Bulk viscosity of strange quark matter

Igor Shovkovy

Physics Department, Western Illinois University, Macomb, IL 61455

WESTERN ILLINOIS UNIVERSITY

Collaborators: **Basil A. Sa'd & Dirk H. Rischke**

J. W. Goethe-Universität, Frankfurt am Main, Germany

JOHANN WOLFGANG GOETHE UNIVERSITÄT FRANKFURT AM MAIN

References: **astro-ph/0607643, astro-ph/0703016, &** ***work in progress***

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Outline

- **Brief introduction**
- **Bulk viscosity of stellar quark matter**
- **Non-leptonic vs. semi-leptonic processes**
- **Results and discussion**
- **Summary**

Introduction

- **An r-mode of a rotating star, as seen by a non-rotating observer**

In *the absence of viscosity*, all rotating stars would spontaneously develop instabilities as a result of the emission of gravitational waves *[Chandrasekhar 1970, Friedman & Schutz 1978]*

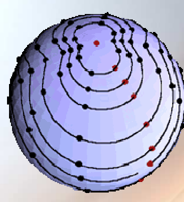


Image from B. J. Owen

- **In a reference frame co-rotating with the star**

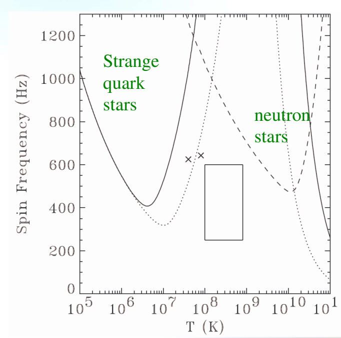
While the total angular momentum and the total energy are decreasing, the velocity of the relative motion (as well as the intensity of the gravitational radiation) is increasing

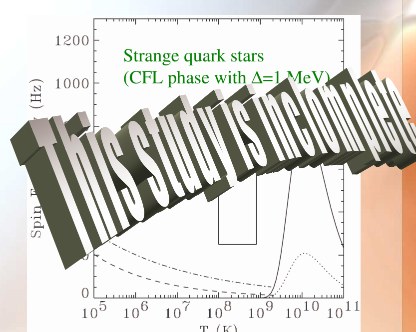
Image from B. J. Owen

Bulk viscosity

- **The instability grows until the energy channeled into the r-mode matches the radiation energy**

[J. Madsen, Phys. Rev. Lett. 85 (2000) 10]



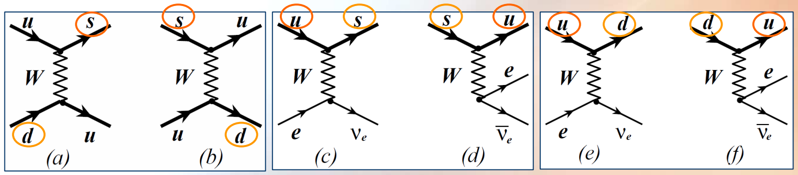


- **Role of the bulk/shear viscosity: it provides a channel to dissipate the r-mode energy (namely, into heat or neutrinos)**

Origin of bulk viscosity

- Let the density oscillate, $\delta n = \delta n_0 \, \mathrm{Re}(e^{i\omega t})$ where ω is in the range from $10\ \mathrm{s}^{-1}$ to $10^3\ \mathrm{s}^{-1}$
- These are the time scales of weak processes

β-equilibrium	Instantaneous quasi-equilibrium
$\mu_s=\mu_d=\mu_u+\mu_e$	$\delta\mu_1=\mu_s-\mu_d\neq 0$ $\delta\mu_2=\mu_s-\mu_u-\mu_e\neq 0$



$\Gamma_a - \Gamma_b = -\lambda_1 \delta\mu_1$ ⇓ heat

$\Gamma_c - \Gamma_d = -\lambda_2 \delta\mu_2$ ⇓ neutrinos

$\Gamma_e - \Gamma_f = -\lambda_3 (\delta\mu_2 - \delta\mu_1)$ ⇓ neutrinos

"Folklore"

- Rates

approximate

$$\lambda_1 \simeq \frac{64}{5\pi^3} G_F^2 \cos^2\theta_C \sin^2\theta_C \mu_d^5 T^2$$

$$\lambda_2 \simeq \frac{17}{40\pi} G_F^2 \sin^2\theta_C \mu_s m_s^2 T^4$$

$$\lambda_3 \simeq \frac{17}{15\pi^2} G_F^2 \cos^2\theta_C \alpha_s \mu_d \mu_u \mu_e T^4$$

Note: $\lambda_1 \gg \lambda_2 \simeq \lambda_3$

- Non-leptonic weak processes d+u⇔u+s give the dominant contribution to ζ
- However, this is true only if $\omega \gg \omega_0$ where

$$\omega_0 = \frac{\sqrt{\lambda_1(\lambda_2+\lambda_3)}}{n^{2/3}} \propto T^3$$

Competition of weak processes. I.

Non-leptonic ζ:

$$\zeta_{\mathrm{non}} \simeq \frac{\lambda_1 C_1^2}{\omega^2 + (\lambda_1 A_1/n)^2}$$

where

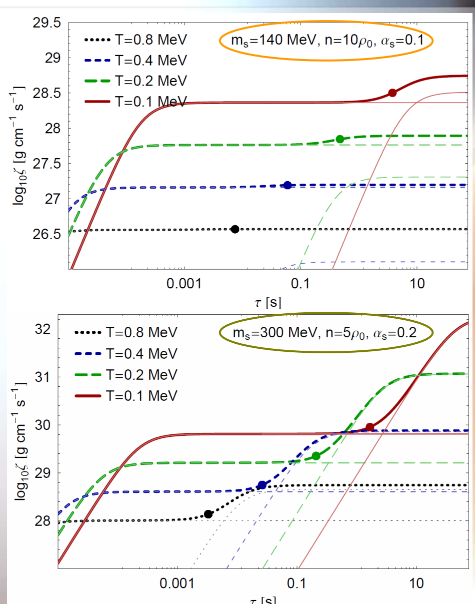
- $A_1 \propto n^{1/3}$
- $C_1 \propto m_s^2/n^{1/3}$

Change of regimes at

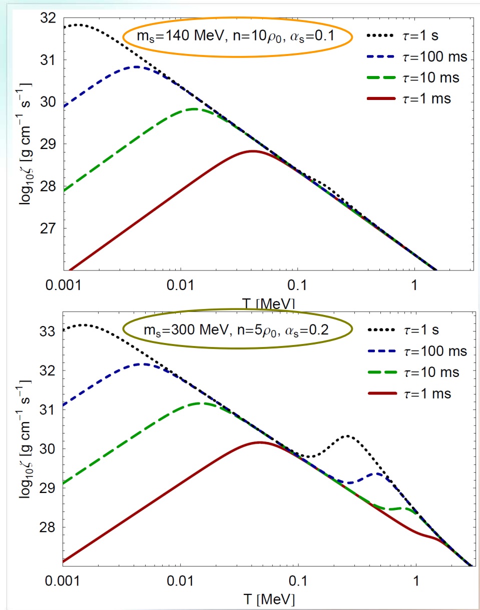
- $10^3\ \mathrm{s}^{-1} \lesssim \omega_0 \lesssim 10\ \mathrm{s}^{-1}$

The role of the Urca processes increases when

- m_s increases (i.e., n decreases)

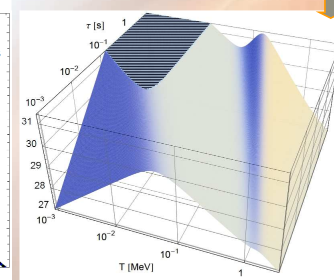


Competition of weak processes. II.



The effect of the Urca processes grows with the period and is largest for
0.1 MeV ≲ T ≲ 1 MeV

$\log_{10}[\zeta(T,\tau)]$ as a function of temperature T and period τ looks as follows:

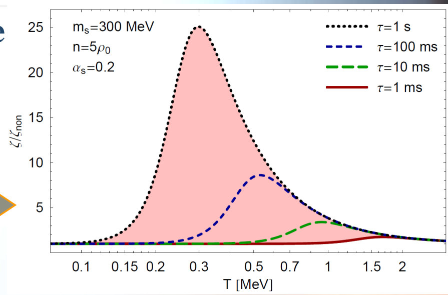


m_s=300 MeV, $n=5\rho_0$, α_s=0.2

Enhancement of bulk viscosity

- The importance of the Urca processes could be revealed by calculating the ratio

ζ/ζ_{non}



- A resonance type of enhancement is observed at

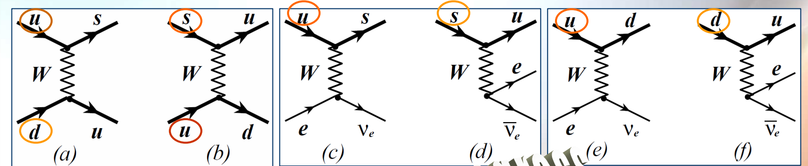
$$T_{max} \propto \tau^{-1/3}$$

which is equivalent to

$$\omega \approx \omega_0 \propto T^3$$

Competition in a color superconductor

- If quasiparticles are gapped, the rates are suppressed ($T \ll T_c$)



$\lambda_1 \propto e^{-2\Delta/T}$ Work in progress $\lambda_3 \propto e^{-\Delta/T}$

- The "resonance" is likely to occur at

$\omega \approx \omega_0 \propto e^{-2\Delta/3T}$ $\Rightarrow$ $T_{max} \propto \Delta/\ln[\tau/\tau_0]$

- The non-leptonic processes have smaller rates than the Urca processes for $T \lesssim T_{max}$

Summary

- There is a subtle interplay between non-leptonic and semi-leptonic contributions to the bulk viscosity of strange quark matter
- The "resonance" condition is $\omega \approx \omega_0$ where

$$\omega_0 = \frac{\sqrt{\lambda_1 (\lambda_2 + \lambda_3)}}{n^{2/3}}$$

- The interplay of various weak processes is expected to be even more interesting in a color superconductor (e.g., in the Color-Spin-Locked phase)

Thank you...