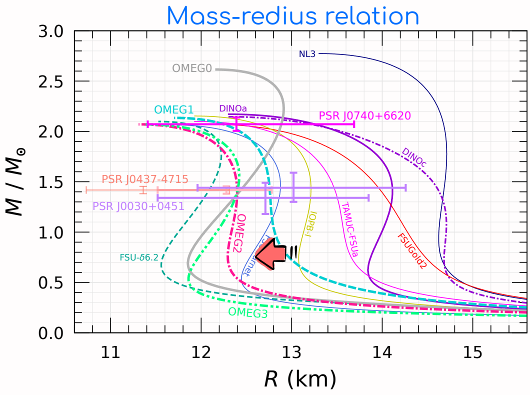




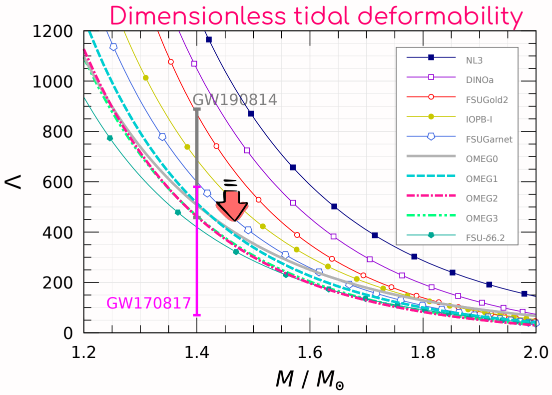
Neutron-star properties

RMF models with isoscalar- and isovector-meson mixing

Mass-redius relation



Dimensionless tidal deformability

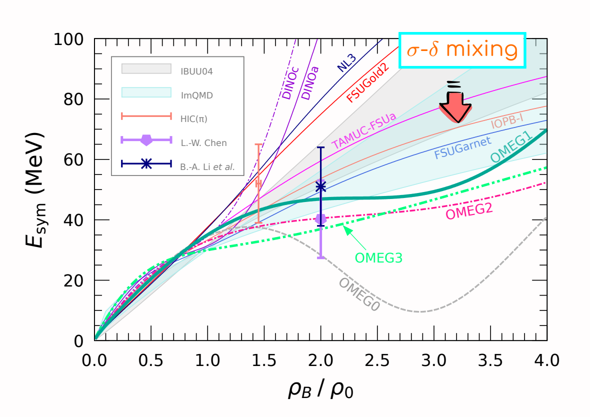


✓ The σ-δ mixing affects P in pure neutron matter and $E_{\rm sym}(\rho_B)$ around $2\rho_0$.

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

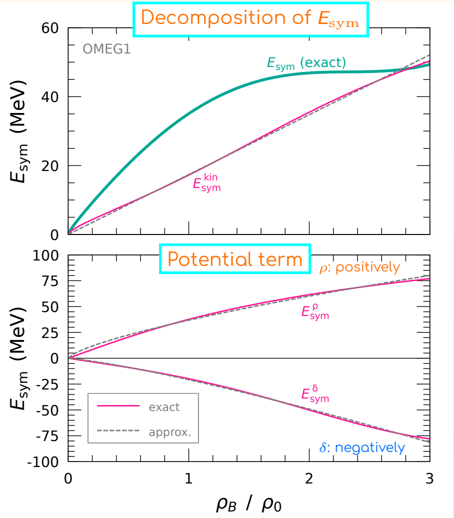
Nuclear symmetry energy

Approximation due to the Lorentz decomposition of $E_{\rm sym}$



$$E_{\rm sym} = E_{\rm sym}^{\rm kin} + E_{\rm sym}^{\rm pot} \left(= E_{\rm sym}^{\rho} + E_{\rm sym}^{\delta}\right)$$

$$\simeq 17.4 \left(\frac{\rho_B}{\rho_0}\right) + 36.8 \left(\frac{\rho_B}{\rho_0}\right)^{0.71} - 20.7 \left(\frac{\rho_B}{\rho_0}\right)^{1.24} \text{ (OMEG1)}$$



Summary

This work was supported by the NRF of Korea (Grant Nos. RS-2023-00242196, NRF-2021R1A6A1A03043957 and NRF-2020R1A2C3006177).

To understand nuclear and neutron-star physics in the same framework:

- 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.
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Neutron skin puzzle:

1. We have introduced the δ-N coupling to solve the neutron skin puzzle (1). However it is still difficult to explain. We perhaps may study the density profiles of $\rho_{\rm ch}$ (ρ_p) and ρ_W (ρ_n) in detail.
2. It is found that the σ-δ mixing is very powerful to understand the terrestrial experiments and astrophysical observations of neutron stars self-consistently—puzzle(2).

Large $R_{\rm skin}^{208}$ (PREX-2) and small $R_{\rm NS}$ (NICER) $\Lambda_{1.4}$ (GW170817)

Thank You for Your Attention.

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