Neutron star matter based on a parity doublet model including the a_0(980) meson

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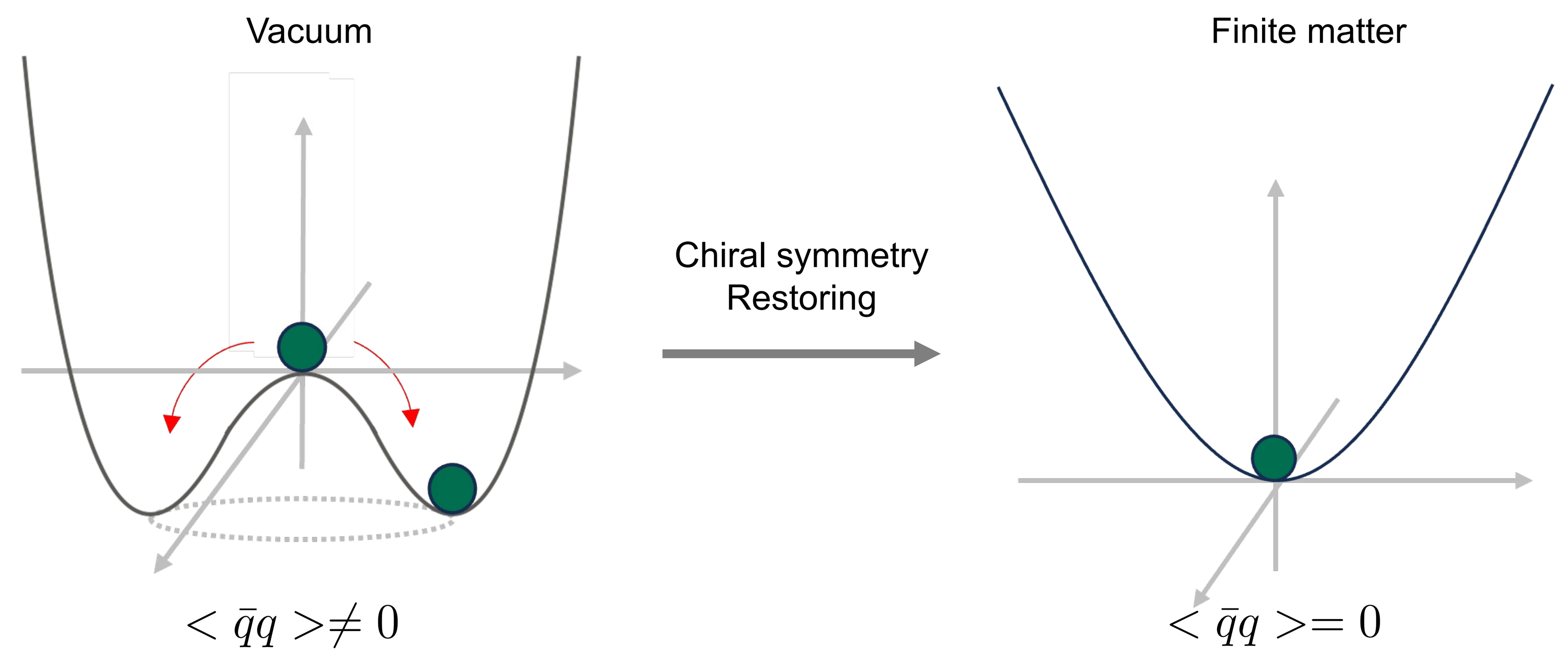
Background

It is known that the mass of hadrons is generated by the spontaneous breaking of chiral symmetry. In recent years, increasing experimental evidences show that the chiral symmetry is restored in high temperature and/or high density QCD matter.



In effective models such as linear sigma model [1], the mass of nucleon is given by

$$m_N \propto < \bar{q}q > \longrightarrow 0 \ ?$$

However, studies such as lattice QCD calculation [2] shows that nucleons (neutron and proton) seems to process non-zero mass in very high temperature where chiral symmetry is restored. It is thus in deep interest to study this phenomenon also in high density matter.

Parity doublet model with a_0(980) meson

In our work, we study the mass of nucleons in finite density matter using a model called Parity doublet model (PDM). PDM is a hadronic model that consider the parity doubling of nucleons. The Lagrangian is given by

$$\mathcal{L} = \mathcal{L}_M + \mathcal{L}_N + \mathcal{L}_V$$

where the scalar meson Lagrangian $\mathcal{L}_M$ is constructed using linear sigma model (see [3] or the QR code) and the vector meson Lagrangian $\mathcal{L}_V$ is constructed using hidden local symmetry [4,5] with isotriplet ρ meson and isosinglet ω meson. In the present work, the scalar meson field M is introduced as the $(2, 2)_{-2}$ representation under the $SU(2)_L \times SU(2)_R \times U(1)_A$ which is parametrized as

$$M = [\sigma + i\vec{\pi}\cdot\vec{\tau}] - [\vec{a_0}\cdot\vec{\tau} + i\eta]$$

The nucleon Lagrangian is given by [6]

$$\mathcal{L}_N = \bar{N}_1 i\partial\!\!\!/ N_1 + \bar{N}_2 i\partial\!\!\!/ N_2 - m_0[\bar{N}_1\gamma_5 N_2 - \bar{N}_2\gamma_5 N_1] - g_1[\bar{N}_{1l} M N_{1r} + \bar{N}_{1r} M^\dagger N_{1l}] - g_2[\bar{N}_{2r} M N_{2l} + \bar{N}_{2l} M^\dagger N_{2r}]$$

By considering two baryons with opposite parity, a mass-like term is allowed without breaking the chiral symmetry explicitly. In this work, the positive and negative parity partner is identified as N(939) and N(1535). In the mean field approximation, the mass of nucleons is then given by

$$m^*_{\alpha j} = \frac{1}{2}\left[\sqrt{(g_1+g_2)^2(\sigma - ja)^2 + 4m_0^2} + \alpha(g_1 - g_2)(\sigma - ja)\right] \ \to \neq 0$$

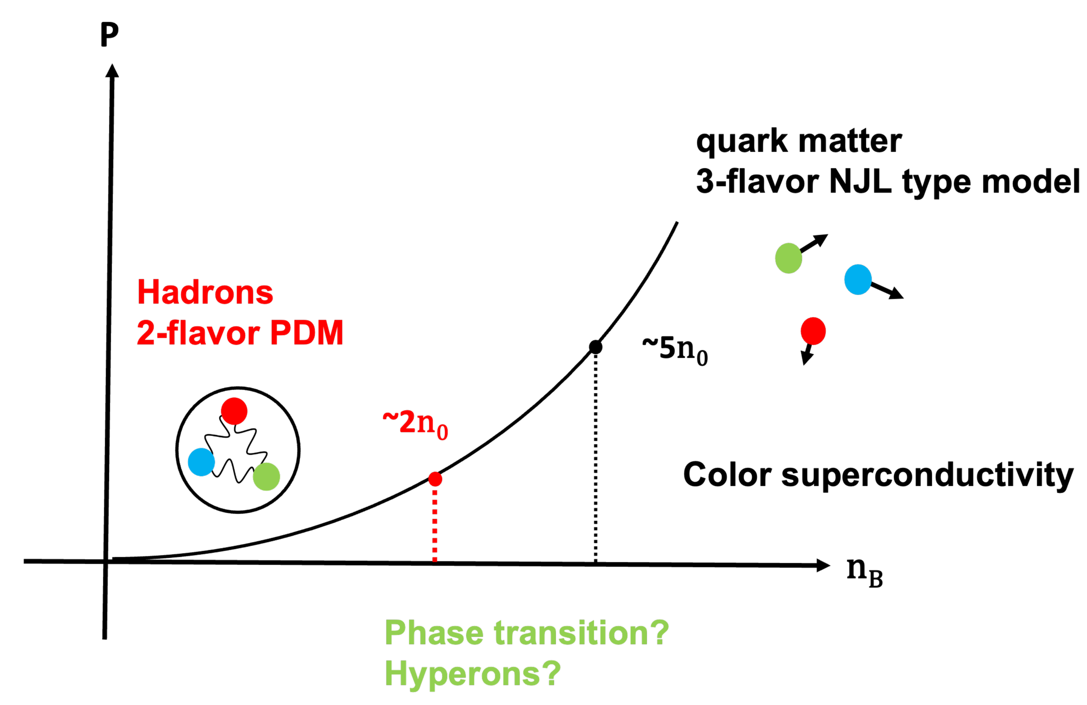
where α = ± denotes the parity and j = p, n the iso-spin of nucleons. *a* is taken to be the mean field of a_0(980) in the direction of iso-spin 3-axis. Since a_0(980) is an iso-vector scalar meson,

$$\vec{a_0} \sim \bar{q}\vec{\tau}q \to \bar{q}\tau_3 q \sim \bar{u}u - \bar{d}d$$

a_0(980) will appear in the asymmetric matter ($n_u \neq n_d$). **In this work, we study the effect of a_0(980) to the NS properties and constrain the chiral invariant mass of nucleons by comparing to the NS observational data.**

Unified equation of state of neutron star

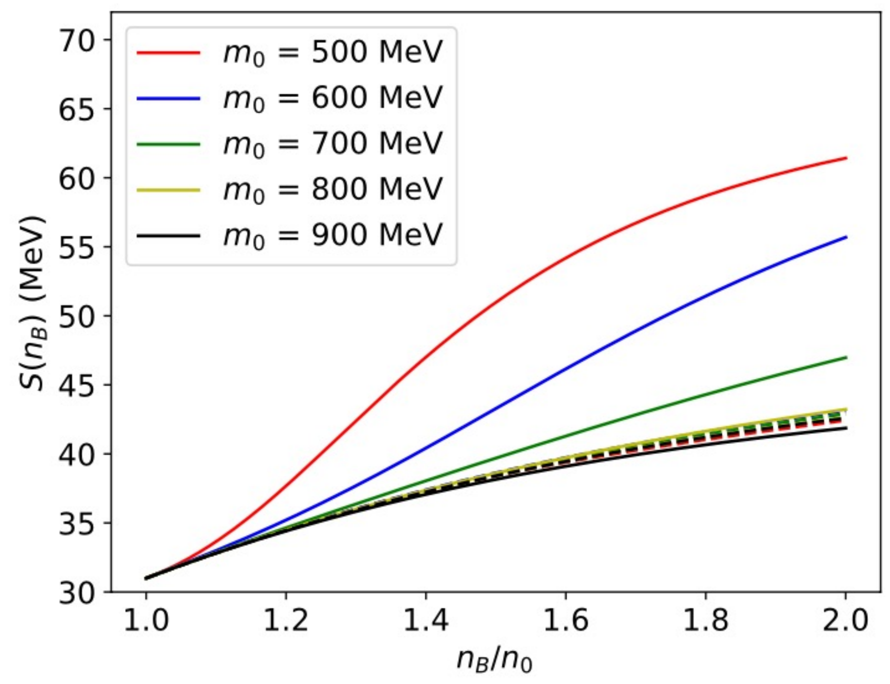
Neutron star (NS) is a very high-density star that mainly compose of neutron. As more observational data available, it provides us a new way to study the properties of hadrons. Many interesting phenomenon such as appearance of hyperons (hadrons with strange quark), QCD phase transition and color superconductivity etc. happen.

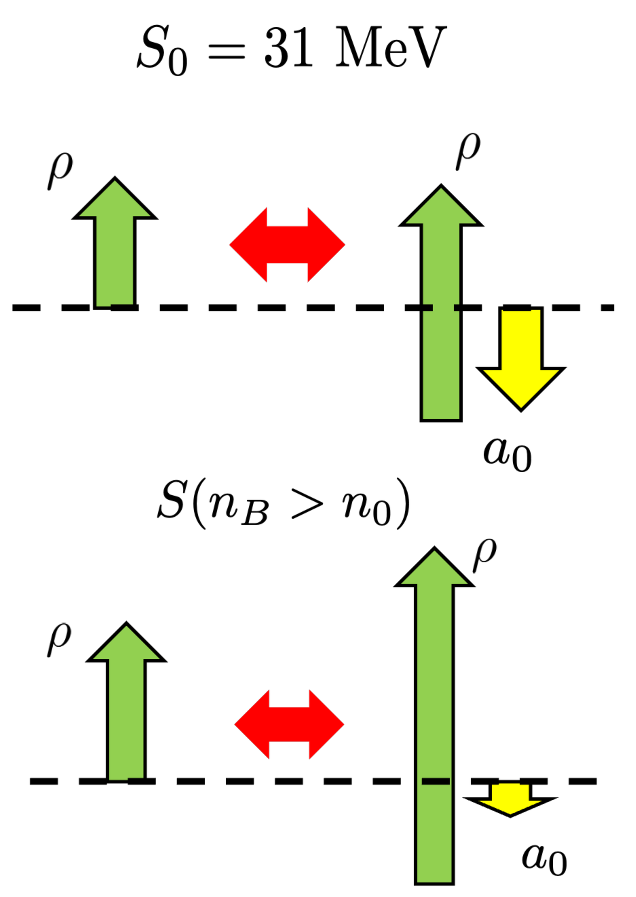


To simplify the model, we construct the NS equation of state (EoS) using the interpolation method as introduced in [7]. The Hadronic EoS is connected to a 3-flavor NJL type EoS by assuming a cross-over QCD phase transition.

Results

- Existence of a_0(980) increases the symmetry energy by strengthening the coupling of repulsive ρ meson

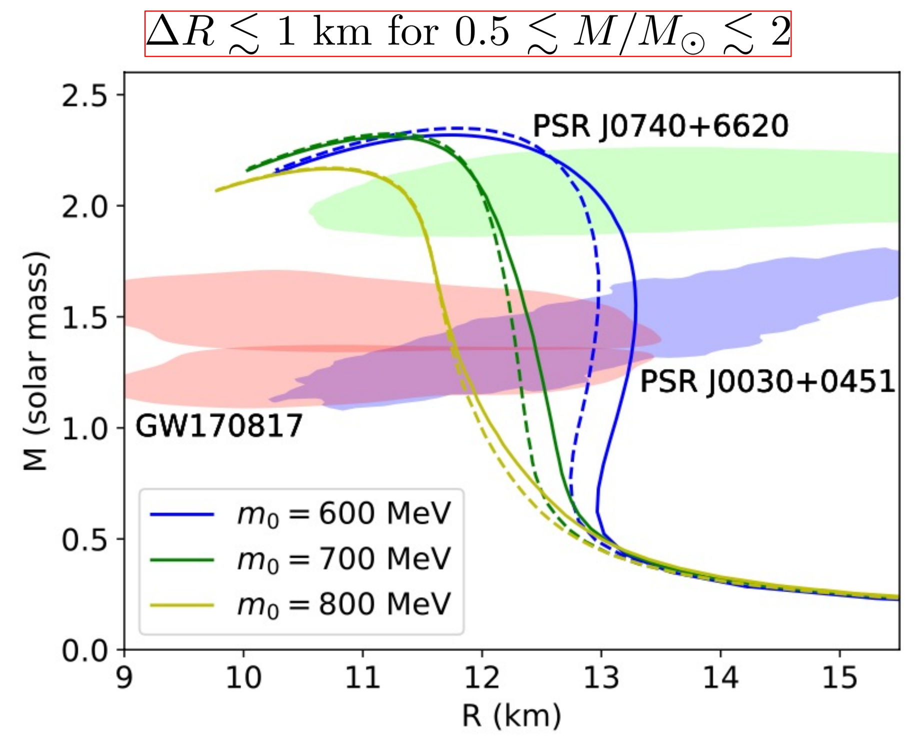




- The radius of intermediate mass NS is increased by existence of a_0(980)
- By comparing to the NS observational data, we constrains the chiral invariant mass to

$$580 \text{ MeV} \lesssim m_0 \lesssim 860 \text{ MeV}$$

$\Delta R \lesssim 1$ km for $0.5 \lesssim M/M_\odot \lesssim 2$



Conclusion

- **We find that the existence of a_0(980) increases the symmetry energy and stiffens the matter by strengthening the coupling of repulsive ρ meson in the iso-vector channel**
- **a_0(980) increases the radius of intermediate mass NS**
- **By comparing to the NS observational data, we constrained the chiral invariant mass to**

$$580 \text{ MeV} \lesssim m_0 \lesssim 860 \text{ MeV}$$

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