Surface tension of quark droplets in compact stars

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We study the surface tension and curvature energy of quark matter in astrophysical conditions, focusing specifically on the thermodynamic conditions prevailing in cold neutron stars and in hot lepton rich protoneutron stars. We analyze quark matter in chemical equilibrium under weak interactions, which is relevant for understanding the internal composition of hybrid stars, as well as "just deconfined" quark matter out of chemical equilibrium, which is the relevant thermodynamic state for describing the nucleation process of quark matter in compact stars. We explore the role of temperature, density, trapped neutrinos, droplet size and magnetic fields within the multiple reflection expansion formalism (MRE). Quark matter is described within the frame of different effective models: the MIT bag model and the SU(3)f Nambu-Jona-Lasinio model (NJL), including color superconductivity and neutrino trapping in both cases. We used as well a mixture of free Fermi gases composed of u, d, s quarks and electrons in chemical equilibrium under weak interactions, for studying magnetized quark matter. We explore some astrophysical consequences of our results.

Finite-size effects are extremely relevant for neutron star physics:

- they determine whether a **mixed phase of quarks and hadrons** may appear inside hybrid stars. In this case matter is in equilibrium under weak interactions (beta equilibrium).
- they have a key role in the beginning of the conversion of a hadronic star into a quark star, because they regulate the **nucleation rate of the initial quark drops that trigger the conversion**. A just deconfined drop is nucleated out of beta equilibrium.
- Systems of strongly interacting matter under the influence of intense **magnetic fields** have direct application to the physics of neutron stars and the properties of quark gluon plasma produced in relativistic heavy ion collisions
- quark confinement at low energies , Polyakov loop in NJL model (PNJL)

MRE – finite volume

$$\int_0^\Lambda \cdots \frac{k^2\,dk}{2\pi^2} \longrightarrow \int_{\Lambda_{IR}}^\Lambda \cdots \frac{k^2\,dk}{2\pi^2}\rho_{MRE}.$$

$$\rho_{MRE}(k,m_f,R) = 1 + \frac{6\pi^2}{kR}f_S + \frac{12\pi^2}{(kR)^2}f_C$$

$$f_S = -\frac{1}{8\pi}\left(1 - \frac{2}{\pi}\arctan\frac{k}{m_f}\right)$$

$$f_C = \frac{1}{12\pi^2}\left[1 - \frac{3k}{2m_f}\left(\frac{\pi}{2} - \arctan\frac{k}{m_f}\right)\right]$$

$$\Omega_{MRE} = -PV + \alpha S + \gamma C,$$

$$P \equiv -\frac{\partial\Omega_{MRE}}{\partial V}\bigg|_{T,\mu,S,C} \qquad \alpha \equiv \frac{\partial\Omega_{MRE}}{\partial S}\bigg|_{T,\mu,V,C} \qquad \gamma \equiv \frac{\partial\Omega_{MRE}}{\partial C}\bigg|_{T,\mu,V,S}$$

$SU(2+1)_f$ NJL model

$$\mathcal{L} = \bar\psi(i\partial - \hat m)\psi + G\sum_{a=0}^{8}[(\bar\psi\tau_a\psi)^2 + (\bar\psi i\gamma_5\tau_a\psi)^2] + 2H\sum_{A,A'=2,5,7}[(\bar\psi i\gamma_5\tau_A\lambda_{A'}\psi_C)(\bar\psi_C i\gamma_5\tau_A\lambda_{A'}\psi)]$$

$$-\,\mathcal{U}(l,\bar l;T)$$

Including **Polyakov loop Potential**

MIT model

$$\Omega_Q = \sum_{c,f}\Omega_{cf} + \sum_L \Omega_L + B,$$

$$\Omega_{cf} = -\frac{\gamma T}{2\pi^2}\int_0^\infty k^2 \ln\left[1 + e^{-\frac{\varepsilon_{cf}}{T}}\right]dk,$$

$$\varepsilon_{cf} = \pm\sqrt{(E_{cf} - \mu_{cf})^2 + \Delta^2}$$

Hadronic model: Walecka

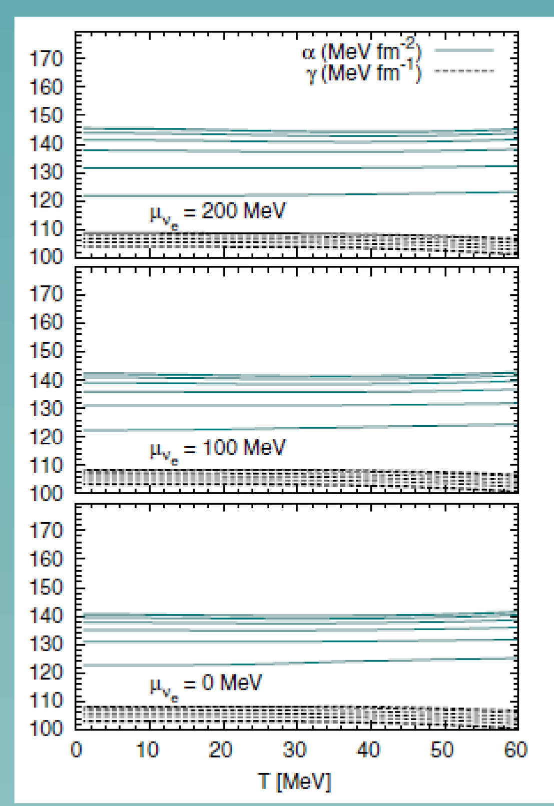
$$\mathcal{L} = \mathcal{L}_H + \mathcal{L}_\ell\,, \qquad \mathcal{L}_\ell = \sum_{\lambda=e^-,\mu^-}\bar\psi_\lambda(i\gamma_\mu\partial^\mu - m_\lambda)\psi_\lambda$$

$$\mathcal{L}_H = \sum_{B=n,p,\Lambda,\Sigma,\Xi}\bar\psi_B\left[\gamma_\mu(i\partial^\mu - g_\omega\omega^\mu - g_\rho\vec\rho_\mu) - (m_N - g_\sigma\sigma)\right]\psi_B + \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2) - \frac{1}{3}b_\sigma m_N(g_\sigma\sigma)^3 - \frac{1}{4}c_\sigma(g_\sigma\sigma)^4 - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{2}m_\rho^2\vec\rho_\mu\cdot\vec\rho^\mu - \frac{1}{4}\vec\rho_{\mu\nu}\vec\rho^{\mu\nu}$$

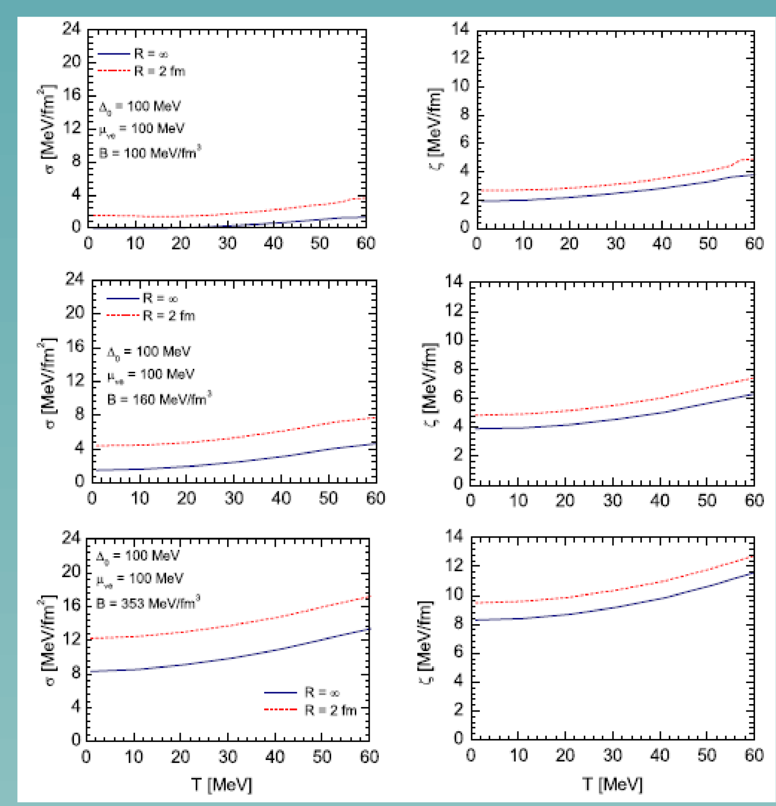
• Barions: p, n, Λ, Σ^+, Σ^+, Σ^0, Ξ^-, Ξ^0 • Mesons: σ, ω, ρ • Leptons: e^-, μ^-

Surface tension in drops nucleated at proto NS conditions
(trapped ν + finite T + initial drops out of beta equilibrium)

NJL



MIT

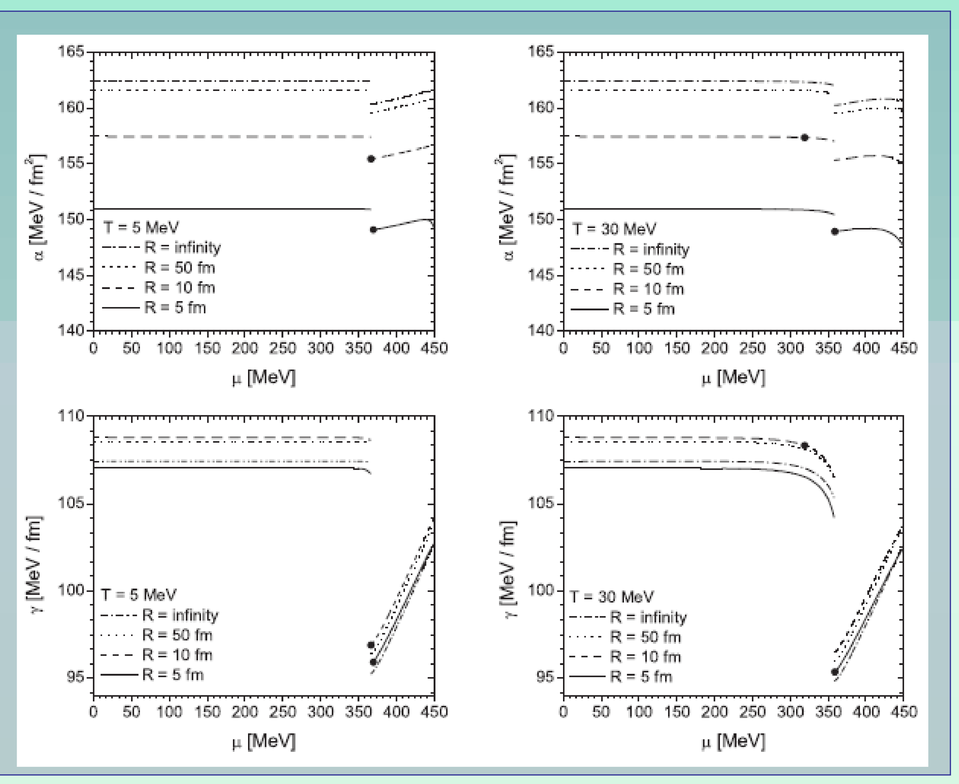


Surface tension within NJL model is significantly larger than within the MIT bag model.

Surface tension in cold hybrid star conditions
(NJL + T=0 + beta equilibrium)

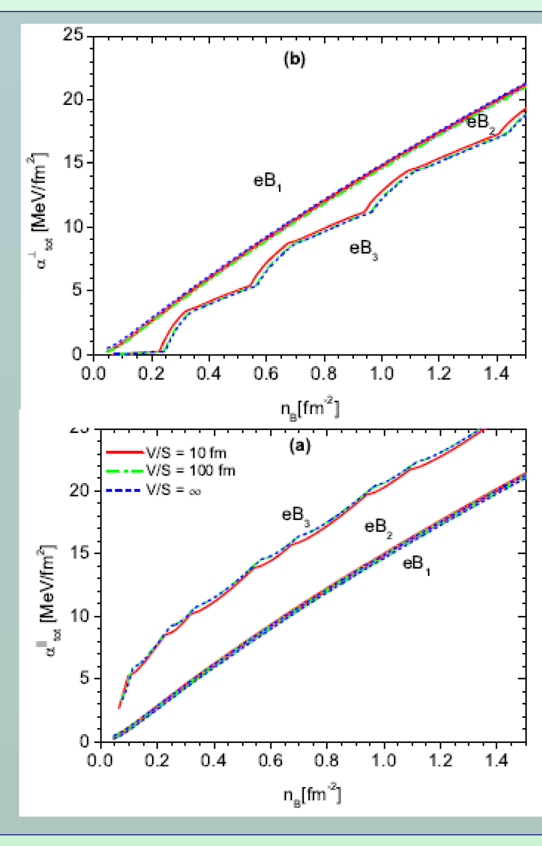
The surface tension is in the range of 145–165 MeV/fm².

For such large values of α mixed phases are mechanically unstable and the hadron-quark interphase in a hybrid star should be a sharp discontinuity.

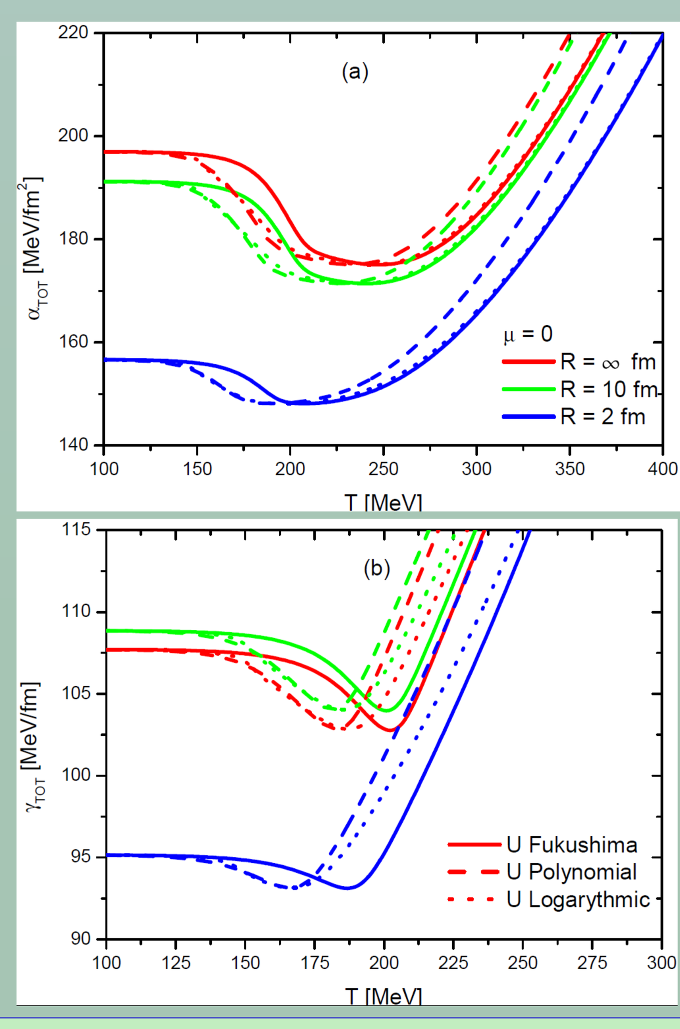


Surface tension in cold hybrid magnetars
(MIT + T=0 + beta equilibrium + strong magnetic field)

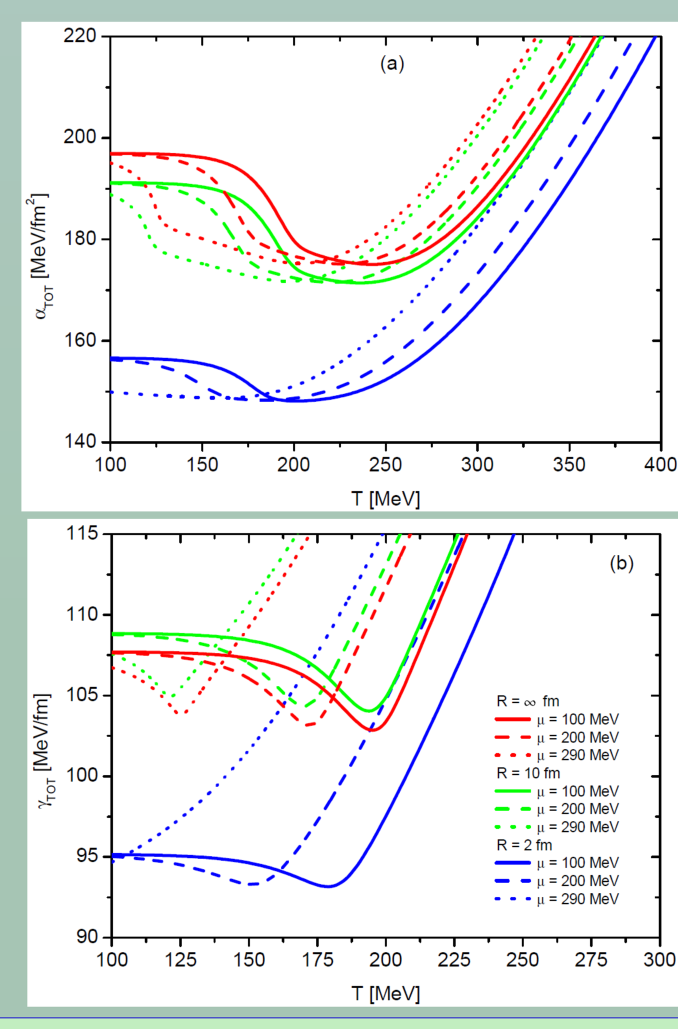
- particles' transverse motion is quantized into Landau levels ➔ α has a different value in the parallel and transverse directions with respect to B.
- For n_B from 2 to 10 n_{sat}, α = 2 – 20 MeV/fm².
- The largest contribution comes from strange quarks
- Total α is quite insensitive to the size of the drop.
- For $eB > \sim 5\times10^{-3}\,\mathrm{GeV}^2$, there is a significant increase in the parallel α and a significant decrease in the transverse α with respect to the unmagnetized case.
- According to this model, the hadron-quark interphase in a hybrid magnetar should be a mixed phase.



S(2+1) NJL + Polyakov loop @ μ = 0



SU(3) NJL + Polyakov loop @ finite μ (PL Fukushima)



Surface tension and curvature with pNJL (relativistic heavy ion collisions, compact stars)

- Critical temperature depends on the system's size, decreasing around 10% when the radius goes from infinity to 2 fm
- α is dominated by the contribution of *s* quarks and γ by *u* and *d* ones
- α and γ change significantly with R and there is also a considerable dependence on the PL potential

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