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

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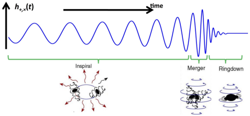
Compact Stars in the QCD phase diagram, 7–11 Oct 2024, Yukawa Institute for Theoretical Physics (YITP)

Neutron Stars

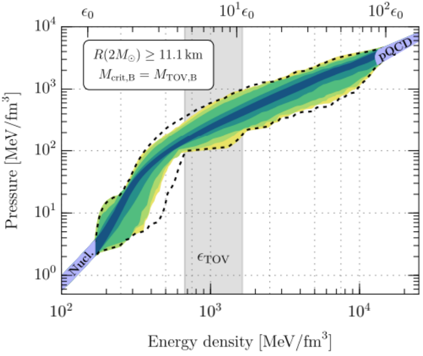
In 1967, Jocelyn Bell Burnell, then a graduate student in radio astronomy at the University of Cambridge, discovered the first radio pulsars.

- The neutron stars (NS) laboratory for dense baryonic matter (the core density $\sim$ 4-5 times nuclear saturation density).
- Very asymmetric nuclear matter $I = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} \sim 0.7$.
- The observational constraints
  - Radio Channel: J1614-2230 $1.97 \pm 0.04 M_\odot$, J0348+0432 $2.01 \pm 0.04 M_\odot$, J0740+6620 $2.14^{+0.10}_{-0.09} M_\odot$, PSR J0740+6620 $2.08^{+0.07}_{-0.07} M_\odot$.
  - X-Ray channel: NICER allowing a prediction of both the NS mass and radius.
  - GW channel: binary neutron star merger GW170817.





Can we extract the NS composition from observations?

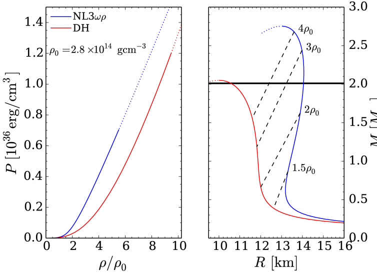


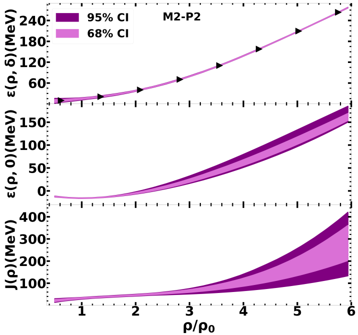
Annala et al, PRX 12, 011058

- **Agnostic approaches analyze:**
  - Speed of sound c_s (Tews ApJ 860, 149; Annala Nat Phys 16, 907; Altiparmak ApJ Lett. 939, L34, Han PRL 128, 161101)
  - Polytropic index $\gamma = \frac{d\ln(p)}{d\ln(\epsilon)}$ (Annala Nat Phys 16, 90)
  - Trace anomaly $\Delta = \frac{1}{3} - \frac{P}{\epsilon}$ (Fujimoto PRL 129, 252702)
  - Trace anomaly related $d_c = \sqrt{\Delta^2 + \Delta'^2}$ (Annala Nat Com 14, 8451)

Probing the interior of Neutron Stars

- mass-radius $\rightarrow$ equation of state $\rightarrow$ composition?





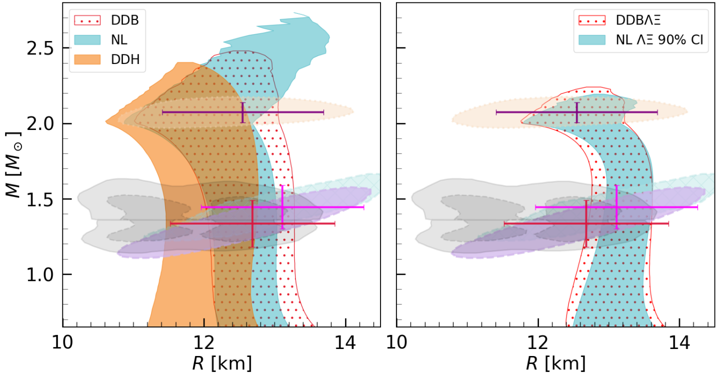
- hyperons?
- deconfined quark matter?
- dark matter?
- ~~or modified gravity?~~

Sk Md Adil Imam et al. PRC 105, 015806 (2022)
See also:

- Tovar et al., PRD 104 (2021)
- Mondal & Gulminelli, PRD 105 (2022)
- Essick, PRL 127, 192701 (2021)

Current comparability of hyperon inclusion with neutron star observations

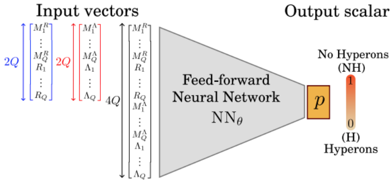
Malik et all, Phys.Rev.D 107 (2023) 10, 103018, Phys.Rev.D 106 (2022) 6, 063024, Astrophys.J. 930 (2022) 1, 17

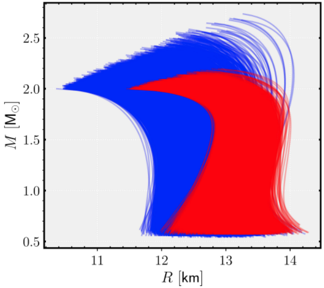


- Inclusion of Hyperons: the nucleonic EOS is harder, larger radii for low and medium mass stars, similar $M_{\max}$.

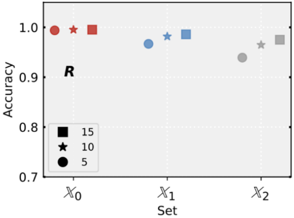
Detecting Hyperons inside NS with a Neural Network Classification Model

Valeria Carvalho, M Ferreira, CP, 2409.12684 [nucl-th]





Detect the presence of hyperons with $\sim 100\%$ (noiseless data) to 94% (very noisy data) accuracy



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: chiral invariant vector self-interaction terms

T Malik, V Dexheimer, Constança Providência, PRD 110,043042

Chiral Mean Field Model: a SU(3) nonlinear realization of the sigma model within the mean-field approximation

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

2)Consider the combination of two terms:

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

3) Consider a combination of the three terms:

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

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:

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

- 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:

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

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

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

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).

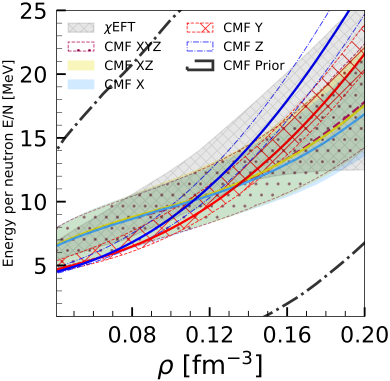
- X-ray observation (NICER):

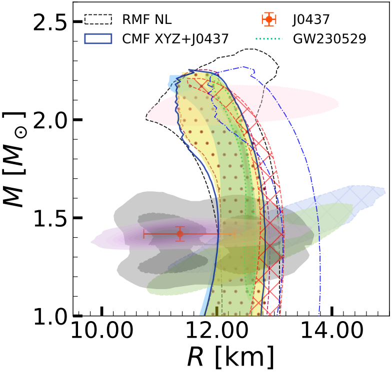
$$P(d_{\rm X-ray}|\mathrm{EoS}) = \int_{M_{\min}}^{M_{\max}} dm\, P(m|\mathrm{EoS}) \times P(d_{\rm X-ray}|m, R(m, \mathrm{EoS})) = \mathcal{L}^{\rm NICER}$$

The final likelihood for the calculation is then given by:

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

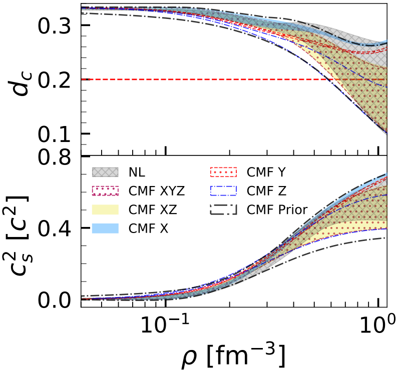
Results & Conclusions





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.

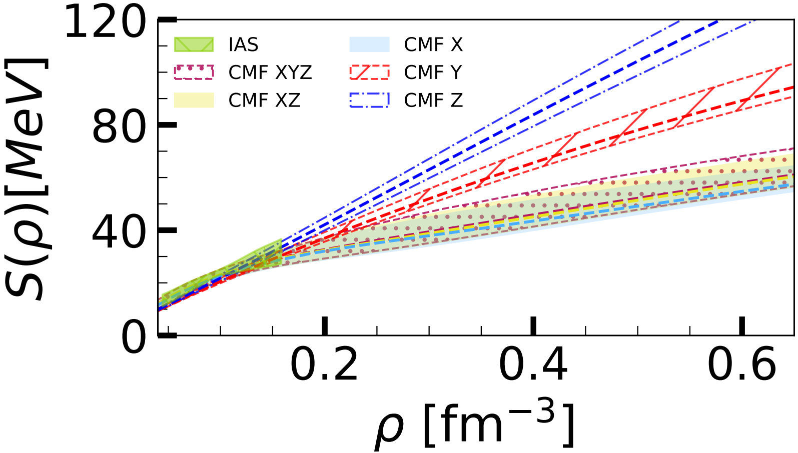
- The $\omega^2\rho^2$ interaction term in the CMF model is essential for precisely capturing current neutron-matter χEFT constraints at low density.
- The latest NICER observations of PSR J0437-4715 achieve a modest reduction of around ~ 0.1 km in the posterior radius of the neutron star mass-radius 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.



- square of speed of sound c_s^2
- $d_c = \sqrt{\Delta^2 + \Delta'^2}$ with
  - trace anomaly: $\Delta = 1/3 - P/\epsilon$
  - $\Delta' = c_s^2\ (1/\gamma - 1)$derivative of with respect to energy density
  - $d_c < 0.2 \rightarrow$ deconfined quarks (Annala et al Nat Commun. 14, 8451),

- Identification of deconfined matter with $d_c < 0.2$ are not unique: Models of nuclear matter (CMF model) with no deconfinement, may exhibit similar properties. The term ω^4 drives this behavior.
- The Bayes factors $\ln K_{\mathrm{xyz,xz}} = 0.05$, $\ln K_{\mathrm{xyz,x}} = -0.73$, $\ln K_{\mathrm{xyz,y}} = 3.4$, $\ln K_{\mathrm{xyz,z}} = 6.09$: a strong evidence of model xyz with respect to models y and z, but no large difference with respect to models x and xz.

Symmetry energy posterior



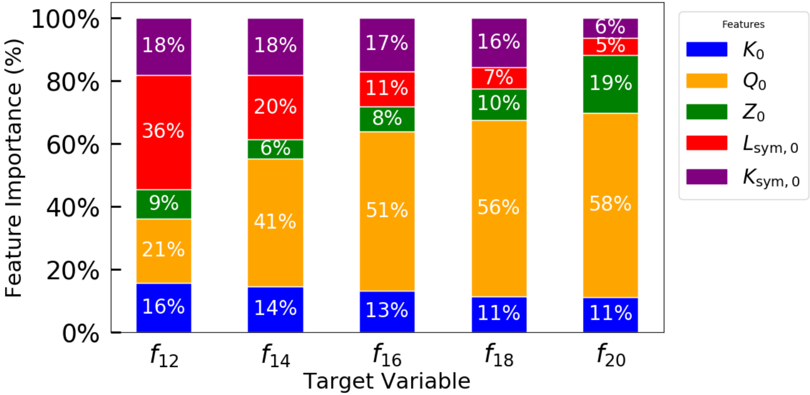
- z (ω^4): predicts harder symmetry energy $S(\rho)$.
- x ($\omega\rho$): necessary to soften the $S(\rho)$ at high density.

Neutron Star EOS: Future

- How can we get the NS composition? Include observations sensitive to composition.

- Use of reverse engineering methods such as Machine Learning (ML) etc to extract information from observation.

The footprint of NMP on the neutron star f mode oscillation frequencies: a machine learning approach



Deepak Kumar et al, arxiv 2402.03054

Collaborators

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Thank You!