Twin neutron stars: probe of phase transition from hadronic to quark matter

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Overview of twin star scenario

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- Equations of state of dense matter are well determined up to nuclear saturation density
- Extreme conditions, favoring even denser forms of matter, are realized in the interior of compact stars
- Recent gravitational wave events bring to light new aspects of the internal structure of these stars
- Some of the events, especially GW170817, are consistent with the existence of hybrid stars, i.e. stars with core composed quarks and outer shells of hadronic matter [1],[3]

Overview of twin star scenario

- Under conditions, relevant to the hadron to quark phase transition, a so called twin star configuration might arise
- This configuration yield a third family of compact stars with the same mass as normal neutron stars or strange quark stars bur rather different radii [3]
- Discovering two compact stars with the same mass but different radii could be a signal of the existence of twin stars and, in turn, of a phase transition in ultra-dense matter [3]

Structure of hybrid stars

Outer shells and core

- The outer region of a hybrid star is mainly composed by hadrons
- Equations of state describing this region might assume the presence of a pure nucleonic phase (e.g. APR-1, APR-2) or the presence of hyperons as well (e.g. FSU2H)
- The core of these stars is composed of deconfined quarks [1], [2], [3], [4]
- The study of such a matter is usually done in the framework of MIT bag model or the Nambu-Jona-Lasinio model [1]. However, for systematic investigation of EOSs, a constant speed of sound (CSS) parametrization is more suitable [1], [2], [3], [4]

Phase transition

- The hadron to quark phase transition (HQPT) in considered of first order [1], [2], [3], [4]
- A common approach is to assume a polytropic EOS to describe it [1], [2], namely

$$p = K\rho^{\Gamma} \quad (1)$$

- In this way one can easily distinguish two different cases: The Maxwell Construction (MC), derived by imposing Γ=0 in (1), and the Gibbs Construction (GC), in which case $\Gamma \neq 0$
- In the former case, the hadron and quark phases are in direct contact with each other. On the contrary, GC assumes intermittent domains of hadrons and quarks, together composing the mixed phase

Maxwell Construction

Maxwell Construction I

- In MC, the energy density suffers a finite discontinuity at the point of transition [1], [2], [3]. Its profile reads [1], [3]

$$e(p) = \begin{cases} e(p)_{model} & p < p_{tr} \\ e(p_{tr})_{model} + \Delta e + \frac{p-p_{tr}}{c_s^2} & p \geq p_{tr} \end{cases} \quad (2)$$

where p is the pressure, c_s the speed of sound, Δe the discrete energy density jump and p_{tr} the value of pressure at the transition point

- In order for the third stable branch to be present, Seidov limit must be satisfied, namely [1], [2], [3]

$$\Delta e \geq \frac{e_{tr} + 3p_{tr}}{2} \quad (3)$$

where e_{tr} is the energy density at the transition point

Maxwell Construction II

- From the aforementioned parametrization (2), MC yields two free parameters: p_{tr} and Δe [1], [3].

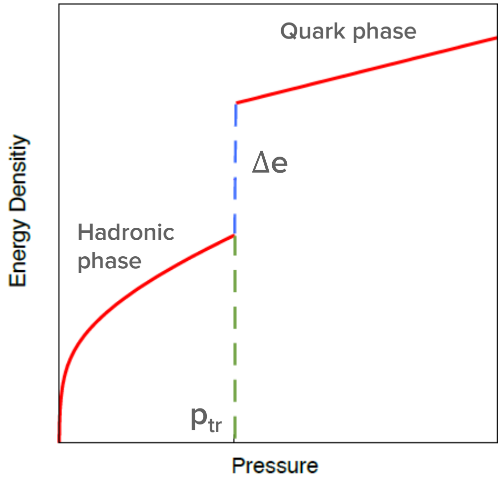


Figure 1: A schematic representation of the energy density profile in MC (2)

Gibbs Construction

Gibbs Construction I

- In GC, there are no discontinuities, in contrast to MC. Energy density profile reads [1]

$$e(p) = \begin{cases} e(p)_{model} & p < p_{tr} \\ \Lambda p^{1/\Gamma} + \frac{p}{\Gamma - 1} & p_{tr} \leq p \leq p_{css} \\ e(p_{css}) + \frac{p - p_{css}}{c_s^2} & p \geq p_{css} \end{cases} \tag{4}$$

  where p is the pressure, c_s the speed of sound, Λ is constant dependent on the model parameters and Γ the polytropic index. Subscripts *tr* and *css* denote the corresponding quantities at the start of the mixed phase and the quark phase respectively
- There is not explicit limit as (3) in this construction. ***Δe*** is not explicitly defined, but we assign to it the rise in energy density during the mixed phase

Gibbs Construction II

- This model also yields two free parameters: p_{tr} and the extension of the mixed phase Δp [1]

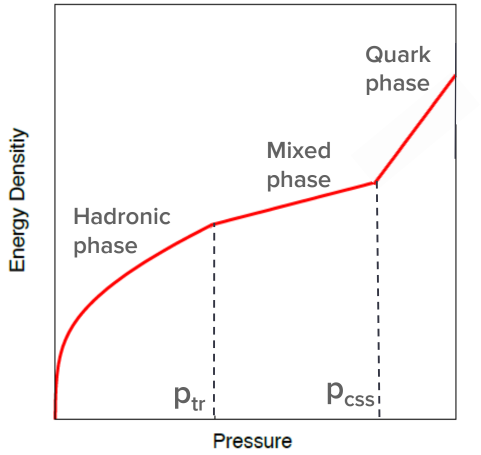
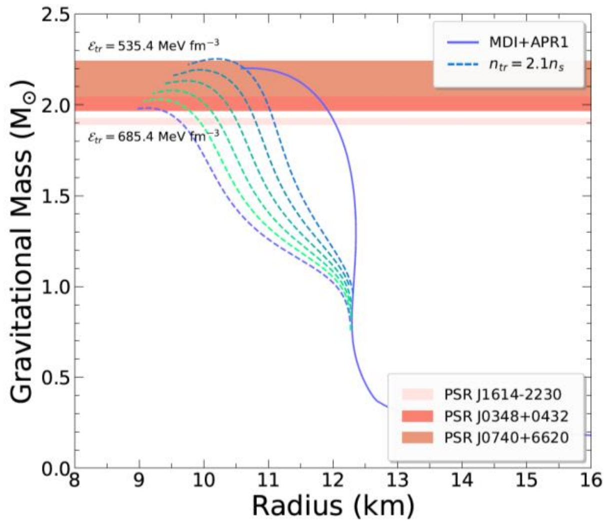


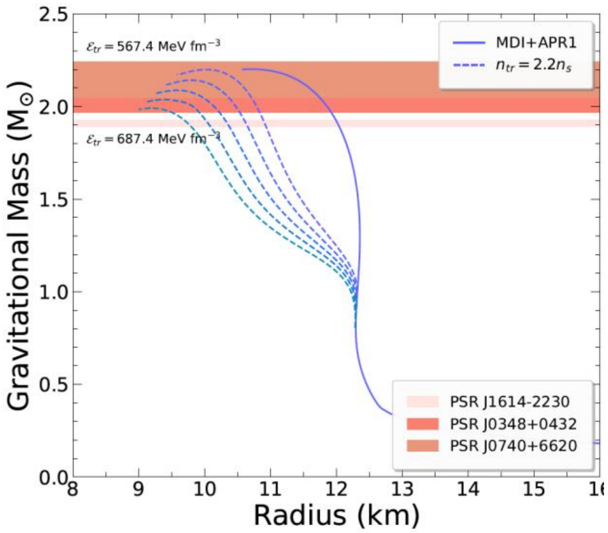
Figure 2: A schematic representation of the energy density profile in GC (4)

Results and conclusion

Results

- Mass-Radius diagrams using APR+MDI model for the hadronic shells and MC





- Figure 3: Primal results on mass-radius diagramms, using MDI+APR1 parametrization for the hadronic shells. The solid line corresponds to the absence of phase transition while the dashed lines correspond to the case of a phase transition assuming MC, for different values of the energy density at the transition point.

Conclusion

- Since our first results, presented previously, reproduce successfully key properties of neutron stars, such as the $M^{max}_{ns} \geq 2M_{o}$ in addition to R~13 km, they constitute a strong indication that a HQPT can exist

- Further improving such models can reveal robust features of super-dense matter, the impact of which affects many fields of study

- Lastly, the discovery of a third branch of compact stars will change what is known in astrophysics

Collaborators

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Sources

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Thank you!