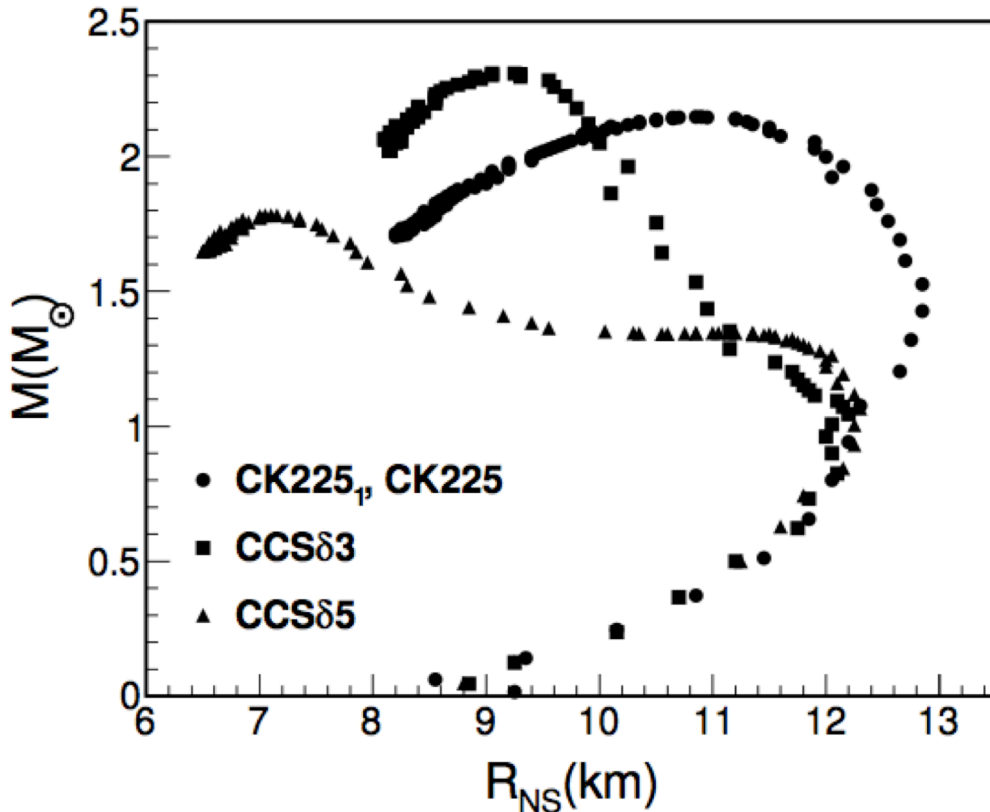


## Neutron stars in the framework of Landau's theory

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A general formula of the symmetry energy for many-body interaction is proposed and the commonly used two-body interaction symmetry energy is recovered. Within Landau's theory (Lt), we generalize two equations of state (EoS) CCS $\delta$ 3 and CCS $\delta$ 5 to asymmetric nuclear matter. We assume that the density and density difference between protons and neutrons divided by their sum are order parameters. We use different EoS to study neutron stars by solving the TOV equations. We demonstrate that different EoS give different mass and radius relation for neutron stars even when they have exactly the same ground state (gs) properties ( $E/A$ ,  $\rho_0$ ,  $K$ ,  $S$ ,  $L$  and  $K_{\text{sym}}$ ). Furthermore, for one EoS we change  $K_{\text{sym}}$  and fix all the other gs parameters. We find that for some  $K_{\text{sym}}$  the EoS becomes unstable at high density even for neutron matter. This suggests that a neutron star (NS) can exist below and above the instability region but in different states: a quark gluon plasma (QGP) at high density and baryonic matter at low density [1].

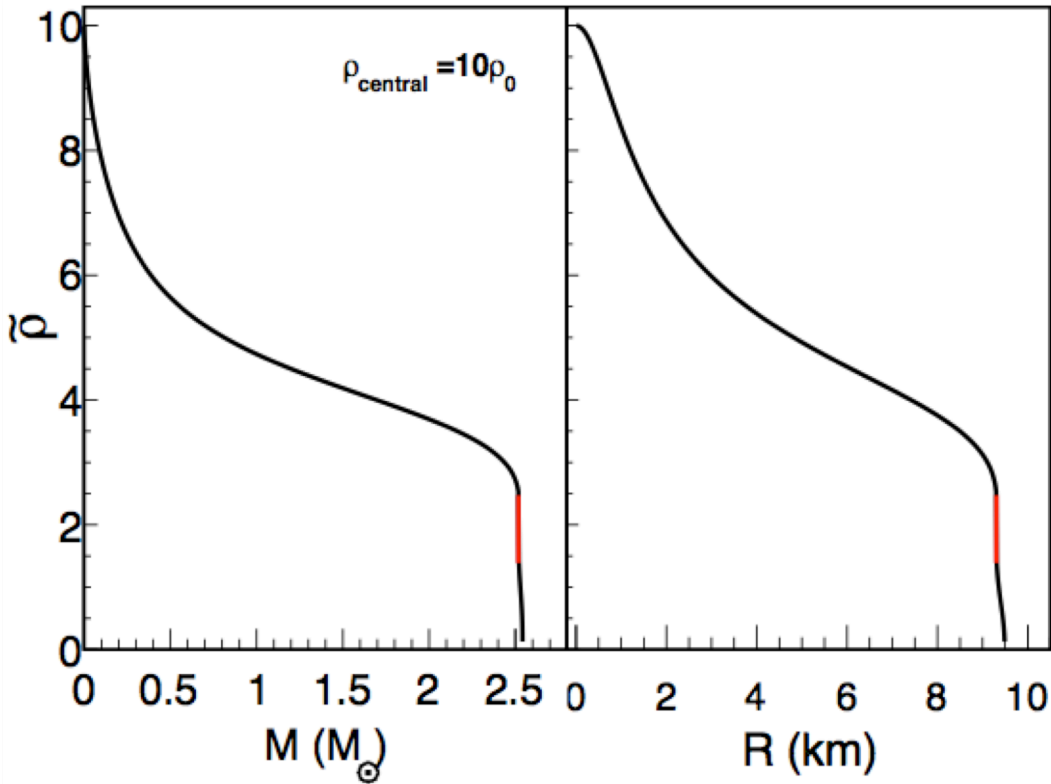
We fix incompressibility  $K=225$  MeV, symmetry energy  $S=28.5$  MeV, and the slope of symmetry energy  $L=73$  MeV from Skyrme EoS CK225 $_1$  [1]. In this case, EoS CK225 $_1$ , CK225 and CCS $\delta$ 3 have the same values for  $K$ ,  $S$ ,  $L$  and  $K_{\text{sym}}$ . This motivates us to fix the same values of  $S$ ,  $L$  and  $K_{\text{sym}}$  for EoS CCS $\delta$ 5. For the four EoS, CK225 $_1$ , CK225, CCS $\delta$ 3 and CCS $\delta$ 5, we solve the TOV equations for the PNM to obtain the mass-radius relation of neutron stars. The results are shown in Fig. 1.



**FIG. 1.** The NS mass-radius relation for CK225 $_1$ , CK225, CCS $\delta$ 3 and CCS $\delta$ 5 with same values of  $K=225$  MeV,  $S=28.5$  MeV,  $L=73$  MeV and  $K_{\text{sym}} = -25$  MeV.

We can see that the mass-radius relations for the neutron stars are different for the four EoS (CK225<sub>1</sub> and CK225 are the same in this case) even though they have the same values of  $K$ ,  $S$ ,  $L$  and  $K_{\text{sym}}$ . This indicates that the mass-radius relation of the NS is not only determined by  $K$ ,  $S$ ,  $L$  and  $K_{\text{sym}}$ , but the high density dependence of the EoS is crucial. We also notice that there are wiggles in the mass-radius relation of PNM NS for CCS $\delta$ 3 and CCS $\delta$ 5 rather than CK225<sub>1</sub> and CK225 because of a cross-over at high density for the two EoS. Thus, the second order PT assumed in deriving CCS $\delta$ 3 and CCS $\delta$ 5 becomes cross-over for these parameters choice. The maximum mass of the NS for CCS $\delta$ 3 is larger than the one for CK225<sub>1</sub> or CK225. The reason for this is because of the higher power of  $\rho$  in CCS $\delta$ 3 compared to CK225. But the maximum mass of the NS for CCS $\delta$ 5 (which contains even higher power density values) is lower than the one for CCS $\delta$ 3. The ‘missed phase transition’ or cross-over softens the EoS and causes the pressure for CCS $\delta$ 5 to decrease compared to the one for CCS $\delta$ 3 at the same density.

The EoS CCS $\delta$ 5 displays an instability when  $K_{\text{sym}} = -215 \text{ MeV}$  corresponding to a first order PT. In this case the TOV equations cannot be solved in the instability region. We have used the Maxwell construction to determine the densities where the two phases (which we call phase A and B) are separated. In Fig. 2, we plot the results obtained solving the TOV equations when the central density is  $10\rho_0$ .



**FIG. 2.** The density profiles of a neutron star with central density  $10\rho_0$  for EoS CCS $\delta$ 5 when  $S = 28.5 \text{ MeV}$ ,  $L = 50 \text{ MeV}$  and  $K_{\text{sym}} = -215 \text{ MeV}$ . The red lines are the Maxwell construction in the instability region.

[1] H. Zhang, J. Sahagun, and A. Bonasera, arXiv: 1411.3030.