# 8
# Conclusions

## 8.1 Summary:

To comprehend compact object systems such as NSs, comprehensive knowledge and insight of the EoS of isospin asymmetric matter is vital. We implement the phenomenological Relativistic Mean-Field theory model to fix every pros and con of exotic matter interaction and describe the particle interactions in the dense matter at high-density regimes. This work incorporates the non-linear scalar and density-dependent coupling schemes within the framework of the RMF theory model. The following objectives have been addressed in this thesis:

- We investigated the condensation of (anti)kaons in $\beta$-equilibrated nuclear matter and found it to be feasible in dense matter for an allowed range of (anti)kaon optical potentials ($-160 \leq U_{\bar{K}} \leq -120$ MeV) in chapter-3. The functionals in the kaonic sector are constrained by the experimental studies on $K^-$ atomic, kaon-nucleon scattering data fits. Based on the (anti)kaon optical potential, the proton fraction in dense matter is affected, leading to asymmetries in the interior to NSs. We also reported a first-order phase transition of (anti)kaon condensation in NS matter, fulfilling current mass-radius constraints.

- In chapter-4, we studied the effect of (anti)kaon condensation on the properties of compact stars that develop hypernuclear cores with and without an admixture of $\Delta$-resonances. Here, the meson-hyperon couplings are adjusted to the fits from $\Lambda$ and $\Xi^-$ hypernuclei data and, for $\Delta$-resonances sector, the couplings are tuned to the data obtained from heavy-ion collision experiments. We found that (anti)kaon condensate leads to softening the EoS and lower maximum masses of compact stars than in the absence of the condensate. Both the $K^-$ and $\bar{K}^0$-condensations occur through a second-order phase transition, implying no mixed-phase formation. For large values of (anti)kaon and $\Delta$-resonance potentials in symmetric nuclear matter, we observe that condensation leads to the extinction of $\Xi^{-,0}$ hyperons. Moreover, the onset of $\Delta$-baryons shifts hyperon thresholds to larger matter densities. Inclusion of heavier baryons and (anti)kaons leads to further constrainment of (anti)kaon optical potential range as well ($-150 \leq U_{\bar{K}} \leq -120$ MeV). Due to the uncertainty of $\sigma^*$-meson role in dense matter behaviour, we also investigated the influence of inclusion of this additional hidden-strangeness meson in the functional. We found that it leads to a substantial softening of the equation of state and delay in the onset of (anti)kaons.

- The nuclear matter properties and astrophysical constraints have strongly impacted ruling out the coupling parametrization models. This point was approached in chapter-5. It was observed that allowing the inclusion of heavier strange and non-strange baryons along with the strict bounds from gravitational waves and massive NS observations constrain theoretical models of nuclear matter behavior in the high density regimes. Considering non-nucleonic degrees of freedom in NS matter composition, most of the NL Walecka type coupling schemes do not support the bounds from astrophysical observations as well as terrestrial experiments, while most of the DD coupling parametrizations satisfy these mentioned bounds. Astrophysical observations are well explained if heavier non-strange baryons are included as one fraction of the dense matter particle spectrum. We reported that for a 1.5 $M_{\odot}$ neutron star, the stringent limits on gravitational wave observables translates to an allowed radius range $11.89 \leq R_{1.5}/\text{km} \leq 12.98$. And based on robust analysis of these EoS models, the lower bound on compactness parameter for a canonical 1.4 $M_{\odot}$ NS is inferred to be $C_{1.4} \geq 0.1608$.

- The effects of nuclear symmetry energy on neutron star dense matter EoS considering exotic degrees of freedom and its impact on NS observables are reported in chapter-6. The slope of symmetry energy parameter ($L_{\text{sym}}$) is adjusted following a density-dependence of isovector meson coupling to baryons. We found that smaller values of $L_{\text{sym}}$ at saturation favour the early appearance of $\Delta$-resonances in comparison to hyperons leading to the latter's threshold at higher matter densities. Thus, based on recent PREX-2 data implying $L_{\text{sym}}(n_0)$ to be in the range $69-143$ MeV, the heavier non-nucleonic degrees of freedom incorporated in this work are comparatively shifted to higher matter density regimes. The dependence of $L_{\text{sym}}$ on tidal deformability and compactness parameter of a canonical 1.4 $M_{\odot}$ NS for different EoSs were analysed, and similar converging behaviour for larger $L_{\text{sym}}$ values was observed.

- A particular class of NSs, namely *magnetars* are reported to possess very large surface magnetic fields in the range of $10^{14}$-$10^{15}$ G. In chapter-7, we investigated the baryonic matter under an intense magnetic field within the framework of RMF theory. The strangeness fraction is enhanced and several matter properties viz. Dirac effective mass, particle abundances show oscillatory behaviour similar to de Haas–van Alphen oscillations in the presence of strong magnetic fields.

To summarize, this thesis work presents the novel aspects of new exotic degrees of freedom addition and its subsequent effects in dense matter EoS while satisfying the stringent constraints on NS astrophysical observables. Firstly, we discussed the possibility of mixed phase region with (anti)kaon condensed phase fulfilling the 2 $M_{\odot}$ mass constraint. Subsequently we estimated the admissible range of very vaguely known (anti)kaon optical potential in symmetric nuclear matter imposing the onset of heavier baryons. Next, we imposed the available terrestrial and astrophysical constraints on various RMF models in both DD and NLW coupling scenarios, thus screening out the parametrization sets to explain dense matter behavior. We also reported and emphasized on the importance of $\Delta$-resonances in dense matter in order to explain as well as satisfy the recent tidal deformability constraint. Also very recently, an updated value of $R_{\text{skin}}$ is reported from the PREX-2 experiment which estimates higher values of isospin parameters. In this thesis work, we also have discussed how the dense matter constituents behave with larger values of $L_{\text{sym}}$ and its subsequent effects on gross global NS properties. Finally, we have reported for the first time the effects of strong magnetic fields on the $\Delta$-admixed hypernuclear matter and discussed the subsequent alterations in microscopic properties of dense matter. Furthermore, a new mass constraint from PSR J0952 − 0607 has been reported in Ref.-Romani et al. [2022] with mass in the range of $2.18 - 2.52\ M_{\odot}$ at $1 - \sigma$ confidence interval. The evaluated dense matter EoSs in our work satisfy this recent mass limit.

## 8.2 Future perspectives:

Further studies are required in constraining the parameter sets of different particle interactions in dense matter. In this regard, the possible extensions of our work can be quantified as:

- The role of yet another possible but not entirely understood boson condensation viz. pion condensation in dense matter regimes can be studied within the framework of phenomenological models.

- In this study, we have not considered rotational effects on NS structure solutions. The role of rotation together with strong magnetic fields may prove to be an exciting study.

- We have explored the temperature-independent ($T = 0$) case in this thesis. We can further study and explore the thermal ($T \neq 0$) effects on dense matter EoSs.

- The updated PREX-2 data implied the range of $L_{\rm sym}$ at $n_0$ to be relatively higher in comparison to earlier studies. This affects the NS radius and tidal response, moving it exterior to the GW bounds. To release this tension, we can explore and recalibrate the coupling parameter sets to constrain dense matter behaviour.

- The observations of the kinematics of vast astrophysical entities viz. galaxies, clusters of galaxies imply the presence of another exotic particle, dark matter (DM). A fascinating study will be to model the NS EoS with DM and heavier strange and non-strange baryons within the phenomenological model theory.

In a nutshell, the study of compact objects such as NSs remains very attractive for nuclear theorists and astrophysicists. A handsome load of work is yet to be accomplished in this particular domain, despite enormous and significant studies reported in the past. Comprehending the role of exotic degrees of freedom of the particle spectrum interior to NSs can shed light on the high-density matter behaviour and the phase transitions that can happen at such extreme conditions.