Astrophysics and Nuclear Physics Informed Interactions in Dense Matter: Inclusion of PSR J0437-4715

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Objectives

- How vector-isoscalar and vector-isovector interactions can be determined within the density regime of neutron stars while fulfilling nuclear and astrophysical constraints?

- The impact of latest radius measurement of **PSR J0437-4715** ($M = 1.418 \pm 0.037\ M_{\odot}$, $R = 11.36^{+0.95}_{-0.63}$ km) from the NASA NICER mission on EOS [Choudhury et al 2024 ApJL 971 L20].

Enforcing Nuclear and Astro Constraints

1. **Minimal Saturation Properties**: The saturation density is $\rho_0 = 0.16 \pm 0.005$ fm^{-3}, with a binding energy per nucleon of $\epsilon_0 = -16.1 \pm 0.2$ MeV, and a symmetry energy of $J_0 = 30 \pm 2$ MeV at saturation.
2. **Low-Density Neutron Matter Constraints**: We impose constraints on the energy per particle at densities of 0.05, 0.1, 0.15, and 0.20 fm^{-3}, as informed by various χEFT calculations.
3. **High-Density Constraints from pQCD**: Constraints derived from perturbative QCD (pQCD) at seven times ρ_0 for the highest renormalizable scale $X = 4$ (Komoltsev Kurkela, PRL128(2022)202701).
4. **Astrophysical Constraints**: Mass-radius measurements from PSR J0030+0451, PSR J0740+6620, and tidal deformability from GW170817. Additionally, we discuss recent mass-radius NICER results for PSR J0437-4715.

CMF

The chiral invariant self-interaction terms of the vector mesons $\mathcal{L}_{\rm vec}^{\rm Self}$:

C1: $\mathcal{L}_{\rm vec}^{\rm Self} = g_{4,1}(\omega^4 + 6\omega^2\rho^2 + \rho^4)$
C2: $\mathcal{L}_{\rm vec}^{\rm Self} = g_{4,2}(\omega^4 + \rho^4)$
C3: $\mathcal{L}_{\rm vec}^{\rm Self} = g_{4,3}(\omega^4 + 2\omega^2\rho^2 + \rho^4)$
C4: $\mathcal{L}_{\rm vec}^{\rm Self} = g_{4,4}(\omega^4)$

We preserve chiral invariance and study combinations of the above coupling schemes to :

1) Isolate each one of the three independent terms:

- **x**: $\mathcal{L}_{\rm vec}^{\rm Self} = \mathrm{x}\rho^2\omega^2$;
- **y**: $\mathcal{L}_{\rm vec}^{\rm Self} = \mathrm{y}\rho^4$;
- **z**: $\mathcal{L}_{\rm vec}^{\rm Self} = \mathrm{z}\omega^4$;

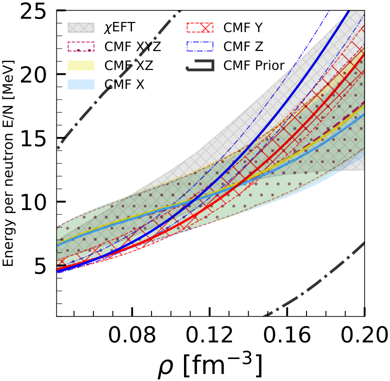
2) Consider the combination of two terms:

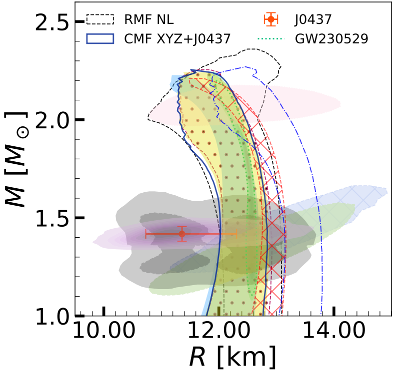
- **xz**: $\mathcal{L}_{\rm vec}^{\rm Self} = \mathrm{x}\rho^2\omega^2 + \mathrm{z}\omega^4$;

3) Consider a combination of the three terms:

- **xyz**: $\mathcal{L}_{\rm vec}^{\rm Self} = \mathrm{x}\rho^2\omega^2 + \mathrm{y}\rho^4 + \mathrm{z}\omega^4$;

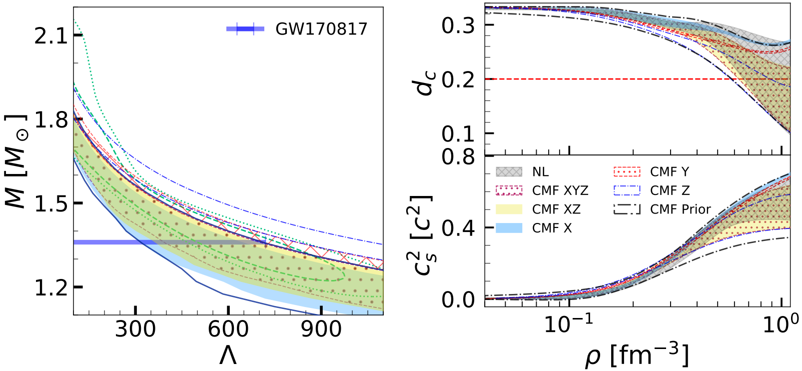
Results & Conclusions





The 90% credible interval region for the resulting posterior in various cases: (left) the equation of state for pure neutron matter, (right) the mass-radius relationship for neutron stars.

- The $\omega^2\rho^2$ interaction term in the CMF model is essential for precisely capturing current neutron-matter χEFT constraints at low density.
- The latest NICER observations of PSR J0437-4715 achieve a modest reduction of around ~ 0.1 km in the posterior radius of the neutron star mass-radius relation but notably decrease the Bayes factor (ln $K_{\mathrm{xyz,xyzJ0437}} = 1.97$). Substantial evidence!
- Indicating discrepancies between recent NICER data and past observations, or that the CMF model with nonlinear components explains older data better, suggesting the need for a new interaction term or additional degrees of freedom.



The 90% credible interval for the resulting posterior: (left) mass-tidal deformability of NS, and (right) quantity d_c related to trace anomaly $d_c = \sqrt{\Delta^2 + \Delta'^2}$. Here, $\Delta' = c_s^2\ (1/\gamma - 1)$ is the logarithmic derivative of $\Delta = 1/3 - P/\epsilon$ with respect to energy density, approaching zero in the conformal limit and squre of speed of sound c_s^2.

- The set z is the one that reproduces the worst of the data, followed by set y.
- The Bayes factor we have obtained $\ln K_{\mathrm{xyz,xz}} = 0.05$, $\ln K_{\mathrm{xyz,x}} = -0.73$, $\ln K_{\mathrm{xyz,y}} = 3.4$, $\ln K_{\mathrm{xyz,z}} = 6.09$, showing that there is a strong evidence of model xyz with respect to models y and z, but no large difference with respect to models x and xz.
- These results indicate that the properties proposed in [Nature Commun. 14, 8451 (2023)] for identifying deconfined matter are not unique. Models of nuclear matter, like the CMF model, which do not include deconfinement, may exhibit similar properties. The term ω^4 drives this behavior.

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Thank You!

Bayesian Setup

- NMP:

$$\mathcal{L}(\mathcal{D}_{\rm NMP}|\theta) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(\frac{-(D(\theta)-D_{\rm NMP})^2}{2\sigma^2}\right) = \mathcal{L}^{\rm NMP}$$

- The PNM constraints for χEFT:

$$\mathcal{L}^{\rm PNM}(\epsilon_{\chi \mathsf{EFT},i}|\theta) = \frac{1}{2\sigma_i} \cdot \frac{1}{\exp\left(\frac{\left|\epsilon_{\chi\mathsf{EFT},i}-\epsilon_{{\rm PNM},i}(\theta)\right|-\sigma_i}{p}\right)+1}$$

- pQCD:

$$\mathcal{L}(d_{\rm pQCD}|\theta) = P(d_{\rm pQCD}|\theta) = \mathcal{L}^{\rm pQCD}$$

where $P(d_{\rm pQCD}|\theta) = 1$ if it is within $d_{\rm pQCD}$;

otherwise zero;

- GW:

$$P(d_{\rm GW}|{\rm EoS}) = \int_{M_{\rm min}}^{M_{\rm max}} dm_1 \int_{M_{\rm min}}^{m_1} dm_2 P(m_1, m_2|{\rm EoS})$$
$$\times P(d_{\rm GW}|m_1, m_2, \Lambda_1(m_1, {\rm EoS}), \Lambda_2(m_2, {\rm EoS})) = \mathcal{L}^{\rm GW}$$

where $P(m|{\rm EoS})$ can be written as:

$$P(m|{\rm EoS}) = \begin{cases} \frac{1}{M_{\rm max}-M_{\rm min}} & \text{if } M_{\rm min} \le m \le M_{\rm max}\ , \\ 0 & \text{otherwise.} \end{cases}$$

Here, $M_{\rm min}$ is 1 $M_\odot$, and $M_{\rm max}$ represents the maximum mass of a NS for the given equation of state (EOS).

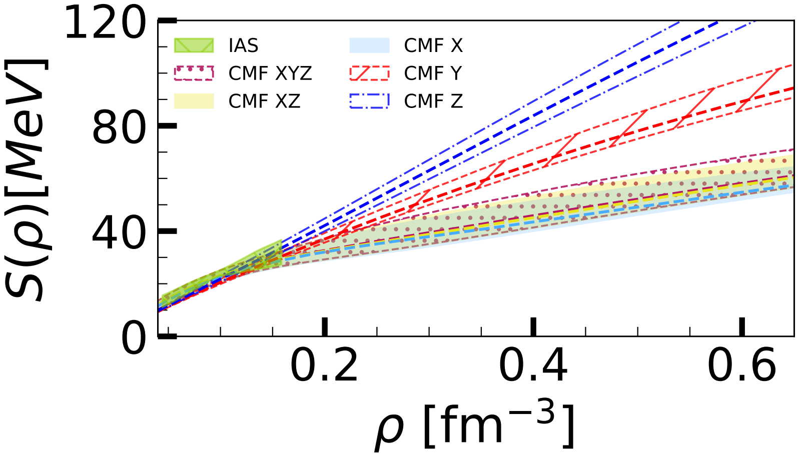
- X-ray observation (NICER):

$$P(d_{\rm X-ray}|{\rm EoS}) = \int_{M_{\rm min}}^{M_{\rm max}} dm\, P(m|{\rm EoS})$$
$$\times P(d_{\rm X-ray}|m, R(m, {\rm EoS})) = \mathcal{L}^{\rm NICER}$$

The final likelihood for the calculation is then given by:

$$\mathcal{L} = \mathcal{L}^{\rm NMP}\mathcal{L}^{\rm PNM}\mathcal{L}^{\rm pQCD}\mathcal{L}^{\rm GW}\mathcal{L}^{\rm NICERI}\mathcal{L}^{\rm NICERII}\mathcal{L}^{\rm NICERIII}$$

Symmetry energy posterior



Symmetry energy posterior with respect to baryon density obtained within the 90% CI for the five distinct groups of CMF instances under study. We also compare the constraints from IAS [P. Danielewicz and J. Lee, Nucl. Phys. A 922, 1 (2014)]