Constraining Hyperon couplings from Gravitational Waves

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Introduction

Nearly about a decade back (2015), with the first Gravitational Wave observation (GW150914: Binary Black Hole merger) [1] by LIGO-Virgo collaborations, opened a new window to the Universe fondly called as the multi-messenger era in Astronomy & Astrophysics and cosmology. Similarly, GW170817 was the first GW observation from coalescence of binary neutron stars [2] that provided vital inputs to constrain the theoretical aspects of the underlying equation of state (EoS). For example, the total mass inferred was estimated to be (2.73 - 3.29) $M_\odot$, where the primary component is (1.36 - 2.26) $M_\odot$ and the secondary component is (0.86 - 1.36) $M_\odot$, very much within the range expected from neutron stars/ pulsars. The compactness parameter of such a system is constrained as well, in terms of the inferred radius of the canonical 1.4 $M_\odot$ object which turns out to be 14 km. Interestingly, the observation was also complimented by with several other wavelengths such as γ-rays, X-rays, UV, IR and Radio, leading to plethora of information about such systems. Therefore we would like to investigate the global properties of such compact systems using the chiral effective field theory and generate hyperon rich matter and the underlying EoS to be compared with several other GW inferences. Our work delineates the strength of the hyperon couplings required to achieve the massive configurations thereby constraining the radius and tidal deformability as well.

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Theoretical Framework

The effective Lagrangian of the model where nucleon doublet interacts through the exchange of the pseudo-scalar meson π, the scalar meson σ, the vector meson ω and the iso-vector $\rho-$meson is described in detail in [3]. The model is then generalized to include the octet of baryons ($B = n^0, p^+, \Lambda^0, \Sigma^{+,0,-}, \Xi^{-,0}$) along with leptons ($L = e^-, \mu^-$) and the energy density and pressure is calculated, which serves as an input to the hydrostatic equilibrium condition to give us the star properties such as Mass, Radius and Tidal deformability in the static limit. In the hyperon sector we vary the scalar coupling keeping it alike for all the hyperon species and tune the vector counterpart so as to reproduce the respective hyperon potentials. The binding energy of the hyperon species in symmetric nuclear matter can then be reproduced by the equation,

$$\left(\frac{B}{A}\right)_H = x_{\omega H} g_{\omega N} \omega_0 + m_H^* - m_H, \quad (1)$$

where $m_H^* = m_H \times Y$ is the effective mass of a particular hyperon species in matter. Recent experimental data indicates that the Λ and the Ξ are bound with $-28MeV$ and $-14MeV$ respectively. However, there is large uncertainty in the Σ sector. Various studies suggests the range $-10 \leq U_\Sigma^N \leq 50$ MeV. In the present work, we fix the Σ coupling by varying the potential depth to $U_\Sigma = 30$ MeV. The density at which the octet of baryons will appear depends on the chemical equilibrium of the two species, i.e., μ_n & μ_e, as,

$$\mu_B = \mu_n - Q_B \mu_e, \quad (2)$$

where Q_B is the electric charge of the concerned baryon species.

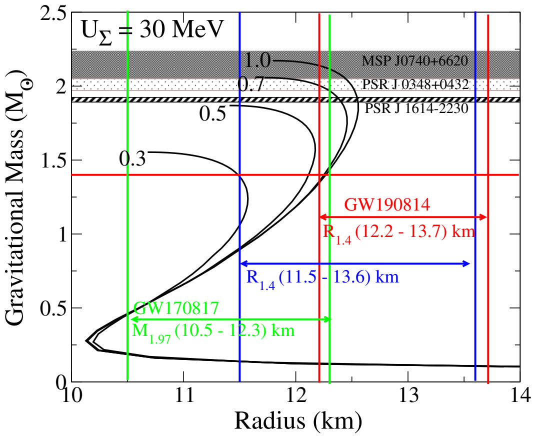

FIG. 1: Neutron star Mass-Radius curve for the choice of couplings as mentioned. The radius constraints obtained from few GW events as indicated and the canonical value $R_{1.4}$ ($M = 1.4M_{\odot}$) is also indicated.

Results & Discussion

In Fig. 1, we plot the Mass-Radius profile of sequence of neutron stars for different couplings and compare them with available constraints. We required $x_{\sigma H} > 0.5$ in order to obtain high mass non-rotating neutron star configuration and satisfy the maximum mass constraint. Our results also agree with the most probable radius ($R_{1.4}$) limits on canonical mass $1.4M_{\odot}$ pulsar as shown. It is to be noted that the secondary component of the GW190814 if assumed to be the most massive pulsar observed till date, then $R_{1.4}$ is limited to ($12.2 - 13.7$ km). The present model predicts $x_{\sigma} > 0.5$ to satisfy this constraint. Similarly for a pulsar of $1.97M_{\odot}$, GW data predicts the radius to be within ($10.5 - 12.3$km). Overall, all of these constraints combined, we limit $0.5 < x_{\sigma} < 0.7$ within the limitations of the model. In Fig. 2 we plot the tidal deformabilities in the phase space of Λ_1 and Λ_2 associated, respectively, with the high-mass m_1 and the low-mass m_2 components of the binary, for the models considered. The curves corresponding to every EoS are obtained by varying the high mass (m_1) independently in the range $1.365 < m/M_{\odot} < 1.60$, whereas the

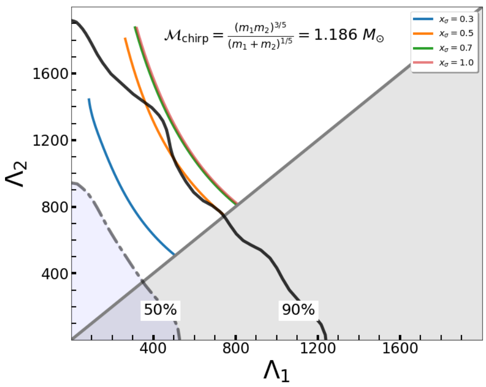

FIG. 2: Individual tidal deformabilities Λ_1 (high mass) and Λ_2 (low mass) components of neutron star binary of the observed GW170817. The 90% and the 50% confidence lines correspond to the low-spin priors.

low mass (m_2) is determined by keeping the chirp mass $\mathcal{M} = (m_1 m_2)^{3/5}(m_1 + m_2)^{-1/5}$ fixed at the observed central value 1.188 $M_{\odot}$ [**?**]. The 90%(solid black) and 50% (dashed black) confidence lines are the bound obtained from GW170817 observation. We find that the EOS for $x_{\sigma} = 0.5$ agrees with the 90% confidence limit obtained for GW170817. It is to be noted that our results are for the static case ($\Omega = 0$). One must correlate the findings in the present work to that of the saturation properties particularly to the dependence on the symmetry energy especially high densities.

References

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[**3**] Malik, Tuhin et.al., Phys. Rev. C **96**, 035803 (2017).