Bulk viscosity of two-color superconducting quark matter in neutron star mergers

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Quark model

The original NJL model, which contains the scalar coupling term with coupling G_S, has been extended to include the vector interactions with coupling G_V and the 't Hooft interaction with coupling K. This model is referred to as the vector-NJL model. In our case, it is further supplemented with a diquark interaction term to describe the color and flavor antisymmetric pairing of u and d quarks, known as 2SC pairing.

$$\mathcal{L}_Q = \bar{\psi}(i\gamma^\mu\partial_\mu - \hat{m})\psi + G_V(\bar{\psi}i\gamma^\mu\psi)^2 + G_S\sum_{\mathrm{a}=0}^{8}[(\bar{\psi}\lambda_{\mathrm{a}}\psi)^2 + (\bar{\psi}i\gamma_5\lambda_{\mathrm{a}}\psi)^2]$$
$$+ G_d\sum_{\gamma,c}[\bar{\psi}^{\mathrm{a}}_\alpha i\gamma_5\epsilon^{\alpha\beta\gamma}\epsilon_{\mathrm{abc}}(\psi_C)^b_\beta][(\bar{\psi}_C)^r_\rho i\gamma_5\epsilon^{\rho\sigma\gamma}\epsilon_{rsc}\psi^8_\sigma] - K\left\{\det{}_f[\bar{\psi}(1+\gamma_5)\psi] + \det{}_f[\bar{\psi}(1-\gamma_5)\psi]\right\}$$

The numerical values of the coupling constants of the Lagrangian are set at $G_S = 1.835/\Lambda^2$ MeV^{-2} and $K = 12.36/\Lambda^5$ MeV^{-5}, with $\Lambda = 602.3$ MeV [2]; while the strength of the vector interaction is fixed at $G_V/G_S = 1$ and that of diquark interaction at $G_D/G_S = 1.1$.

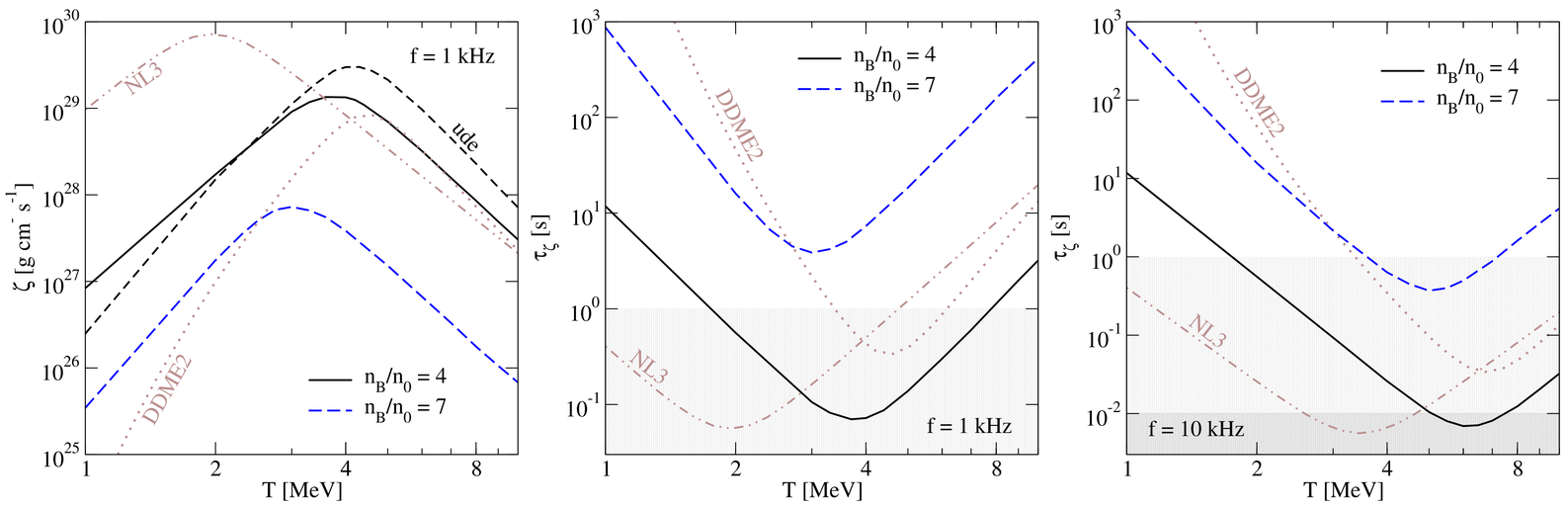
Bulk viscosity and timescale

The bulk viscosity coefficient for small-amplitude density oscillations of frequency ω is given by

$$\zeta = \frac{C^2}{A}\frac{\gamma}{\omega^2+\gamma^2}, \quad \text{where} \quad C = n_B\left.\frac{\partial\mu_\Delta}{\partial n_B}\right|_{x_u}, \quad A = -\frac{1}{n_B}\left.\frac{\partial\mu_\Delta}{\partial x_u}\right|_{n_B},$$

which has the classic resonant form depending on two quantities: the relaxation rate γ and the susceptibility prefactor C^2/A computed in β-equilibrium, solely depending on the equation of state. The bulk viscosity ζ has a maximum at the temperature where $\omega = \gamma$.

- For a characteristic to BNS mergers density oscillation frequency of $f = 1$ kHz, maximum of ζ shifts slowly to lower temperatures as density increases.
- Overall magnitude and maximum value are sensitive to density through the susceptibility prefactor C^2/A; they both decrease at higher densities.
- Neglecting s-quark contribution underestimates the bulk viscosity at low temperatures and overestimates it at higher temperatures.
- Including s-quark slightly shifts ζ_{max} to lower temperatures: its location does not change significantly, since d and s URCA processes have comparable rates.



The bulk viscous damping timescale of the density oscillations is given by

$$\tau = \frac{1}{9}\frac{Kn_B}{\omega^2\zeta},$$

where K the incompressibility. The damping timescale exhibits a temperature dependence that is inverse to that of bulk viscosity, as K remains insensitive across the considered temperature range.

- τ is shortest when the bulk viscosity is largest:
  at $T = 3-4$ MeV for $f = 1$ kHz oscillations,
  at $T = 5-6$ MeV for $f = 10$ kHz.
- The values of minima range between a few to a few hundred ms, lying within the typical short-term evolution timescales of the postmerger object.

⇒ Bulk viscosity of 2SC quark matter may significantly contribute to energy dissipation in BNS mergers at these temperatures.

Processes

In neutrino-transparent *udse* quark matter, the simplest (semileptonic) β-equilibration processes are the d-quark decay, the s-quark decay and their inverse electron-capture processes:

$$d \to u + e^- + \bar{\nu}_e,$$
$$u + e^- \to d + \nu_e,$$
$$s \to u + e^- + \bar{\nu}_e,$$
$$u + e^- \to s + \nu_e.$$

The nonleptonic processes $u+d \rightleftarrows u+s$ proceed much faster than the above URCA processes. Hence, in the regime where URCA-process-driven bulk viscosity is at its maximum, the non-leptonic equilibration is effectively instantaneous, and one can assume $\mu_s = \mu_d$ at all times. The only equilibrating quantity is then $\mu_\Delta \equiv \mu_d - \mu_u - \mu_e$, which measures the deviation of the system from the β-equilibrium state by a cycle of compression and rarefaction.

Rates

The interaction rates affect the relaxation rate of the system $\gamma = \lambda A$, via the equilibration coefficient

$$\lambda = \frac{d\Gamma}{d\mu_\Delta},$$

where Γ is the total rate of the URCA processes computed in β-equilibrium.

- Difference in T scaling
  $\Rightarrow \lambda_d$-λ_s intersection at $T \approx 1$ MeV.
- d-decay channel only thermally open;
  s-decay open due to large s-quark mass

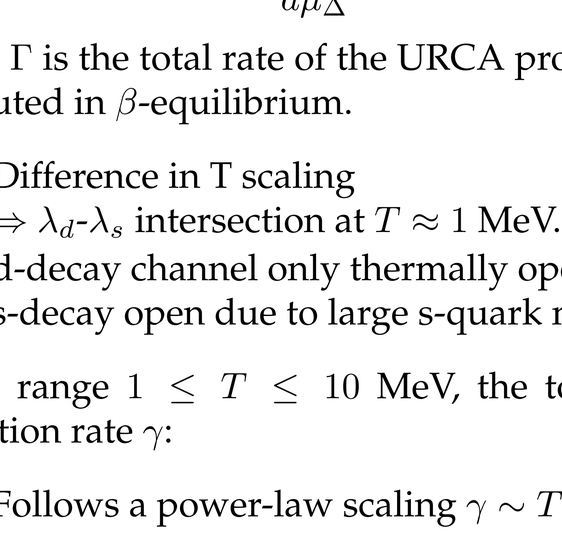
In the range $1 \le T \le 10$ MeV, the total β-relaxation rate γ:

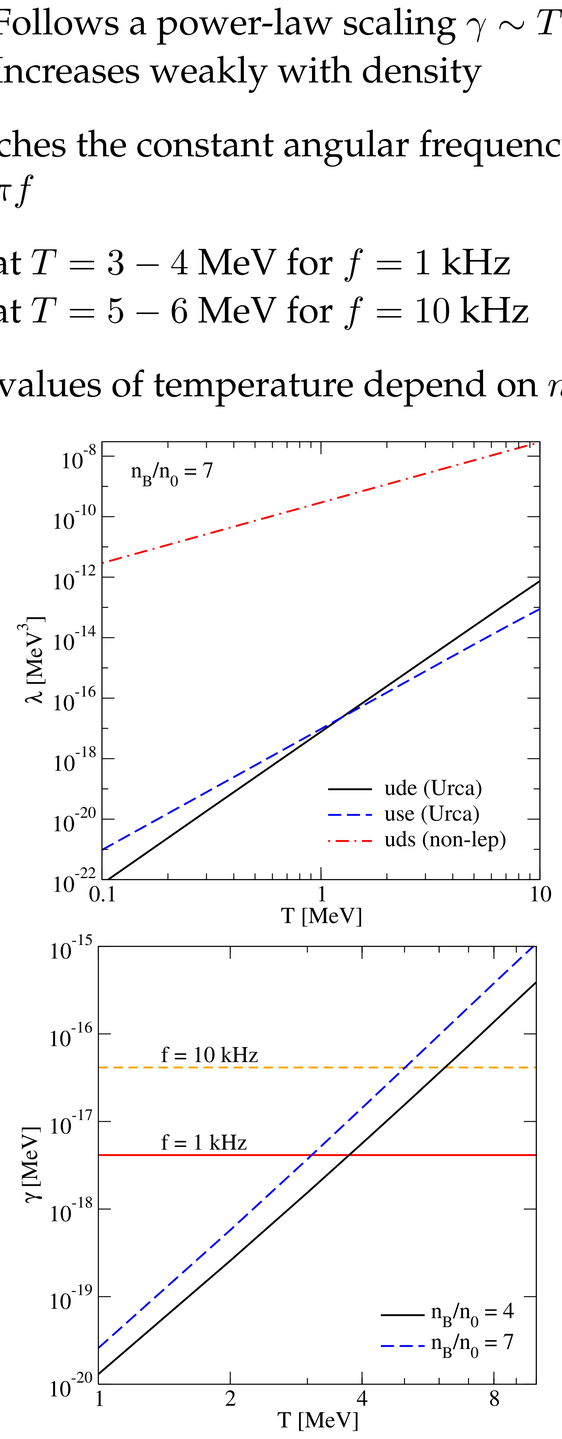
- Follows a power-law scaling $\gamma \sim T^{4.5}$
- Increases weakly with density

It matches the constant angular frequency $\omega = 2\pi f$

- at $T = 3-4$ MeV for $f = 1$ kHz
- at $T = 5-6$ MeV for $f = 10$ kHz

Exact values of temperature depend on n_B.





References

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[2] L. Bonanno, A. Sedrakian. *Composition and stability of hybrid stars with hyperons and quark color-superconductivity*. Astron. & Astrophys. **539**:A16 (2012).

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