Constraining nuclear physics parameters using neutron star M-R measurements

Chun Huang
WUSTL physics/UvA
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Collaborators: Anna Watts, Geert Raaijmakers, Laura Tolos, Constança Providência

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Contents

- Data we are using
  a) NICER mission
  b) Gravitational Wave detection

- Real physical model constrain
  a) RMF model construction
  b) Current observation study
  c) Future case study
  d) Future-X cases study

- Conclusion
How we constrain EoS

Micro physics

Equation of State

Mass and Radius

P(ρ) ↗

M ↗

ρ ↘

R ↘

Detectors

Neutron Star
Neutron star Interior Composition Explorer

NICER mission:

◮ “To the study of neutron stars through soft X-ray timing”
**J0030**

~1.4 solar masses

**J0740**

~2.1 solar masses
Neutron star Interior Composition Explorer

PSR J0030+0451 M-R (Riley+ 2019)

PSR J0740+6620 M-R (Salmi+ 2022) (update compared to Riley et al. 2021, uses NICER 3C50 background)
GW170817

- Neutron star tidal deformability and mass as observables.
How we constrain EoS

Micro physics

Equation of State

Mass and Radius

$P(r)$

$M$

$\rho$

$R$

Detectors

Neutron Star
How we constrain EoS

Micro physics

Equation of State

Mass and Radius

Neutron Star

Detections
How we constrain EoS

Micro physics

Equation of State

Mass and Radius

\[ P(\theta \mid D) \propto \pi(\theta)P(M, R \mid D) \]

Neutron Star

Detectors
How we constrain EoS

Equation of State

\[ P(\theta | D) \propto \pi(\theta) P(M, R | D) \]

Mass and Radius

\[ P(\rho) \]

\[ M \]

\[ \rho \]

\[ R \]

Detectors

Neutron Star
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Moving to a more physical EoS model

We would like to test a more physical EoS. Relativistic mean field theory construction:

- Hypothetical Lagrangian
  - sigma meson, rho meson, phi meson.....
  - neutron, proton, hyperon.....

- equation of motion

- EoS ingredients (P, rho)
  - things we need.....
Relativistic Mean Field Model

\[ \mathcal{L} = \sum_{b} \mathcal{L}_b + \mathcal{L}_m + \sum_{l} \mathcal{L}_l \]

\[ \sum_{N} \mathcal{L}_N = \sum_{N} \bar{\Psi}_N (i \gamma_{\mu} \partial^{\mu} - m_N + g_{\sigma} \sigma \]
\[ - g_{\omega} \gamma_{\mu} \omega^{\mu} - g_{\rho} \gamma_{\mu} \bar{I}_N \cdot \bar{\rho}^{\mu} ) \bar{\Psi}_N, \]

\[ \sum_{l} \mathcal{L}_l = \sum_{l} \bar{\psi}_l (i \gamma_{\mu} \partial^{\mu} - m_l) \psi_l, \]

\[ \mathcal{L}_M = \frac{1}{2} \partial_{\mu} \sigma \partial^{\mu} \sigma - \frac{1}{2} m_{\sigma}^2 \sigma^2 - \frac{\kappa}{3!} (g_{\sigma} \sigma)^3 - \frac{\lambda_0}{4!} (g_{\sigma} \sigma)^4 \]
\[ - \frac{1}{4} \Omega^{\mu \nu} \Omega_{\mu \nu} + \frac{1}{2} m_{\omega}^2 \omega_{\mu} \omega^{\mu} + \frac{\zeta}{4!} g_{\omega}^4 (\omega_{\mu} \omega^{\mu})^2 \]
\[ - \frac{1}{4} \bar{R}^{\mu \nu} \cdot \bar{R}_{\mu \nu} + \frac{1}{2} m_{\rho}^2 \bar{\rho}_{\mu} \cdot \bar{\rho}^{\mu} + \Lambda_{\omega} g_{\rho}^2 \bar{\rho}_{\mu} \cdot \bar{\rho}^{\mu} g_{\omega}^2 \omega_{\mu} \omega^{\mu}, \]

- FSU2R, Z272v, FSU, IUFSU, TM1\_\omega_{\rho}, TM1e, TM1-2\_\omega_{\rho} and Big Apple.... Many EoS model are based on this same framework.

- Since all of them are in the same framework, we can do direct evidence computation for each of them using Bayesian inference.
Free Parameters

RMF construction

\[ \kappa \quad \lambda \quad \zeta \quad \Lambda_\omega \quad g_{\sigma N}^2 \quad g_{\rho N}^2 \quad g_{\omega N}^2 \quad m_\rho \quad m_\omega \quad m_\sigma \]

= Infinite number of Nucleonic EoS models

\( \sigma \) meson self interaction  

quadratic self-coupling of the \( \omega \) meson
Combining all current observations:
GW events (GW190425, GW170817), NICER results (J0030, J0740), Radio timing (J0740 mass)

Prior distribution:
➢ Reflect our minimum knowledge.
“Flat”: we know nothing but hard cut
“Gaussian”: some value we believe is more likely

Combining all current observations:
GW events (GW190425, GW170817), NICER results (J0030, J0740), Radio timing (J0740 mass)
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➢ We are sensitive to zeta, since it determines the stiffness.
Combining all current observations: GW events (GW190425, GW170817), NICER results (J0030, J0740), Radio timing (J0740 mass)

➢ it is still **not possible** to extract **strong constraints** on all of the model parameters.
The importance of knowing radius ....

\[ \lambda_0 = 0.0033^{+0.0096}_{-0.0090} \]

\[ \zeta = 0.0227^{+0.0048}_{-0.0048} \]

➢ It is good to know that **single radius** measurements can have such a significant effect.
Model comparison

Using the three decoupled parameters, we can compute evidences for different models, and test their reliability given the current observations. Some of them appear to be disfavoured.
Proton fraction and speed of sound

We can derive the proton fraction (related to cooling) and speed of sound constraints from current observations.
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**WHAT IF WE TRIED MORE POWER?**
Larger effective area, broader band coverage than NICER
Proposal being prepared for NASA Probe-class mission call due November 2023
eXTP: a future China-EU X-ray mission to study matter under extreme conditions
Future case: near future capability

[1, 2, 1.4, 1.9, 2.0, 2.1, 2.2] $M_\odot$, PSR J0740+6620 (2.1 $M_\odot$), PSR J1614-2230 (1.9 $M_\odot$) and PSR J0437-4715 (1.4 $M_\odot$).

- six +/- 5% uncertainty M-R measurements along two different “ground-truth” EoS. **ONLY consider the X-ray (M-R) measurements**
With six 5% M-R measurements, the constraint is comparable to that achieved by current multi-messenger observations.
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Future-X case:

- $[1, 2, 1.4, 1.9, 2.0, 2.1, 2.2] \, M_{\odot}$, PSR J0740+6620 (2.1 $M_{\odot}$), PSR J1614-2230 (1.9 $M_{\odot}$) and PSR J0437-4715 (1.4 $M_{\odot}$).

- Six +/- 2% uncertainty M-R measurements for two different “ground-truth” (injected) EoS. This is a “best-case” study.
➢ With six 2% measurements, all of the parameter distributions start to be re-shaped, which means they are being constrained by the observations.
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The central value of the distribution will become closer to the “ground-truth” value.

Our inference recovers the injected EoS!
Conclusions

➢ We have considered a **microscopic nuclear model** based on a field theoretical approach. and derive constraints from
  - All current observations,
  - Future observations (Future)
  - Best-case future observations with e.g. STROBE-X/eXTP (Future-X)

➢ With Current observations, we can constrain on the **proton fraction** and **speed of sound**, can compute **evidence** for all the models based on the same framework.

➢ When upgrading to the Future case, it just **comparable** with current multi-messenger observation constraint (using M-R alone, so we can crosscheck with GW).

➢ When upgrading to the Future-X case, we can constrain the **whole parameter space** and **recover** the underlying EoS using X-ray observations alone.

➢ Next, Hyperon degrees of freedom will be added! We want to explore how future observations could inform this – important work for science case for future missions.
Thanks !!!