Observational constraints on the properties of the neutron star matter

(Impact of recent PSR J0437-4715 NICER measurements)

Tuhin Malik

CFisUC, University of Coimbra, Portugal

January 13, 2025

10th Asian Triangle Heavy-Ion Conference - ATHIC 2025, 13–16 Jan 2025, Berhampur, Odisha

Constança Providência

Helena Sofia Pais

Márcio Ferreira

Centro de Física da Universidade de Coimbra (CFisUC)

5 Working Groups

WG1 — Hadron Physics and Fundamental Interactions

WG2 — Multifunctional Materials

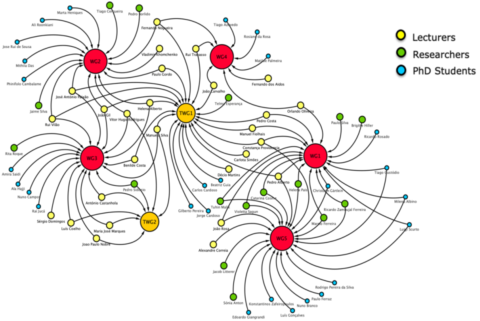
WG3 — Chemical and Applied Condensed Matter Physics

WG4 — Soft and Biological Matter

WG5 — Astrophysics and Cosmology

Tuhin Malik

Valéria Maria Dinis Carvalho



CFisUC

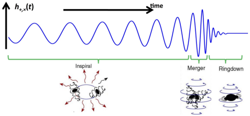
1 2 9 0

UNIVERSIDADE Ð COIMBRA

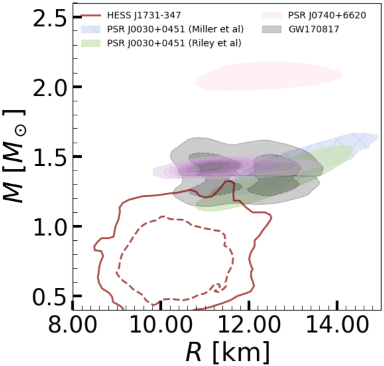
Neutron Stars

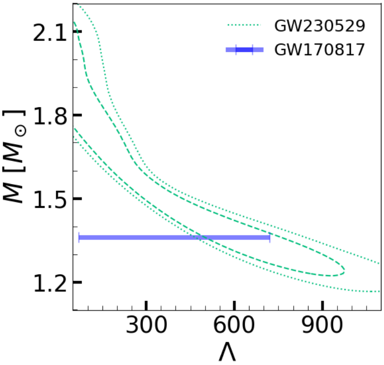
In 1967, Jocelyn Bell Burnell, then a graduate student in radio astronomy at the University of Cambridge, discovered the first radio pulsars.

- 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.



Observational Constraints





- HESS J1731-347: A strangely light neutron star within a supernova remnant, Nature Astronomy volume 6, pages1444–1451 (2022).

$$M = 0.77^{+0.20}_{-0.17}\, M_\odot \quad \text{and} \quad R = 10.4^{+0.86}_{-0.78}\ \text{km},$$

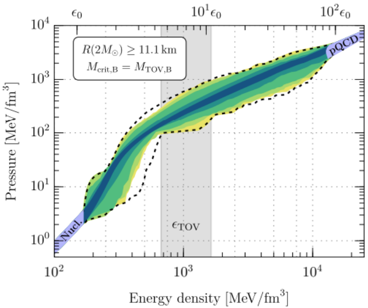
- GW230529: fourth observing run of the LIGO–Virgo–KAGRA. APJ Letter 970:L34 (39pp), 2024.

$$\text{Primary mass } \frac{m_1}{M_\odot} = 3.6^{+0.8}_{-1.2}, \text{Secondary mass } \frac{m_2}{M_\odot} = 1.4^{+0.6}_{-0.2}$$

Other 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**: The 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).

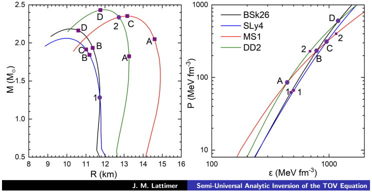
Progress made utilizing agnostic methodologies up to now



- Speed-of-sound (C_s^2) interpolation
- Piecewise polytropic interpolation
- Gaussian process EoS
- Taylor expansion EoS

- L. Lindblom et al, Phys. Rev. D 86, 084003 (2012)
- A. Kurkela et al, Astrophys. J. 789, 127 (2014)
- E. R. Most et al, Phys. Rev. Lett. 120, 261103 (2018)
- E. Lope Oter et al, J. Phys. G 46, 084001 (2019)
- G. Raaijmakers et al, The Astrophysical Journal Letters, Volume 918 (2021), L29
- Sinan Altiparmak et al, Astrophys.J.Lett. 939 (2022) 2, L34
- Sabrina Huth et al, Nature volume 606, pages276–280 (2022)
- E. Annala et al, Nature Phys. 16, 907 (2020), Phys. Rev. X 12, 011058 (2022)
- Rahul Somasundaram et al, Phys.Rev.C 107 (2023) 2, 025801
- Márcio Ferreira et al, Phys.Rev.D 110 (2024) 6, 063018
- Asim Kumar Saha and Ritam Mallick, arXiv:2407.13149

Progress made on reverse engineering up to now



Taken from a talk by J.M. Lattimer at CSQCD 24, held in Kyoto, Japan

Inverting NS observation to EoS

- Semi-analytical
- Deep neural network
- Symbolic regression

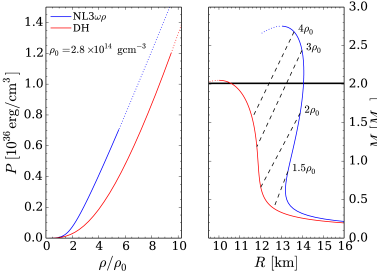
- Symbolic regression techniques to map mass-radius-tidal deformability to nuclear matter parameters, key quantity to define EoS. Sk Md Adil Imam et al, arxiv: 2407.08553 (accepted in PRD)
- Using Power-law inversion of mass-radius to EoS.
  The dimensionless functions f_M, f_R, and f_c have the generic form

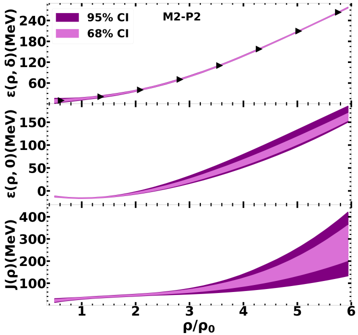
$$f_i = c_i \left(\frac{P_{\rm TOV}}{\rho_0 c^2}\right)^{a_i} \left(\frac{\rho_{\rm TOV}}{\rho_0}\right)^{b_i} + d_i.$$

  Dmitry D. Ofengeim et al, arXiv:2404.17647
- Reconstruction of the EoS via deep neural networks using mass-radius Shriya Soma et al, JCAP 08 (2022) 071
- Deep neural network from NS observations to nuclear matter properties, Valéria Carvalho et al, Phys.Rev.D 109 (2024) 12, 123038

Probing the interior of Neutron Stars

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





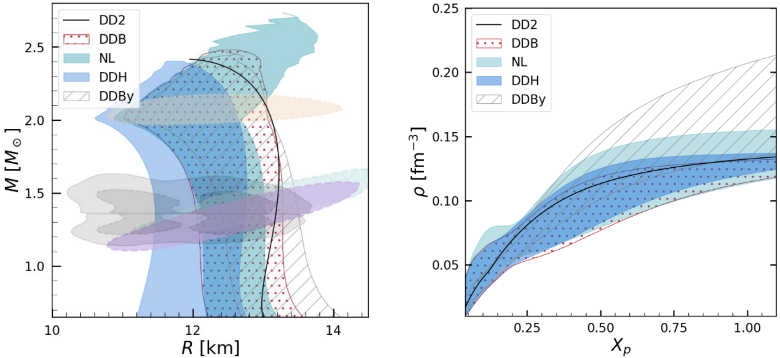
- hyperons?
- deconfined quark matter?
- dark matter?
- ~~or modified gravity?~~

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)

EOS Model Dependencies in Neutron Star Matter

(With Only Nucleonic Degrees of Freedom)

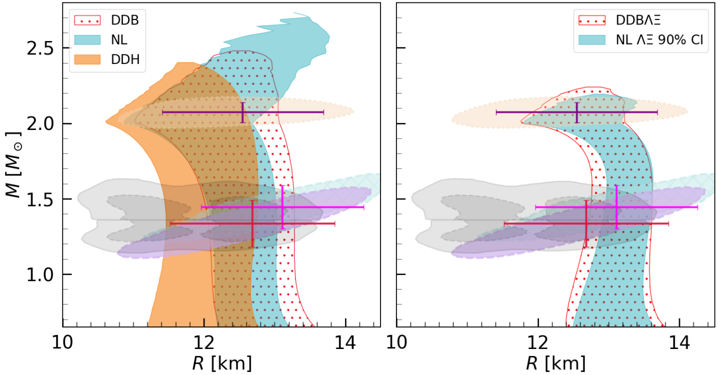


@ Providência *et all*, e-Print: 2307.05086 [nucl-th]

- The need for precise and diverse observational data is critical.
- Development of a generalized EOS model incorporating compositional information is essential.

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 $M_{\max}$.

An open-source package for neutron star whole workflow Bayesian inference constraining Neutron star EoS package

CompactOject (github)

An effort within the global neutron star physics community aims to develop an open-source package for EoS that incorporates a range of phenomenological EoS models.

- Contributors from UC:

  João Cartaxo, Tuhin Malik, Constança Providência

The impact of recent PSR J0437-4715 NICER measurements on EOS

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 study combinations of the above coupling schemes to :

1) Isolate each one of the three independent terms:

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

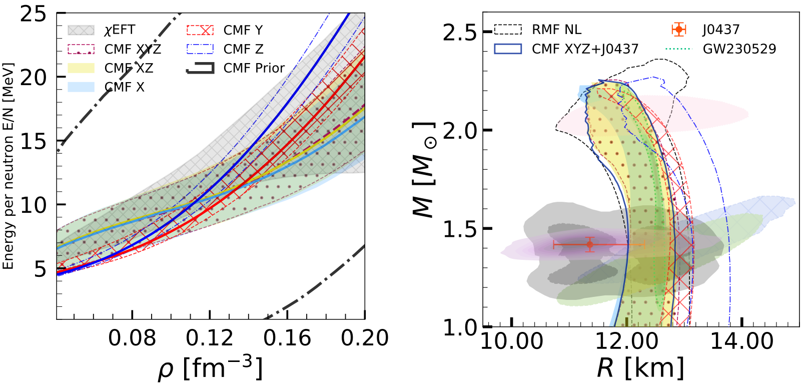
2)Consider the combination of two terms:

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

3) Consider a combination of the three terms:

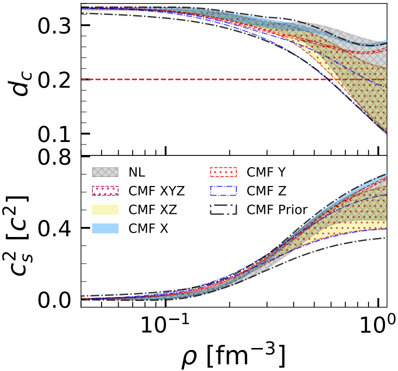
- **xyz**: $\mathcal{L}_{\rm vec}^{\rm Self} = x\rho^2\omega^2 + y\rho^4 + z\omega^4$;

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.



- 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),

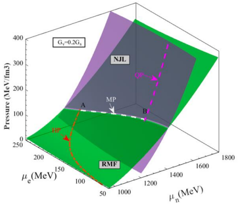
- Identification of deconfined matter with $d_c < 0.2$ are not unique: Models of nuclear matter (CMF model) with no deconfinement, may exhibit similar properties. The term ω^4 drives this behavior.
- The Bayes factors $\ln K_{\mathrm{xyz,xz}} = 0.05$, $\ln K_{\mathrm{xyz,x}} = -0.73$, $\ln K_{\mathrm{xyz,y}}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

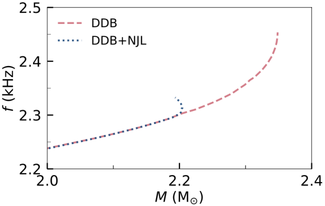
Neutron Star EOS: Future

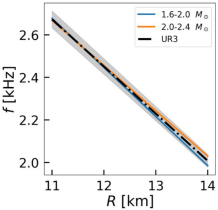
- How can we get the NS composition? Include observations sensitive to composition.

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

The f – mode oscillation frequencies

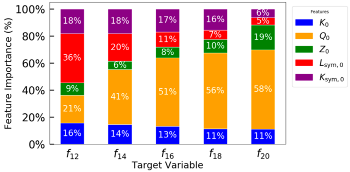






Very strong correlation

Deepak Kumar et all, arxiv 2402.03054



The footprint of nuclear saturation properties on f mode oscillation frequency

Reference

1. Deepak Kumar *et al* JCAP02(2023)015, PRD 108, 083008 (2023)

2. Debanjan Guha Roy *et al* 2024 *ApJ* **968** 124, Phys. Lett. B 859 (2024) 139128

3. Pratik Thakur et al, PRD 110, 103045 (2024)

4. Bikram Keshari Pradhan et all, Mon.Not.Roy.Astron.Soc. 531 (2024) 4, 4640-4655

5. Athul Kunjipurayil et all, PRD 106 (2022) 6, 063005

Collaborators

- Hiranmaya Mishra, Deepak Kumar (India)
- T. K. Jha, N.K. Patra (China), Prashant Thakur, Harsh Chandrakar (India)
- B. K. Agrawal (India), Sk Md Adil Imam (Chile)
- Sarmistha Banik, Debanjan Guha Roy, Anagh Venneti, Swastik Bhattacharya (India)
- Veronica Dexheimer (USA)
- Arpan Das (India)
- Débora P. Menezes, Lavínia Gabriela Teodoro dos Santos (Brazil)

Acknowledgments

- This work was supported by national funds from FCT (Fundação para a Ciência e a Tecnologia, I.P, Portugal) under projects UIDB/04564/2020 and UIDP/04564/2020, with DOI identifiers 10.54499/UIDB/04564/2020 and 10.54499/UIDP/04564/2020, respectively, and the project 2022.06460.PTDC with the associated DOI identifier 10.54499/2022.06460.PTDC.
- Advanced Computing Project 2024.14108.CPCA.A3, RNCA, funded by the FCT, Portugal, and this work was produced with the support of Deucalion HPC, Portugal.

Thank You! Contact: `tm@uc.pt, tuhin.malik@gmail.com`