On the Survival of Strong Nuggets in the Early Universe

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Outline

Background

- **Strange quark matter**: the true ground state of strongly interacting matter at high baryon density.
- **Dark matter**: relic quark objects from the early Universe survive and account for dark matter.
- **Compact stars**: stiff EoS of strangeon stars → massive pulsars ($2M_\odot$); strange quark stars → ultralow mass compact stars.

The paper focus on

strange quark matter → **strangeon matter**.

Key idea

One of the important factors that determine lifetime of strange stars is **evaporation**:

- strange quark: $A > 10^{52}$ can survive evaporation (Alcock and Farhi, 1985)
- **strangeon**: much slower

1. strangeons evaporate (and decay into nucleons): suppressed by strong barrier

   (J. Madsen, Phys. Rev. D 47, 325 (1993))
2. strangeons decay into nucleons and evaporate: decay needs a much slower weak interaction.

The thermal history is:

$$\text{Quark-Gluon Plasma} \to \text{Strange Quark Nuggets} \to \text{Strangeon Nuggets}$$

- During a first-order QCD transition, baryons are trapped in shrinking false vacuum.
- These domains form dense **strange quark nuggets**.
- The resulting **strangeon nuggets** are more resistant to evaporation and can persist to the present epoch as dark matter.

Strange quark matter

A MIT bag model:

$$\Omega = -6 \sum_{i=u,d,s} \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \frac{k^2}{3E_i} (f_i + \bar{f}_i) + B$$

$$f_i(\bar{f}_i) = \frac{1}{1 + exp(\frac{E_i \pm \mu_i}{T})}$$

β equilibrium and charge neutrality

$$\mu_s = \mu_d = \mu_u + \mu_e, \mu_\mu = \mu_e$$

$$2n_u - n_d - n_s = 3n_e + 3n_\mu$$

Strangeon

A double Yukawa potential describes the residual strong interaction between strangeons

$$V(r) = g_1 \frac{e^{-m_1 r}}{r} - g_2 \frac{e^{-m_2 r}}{r},$$

the equilibrium state

$$V(r_0) = -u_0 \, , \quad \left.\frac{dV}{dr}\right|_{r_0} = 0 \, ,$$

r_0, u_0 are temperature dependent undetermined parameters with confinement temperature $T_0 \sim 100$ MeV

$$u_0 = u_0^{(0)} \exp\left(-T/T_0\right) \, ,$$
$$r_0 = r_0^{(0)} \exp\left(T/T_0\right) \, ,$$

(these two equations are not understood.)

Strangeon

At sufficiently low temperatures, strangeons may form a crystalline lattice as a result of their strong mutual interactions. X. Y. Lai and R. X. Xu, Mon. Not. R. Astron. Soc. 398, L31 (2009).

The total potential energy density at low temperature (n number density)

$$\varepsilon_{\rm p} = \frac{n}{2} \sum_{\substack{(N_1,N_2,N_3)\\ \in\mathbb{Z}^3\backslash(0,0,0)}} V\left(n^{-1/3}\sqrt{N_1^2+N_2^2+N_3^2}\right)$$

The dominant contribution to the potential energy arises from nearest neighbor interactions, which do not differ significantly with temperature.

Large mass strangeons obey Maxwell-Boltzmann distribution

$$s = \frac{5}{2}n + n\ln\left[(mT/2\pi)^{3/2}\,n^{-1}\right]$$
$$\varepsilon_{\rm k} = \frac{3}{2}nT\,.$$

$$\varepsilon = \varepsilon_{\rm p} + mn + \varepsilon_{\rm k}$$

Strangeon

Four free parameters now: $m_1, m_2, u_0^{(0)}, r_0^{(0)}$

1. $u_0^{(0)}$ is set $0 \sim 400$ MeV
2. m_1 and m_2 are chosen in the range $60 \sim 1200$ MeV and satisfy $m_1 > m_2$.
3. $r_0^{(0)}$ ensures strangeon density excesses the nuclear saturation density.
4. strangeon rest matter $m \sim 5580$ MeV. W. L. Yuan, C. Huang, C. Zhang, E. Zhou, and R. Xu, Phys.Rev. D 111, 063033 (2025)

The scenario: if strange quarks undergo a phase transition into strangeons, the evaporation process can be strongly suppressed because the evaporation of strangeon nuggets requires the **weak interaction** conversion from strangeons to nucleons on the surface of strangeon nuggets, which is 10^{-13} times the rate of strong-interaction quark assembling when strange quark matter evaporates nucleons.

Backup

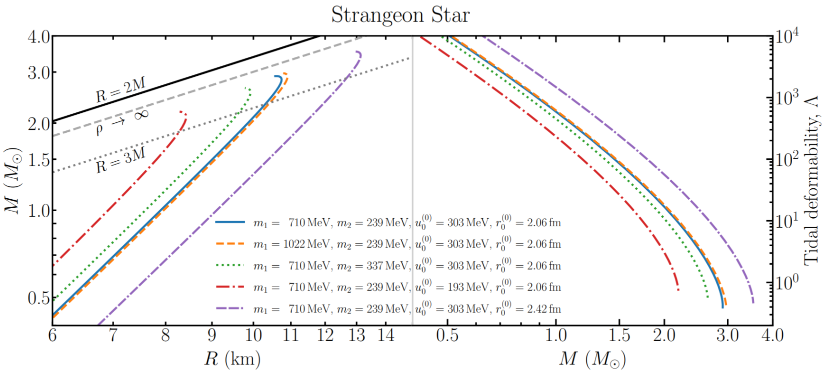
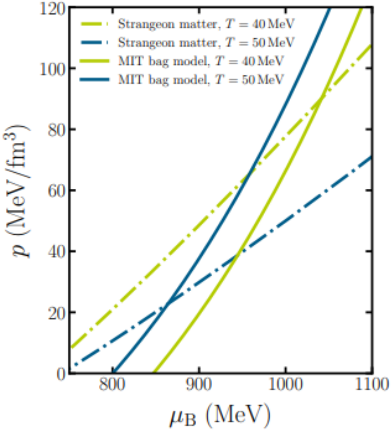
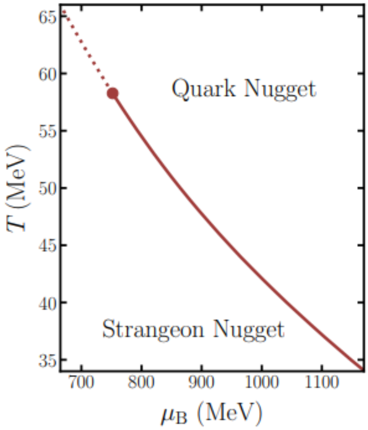


FIG. 4. The left panel is the mass-radius curves of the strangeon stars calculated through the TOV equations [86]. The right panel is the tidal deformability-mass curves of the strangeon star calculated by the gauge perturbation equations [87]. The solid-blue line shows that four EoS parameters are equal to their average value inferred in the right panel of Fig. 3, i.e. $m_1 = 710$ MeV, $m_2 = 239$ MeV, $u_0^{(0)} = 303$ MeV, $r_0^{(0)} = 2.06\,\text{fm}$. The other four lines each change one of the four parameters. The dashed-orange line represents the change in m_1 to 1022 MeV. The dotted-green line alters m_2 to 337 MeV. The dash-dotted-red line turns $u_0^{(0)}$ to 193 MeV. The dash-dash-dotted-purple line changes $r_0^{(0)}$ to $2.42\,\text{fm}$.

Main results





Main results

δE binding energy.
Phase transition at T_15

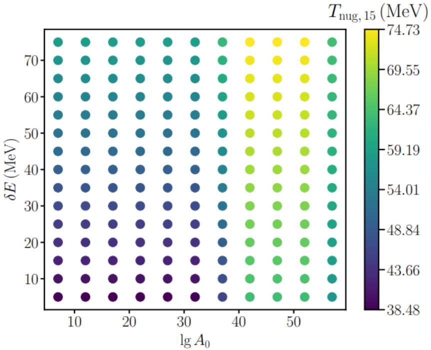


FIG. 2. The strange quark nugget temperature at which it loses 15% of its baryon number due to evaporation (we define it as $T_{\text{nug, 15}}$). In the calculation, we assume the strange quark nugget forming temperature $T_{u0} = 100\,\text{MeV}$, with initial baryon number A_0 ranged from 10^7 to 10^{57} and binding energy per baryon δE from 0 to 75 MeV.

Main results

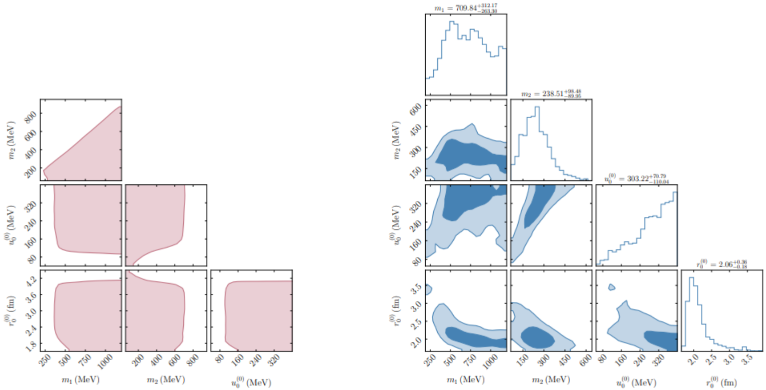


FIG. 3. Left panel: the parameter space of strangeon EoS in which the corresponding phase transition temperature cause strange quark nugeets to undergo phase transition to strangeon nuggets at a certain A_0 and δE, retaining 85% of its baryon number. The red area contains 90% of the sampled dots. In the calculation, T_0 in Eq. (10) is set to 100 MeV, at the same level as the QCD phase transition temperature [47–49]. Right panel: the parameter space of strangeon EoS obtained by a Bayesian inference using the mass-radius measurements from NICER, such as PSR J0030+0451 [88–90], PSR J0437-4715 [91, 92], PSR J0740+6620 [93, 94], and the tidal deformability measurement of LIGO/Virgo from GW170817 [7–9], within the allowed parameter space in the left panel. The contour confidence levels are 50% and 90%.

Conclusion

This paper presents a unified picture in which:

- a first-order cosmic QCD transition forms dense strong nuggets,
- a later conversion to strangeon matter stabilizes them,
- the surviving relics can contribute to dark matter,
- and the same framework is testable through compact-star observations.

Final message:

The survival of strong nuggets may depend crucially on the internal QCD phase structure of dense matter.