Bulk viscosity and damping of density oscillations in binary neutron star mergers

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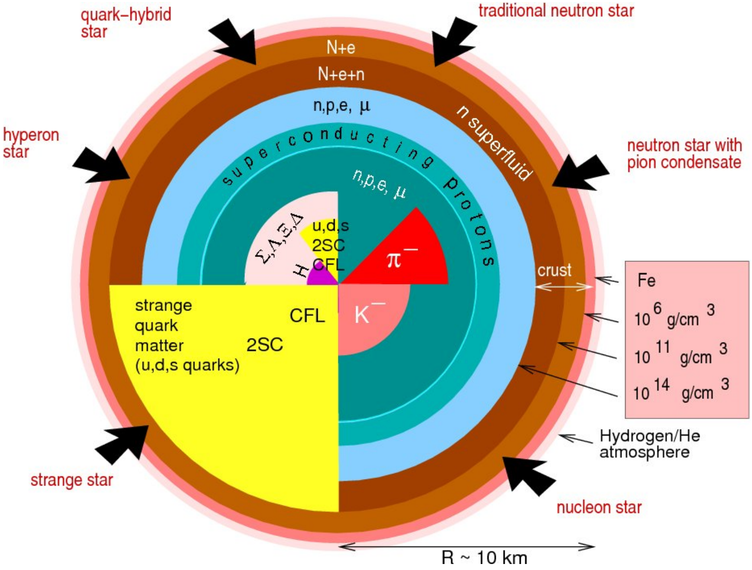
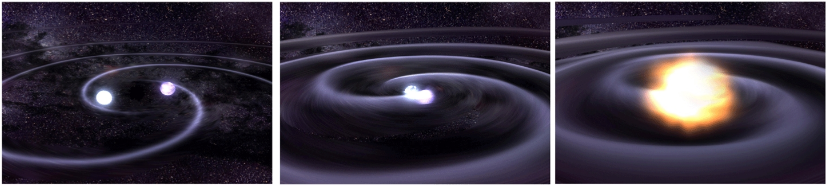
Outline

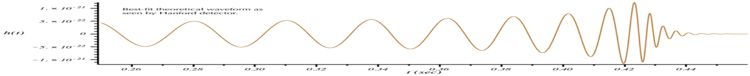
- Introduction
- Weak interactions in dense matter
    - Baryonic matter
    - Quark matter (2SC phase)
- Models of neutron star matter
- Bulk viscosity from weak interactions
- Damping of density oscillations
- Conclusions

The structure of neutron stars



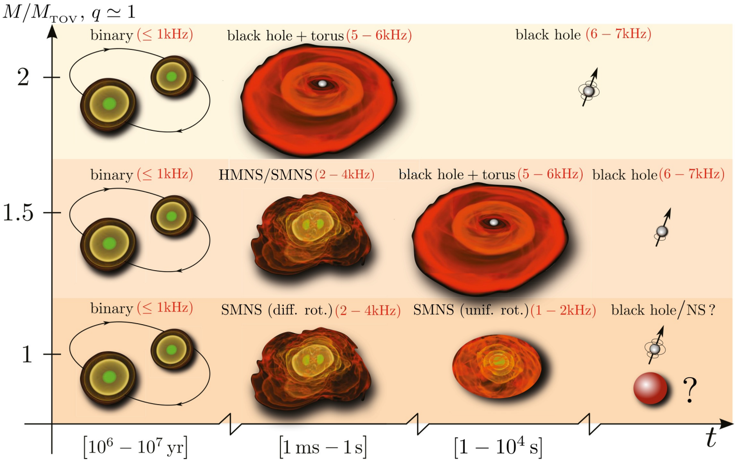
Neutron star binary systems





- Compact stars are natural laboratories to test the properties of **dense matter** in extremely **strong gravitational fields**.
- **Gravitational wave signal** from binary neutron star systems carries reach information about the **structure of dense matter**.
- **Gravitational waveform** might be affected by **damping of density oscillations** after merging of two compact stars.

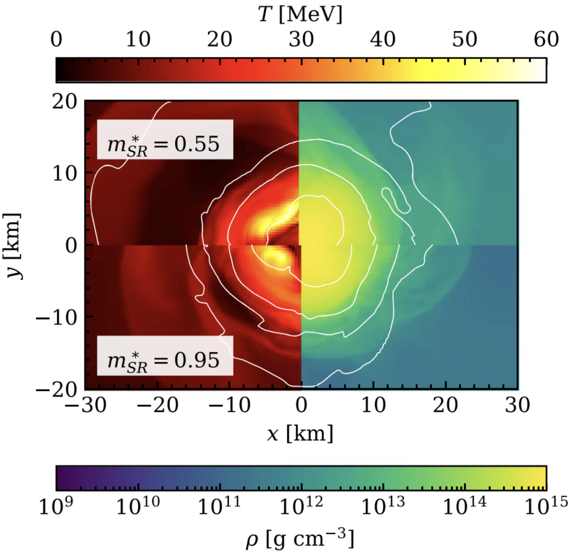
Dynamics of BNS mergers



- Characteristic timescales of **initial phase of post-merger** $\sim$ **10 ms** (over which intense gravitational wave emission is expected); **long-term post-merger evolution phase** $\sim$ **1 s**
- Characteristic oscillation **frequencies** in BNS mergers lie in the range **1–10 kHz**

L. Rezzolla and O. Zanotti, *Relativistic Hydrodynamics* (Oxford University Press, 2013).

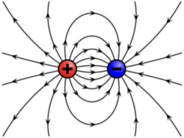
Temperature-density profiles of post-merger object



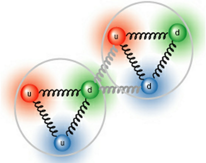
J. Fields, *et. al.*, *Thermal Effects in Binary Neutron Star Mergers*. ApJL **952** L36 (2023)

Four fundamental forces of nature in neutron stars

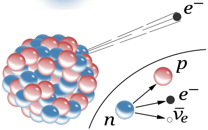
- Gravity
  - Star formation, BNS mergers
  - Gravitational waves (LIGO, Virgo)



- Electromagnetism
  - Crust structure, transport properties
  - Evolution of magnetic fields



- Strong interactions
  - Equation of state, mass-radius relation
  - Core composition and phase structure



- Weak interactions
  - β-equilibrium, neutronization of matter
  - ν-transport, cooling, **bulk viscosity**

Motivation of our work

- **Bulk viscosity** describes energy dissipation in thermodynamic systems when pressure falls **out of equilibrium** due to fluid expansion and contraction
- **Out of equilibrium** phenomena like weak interactions can lead to **bulk viscosity**

Aim of this work

1. Study of weak interactions in **baryonic** ($npe\mu$) and **quark** ($udse$) cores of neutron stars
2. Computation of **bulk viscosity** from weak interactions in binary neutron star mergers
3. Assessment of **bulk viscous damping** rates of density oscillations of post-merger object; comparison between **baryonic composition** and **quark composition**

This talk is based on two recent papers:

- M. Alford, A. Harutyunyan, A. Sedrakian, *Bulk viscosity from URCA processes: npeμ matter in the neutrino-transparent regime*. Phys. Rev. D **108** 083019 (2023); arXiv:2306.13591 [nucl-th]
- M. Alford, A. Harutyunyan, A. Sedrakian, S. Tsiopelas, *Bulk viscosity of two-color superconducting quark matter in neutron star mergers*. Phys. Rev. D Letters **110**, L061303 (2024); arXiv:2407.12493 [nucl-th]

Literature on bulk viscosity

1. Baryonic matter
    - R. F. Sawyer, *Damping of neutron star pulsations by weak interaction processes*. Astrophys. J. **237** (1980) 187-197.
    - R. F. Sawyer, *Bulk viscosity of hot neutron-star matter and the maximum rotation rates of neutron stars*. Phys. Rev. D **39** (1989) 3804-3806.
    - P. Haensel and R. Schaeffer, *Bulk viscosity of hot-neutron-star matter from direct URCA processes*. Phys. Rev. D **45** (1992) 4708-4712.
    - M. Alford and S. Harris, *Damping of density oscillations in neutrino-transparent nuclear matter*. Phys. Rev. C **100** (2019) 035803.
    - M. G. Alford, A. Harutyunyan, A. Sedrakian. *Bulk Viscous Damping of Density Oscillations in Neutron Star Mergers*. Particles **3** (2020) 500-517.
    - M. Alford, A. Harutyunyan, A. Sedrakian, *Bulk viscosity from URCA processes:* $npe\mu$ *matter in the neutrino-transparent regime*. Phys. Rev. D **108** (2023) 083019.
2. Hyperonic matter
    - P. B. Jones, *Bulk viscosity of neutron-star matter*. Phys. Rev. D **64** (2001) 084003.
    - M. G. Alford, A. Haber, *Strangeness-changing rates and hyperonic bulk viscosity in neutron star mergers*. Phys. Rev. C **103** (2021) 045810.
3. Quark matter
    - M. G. Alford, A. Schmitt. *Bulk viscosity in 2SC quark matter*. J. Phys. **G34** (2007) 67-102.
    - M. G. Alford, S. Mahmoodifar and K. Schwenzer, *Large amplitude behavior of the bulk viscosity of dense matter*. Journal of Physics G Nuclear Physics **37** (2010) 125202.
    - J. L. Hernandez, C. Manuel, L. Tolos. *Damping of density oscillations from bulk viscosity in quark matter*. Phys. Rev. D **109** (2024) 123022.
    - J. Cruz Rojas, T. Gorda, C. Hoyos, et al. *Estimate for the Bulk Viscosity of Strongly Coupled Quark Matter Using Perturbative QCD and Holography*. Phys. Rev. Lett. **133** (2024) 071901.

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Weak interactions in baryonic matter

- Simplest semi-leptonic weak-interaction processes – **direct Urca processes**

$$\begin{aligned} &n \to p + e^- + \bar{\nu}_e && \text{neutron } e\text{–decay} \\ &n \to p + \mu^- + \bar{\nu}_\mu && \text{neutron } \mu\text{–decay} \\ &p + e^- \to n + \nu_e && \text{electron capture} \\ &p + \mu^- \to n + \nu_\mu && \text{muon capture} \end{aligned}$$

- Pure leptonic process – muon decay

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

- Neutrinos escape the star at temperatures $T \leq 10$ MeV
- In β-equilibrium $\mu_n = \mu_p + \mu_e = \mu_p + \mu_\mu$. Departure from equilibrium is measured by

$$\delta\mu_e = \mu_n - \mu_p - \mu_e \neq 0, \qquad \delta\mu_\mu = \mu_n - \mu_p - \mu_\mu \neq 0$$

- Muon decay process is typically much slower than semi-leptonic processes
  ⇒ bulk viscosity arises from two independent oscillatory degrees of freedom

Urca process rates in baryonic matter

- Rate of neutron decay $n \to p + l^- + \bar{\nu}_l$ $\left[\bar{f}(k) = 1 - f(k)\right]$

$$\Gamma_{n\to pl\bar{\nu}} = \int d\Omega_k |\mathcal{M}_{\text{Urca}}|^2 f(k_n)\bar{f}(k_l)\bar{f}(k_p)\,(2\pi)^4\,\delta^{(4)}(k_p + k_l + k_{\bar{\nu}} - k_n)$$

- The squared matrix element of Urca processes $[G = G_F \cos\theta_c(1 + g_A)]$

$$|\mathcal{M}_{\text{Urca}}|^2 \simeq 32G^2(k_e \cdot k_p)(k_{\bar{\nu}} \cdot k_n)$$

- In β-equilibrium $\Gamma_{n\to pl\bar{\nu}} = \Gamma_{pl\to n\nu}$; for small departures from equilibrium

$$\boxed{\delta\Gamma_l = \Gamma_{n\to pl\bar{\nu}} - \Gamma_{pl\to n\nu} = \lambda_l \delta\mu_l, \qquad \lambda_l = \frac{\delta\Gamma_l}{\delta\mu_l}}$$

- In degenerate matter where $T \ll \mu^*$

$$\lambda_l = \frac{17}{480\pi} G^2 T^4 \mu_n^* (p_{Fp}^2 + p_{Fl}^2 + 2\mu_l\mu_p^* - p_{Fn}^2)\,\underbrace{\theta(p_{Fl} + p_{Fp} - p_{Fn})}_{\text{Pauli blocking factor}}$$

- If $\theta = 0$, **modified Urca processes** with spectator nucleon should be included

$$N + n \to N + p + l^- + \bar{\nu}_l, \qquad N + p + l^- \to N + n + \nu_l$$

Weak interactions in quark matter

- Semi-leptonic weak-interaction processes in quark matter of **direct Urca-type**

$$\begin{aligned} d &\to u + e^- + \bar{\nu}_e \qquad & u + e^- &\to d + \nu_e \\ s &\to u + e^- + \bar{\nu}_e \qquad & u + e^- &\to s + \nu_e \end{aligned}$$

- In β-equilibrium $\mu_d = \mu_s = \mu_u + \mu_e$. Out of equilibrium

$$\delta\mu_{d/s} = \mu_{d/s} - \mu_u - \mu_e \neq 0$$

- **Non-leptonic** weak-interaction processes in quark matter

$$u + d \leftrightarrow u + s$$

- They equilibrate much faster than Urca processes at temperatures $T \leq 10$ MeV
- Therefore, *d* and *s* quarks are always equilibrated with $\mu_d = \mu_s$
  $\Rightarrow$ bulk viscosity arises from one independent oscillatory degree of freedom

Urca process rates in quark matter

- For small departures from equilibrium $\delta\Gamma_{d/s} = \lambda_{d/s}\,\delta\mu$; for degenerate quarks $T \ll \mu_i^*$

$$\lambda_d \simeq 0.2 G_F^2 \cos^2\theta_c p_{Fd}^2 T^5, \qquad \lambda_s \simeq 0.03 G_F^2 \sin^2\theta_c \mu_s^* m_s^{*2} T^4$$

- d-Urca rate has no threshold, but additional power of T as compared to baryons $\lambda \sim T^4$
- For ultrarelativistic u, d quarks in β-equilibrium $p_{Fu} + p_{Fe} \simeq p_{Fd}$ $\Rightarrow$ Fermi momenta are on the borderline between the Urca process being allowed and being forbidden $\Rightarrow$ direct Urca channel for light d-quark is only thermally allowed
- Urca channel for massive s-quark is always open with $p_{Fu} + p_{Fe} - p_{Fs} \geq 70$ MeV
- The rate of the non-leptonic processes

$$\lambda_{\mathrm{non-lep}} = \frac{64}{5\pi^3} G_F^2 \sin^2\theta_c \cos^2\theta_c \mu_d^{*5} T^2 \sim T^2$$

- Fast non-leptonic equilibration $\lambda_{\mathrm{non-lep}} \gg \lambda_{d/s}$ in degenerate matter

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Baryon-meson Lagrangian for nuclear matter (Walecka model)

$$\mathcal{L} = \underbrace{\sum_b \bar{\psi}_b \left[\gamma^\mu \left(i\partial_\mu - g_\omega \omega_\mu - \frac{1}{2} g_\rho \boldsymbol{\tau} \cdot \boldsymbol{\rho}_\mu\right) - (m_b - g_\sigma \sigma)\right]\psi_b}_{\text{baryons}} + \underbrace{\sum_l \bar{\psi}_l (i\gamma^\mu \partial_\mu - m_l)\psi_l}_{\text{leptons}}$$

$$+\underbrace{\frac{1}{2}\partial^\mu \sigma \partial_\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - U(\sigma) - \frac{1}{4}\omega^{\mu\nu}\omega_{\mu\nu} + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu - \frac{1}{4}\boldsymbol{\rho}^{\mu\nu}\boldsymbol{\rho}_{\mu\nu} + \frac{1}{2} m_\rho^2 \boldsymbol{\rho}^\mu \boldsymbol{\rho}_\mu}_{\text{mesons}}$$

- Baryon sum is over n and p
- Leptons include e, μ and (at $T \geq 10$ MeV) also ν_e and ν_μ
- Mesonic fields include σ, ω_μ and $\boldsymbol{\rho}_\mu$ mesons

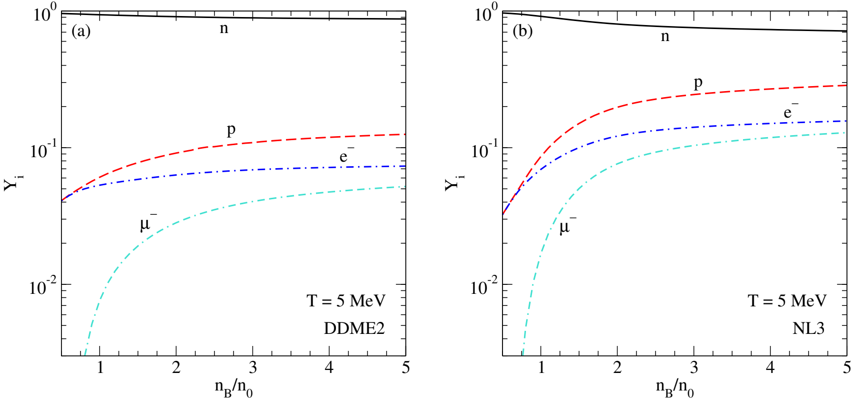
We consider two baryonic models based on relativistic Lagrangians:

- **DDME2 (softer):** linear mesonic fields $U(\sigma) = 0$; density-dependent couplings $g_{\sigma,\omega,\rho}$
- **NL3 (stiffer):** non-linear mesonic fields $U(\sigma) = g_2\sigma^3/3 + g_3\sigma^4/4$; constant couplings

Particle fractions in equilibrium (DDME2 & NL3)

Conditions determining the equilibrium state

$\mu_n = \mu_p + \mu_l$	$\beta-$equilibrium
$n_B = n_n + n_p$	baryon conservation
$n_p = n_e + n_\mu$	charge neutrality



NJL model for quark matter

$$\begin{aligned}\mathcal{L} = {} & \underbrace{\bar\psi(i\gamma^\mu\partial_\mu - \hat{m})\psi}_{\text{free Dirac fields}} + G_S\sum_{a=0}^{8}\underbrace{\left[(\bar\psi\lambda_a\psi)^2 + (\bar\psi i\gamma_5\lambda_a\psi)^2\right]}_{\text{scalar interactions}} + G_V\underbrace{(\bar\psi i\gamma^\mu\psi)^2}_{\text{vector int.}} \\ & + G_D\sum_{\gamma,c}\underbrace{\left[\bar\psi^a_\alpha i\gamma_5\epsilon^{\alpha\beta\gamma}\epsilon_{abc}(\psi_C)^b_\beta\right]\left[(\bar\psi_C)^r_\rho i\gamma_5\epsilon^{\rho\sigma\gamma}\epsilon_{rsc}\psi^s_\sigma\right]}_{\text{diquark interaction (color supeconductivity)}} \\ & - \underbrace{K\left\{\det{}_f[\bar\psi(1+\gamma_5)\psi] + \det{}_f[\bar\psi(1-\gamma_5)\psi]\right\}}_{\text{'t Hooft interaction } (U_A(1) \text{ anomaly})} + \underbrace{\sum_l \bar\psi_l(i\gamma^\mu\partial_\mu - m_l)\psi_l}_{\text{leptons}}\end{aligned}$$

- $\psi = (\psi_u, \psi_d, \psi_s)$ is the isotriplet Dirac field of 3-flavor quark matter
- Attractive scalar interactions + repulsive vector interactions
- Attractive diquark channel for color- and flavor-antisymmetric pairing of u and d quarks; unpaired s quarks because of higher mass $\Rightarrow$ 2-flavor-color superconductivity (2SC)

Density oscillations in quark matter

- Pairing in 2SC phase is only between *red* and *green* quarks; the gap is given by

$$\Delta = G_D \left\langle (\bar{\psi}_C)^a_\alpha i\gamma_5 \epsilon^{\alpha\beta c} \epsilon_{abc} \psi^b_\beta \right\rangle$$

- In neutrino-transparent matter $T \ll \Delta \simeq 150 \div 200$ MeV
- Constituent masses and effective quark chemical potentials are given by

$$M_\alpha = m_\alpha - 4G_S\sigma_\alpha + 2K\sigma_\beta\sigma_\gamma \qquad \mu^* = \mathrm{diag}_f\,(\mu_u - \omega_0, \mu_d - \omega_0, \mu_s - \phi_0)$$

- Quark-antiquark condensates in the mean field approximation are given by

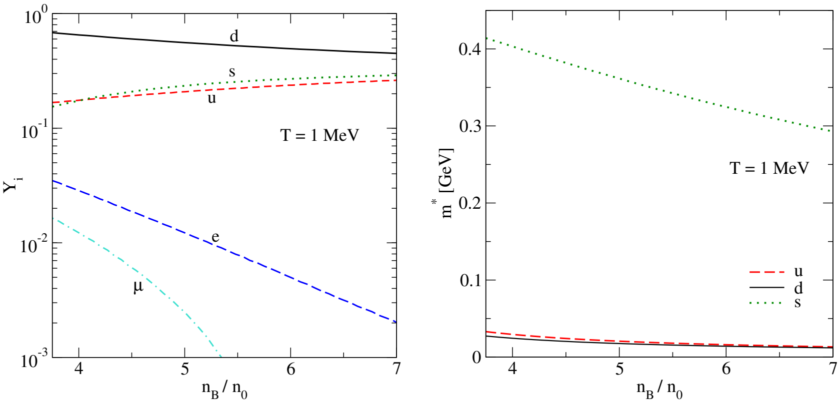
$$\sigma_\alpha = G_S \left\langle \bar{\psi}_\alpha \psi_\alpha \right\rangle \qquad \omega_0 = G_V \langle \psi_u^\dagger \psi_u + \psi_d^\dagger \psi_d \rangle \qquad \phi_0 = 2G_V \langle \psi_s^\dagger \psi_s \rangle$$

- Charge neutrality (both color and electric) and baryon conservation imply

$$\begin{aligned} \tilde{n}_u + \tilde{n}_d + \tilde{n}_s = 2(n_u + n_d + n_s) &= 2n_b \\ \frac{2}{3}(n_u + \tilde{n}_u) - \frac{1}{3}(n_d + n_s + \tilde{n}_d + \tilde{n}_s) &= n_e + n_\mu \end{aligned}$$

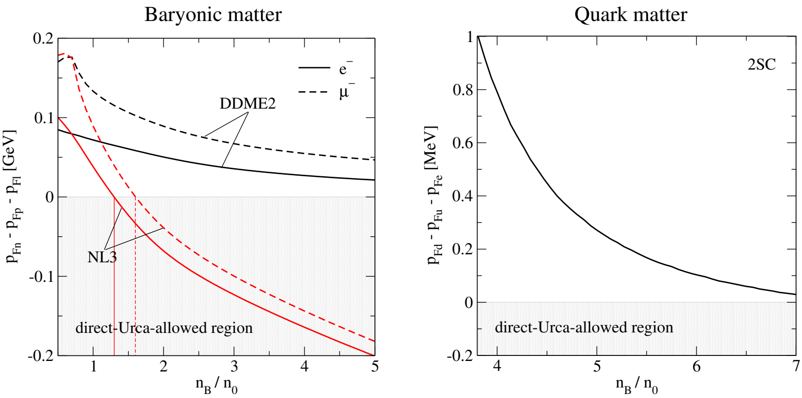
n_i are densities of *blue* quarks, and $\tilde{n}_i$ are summed densities of *red* and *green* quarks.

Unpaired particle fractions in equilibrium (NJL)



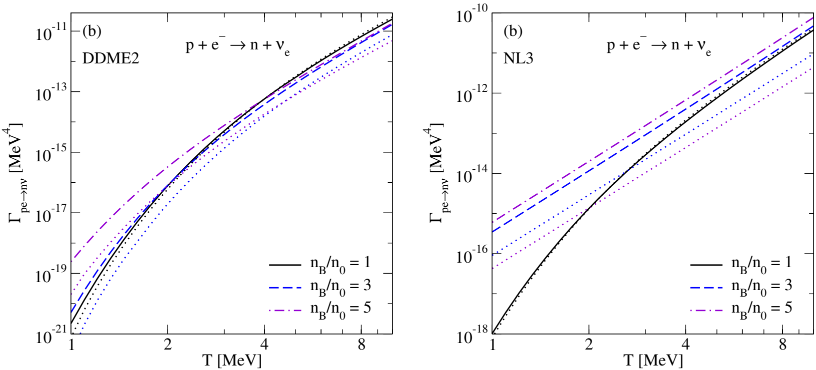
- Only blue components of *u* and *d* quarks are unpaired
- *s* quarks are totally unpaired; they reduce the population of leptons
- *u*, *d* quarks are ultrarelativistic, whereas *s* quarks remain massive

Direct Urca threshold



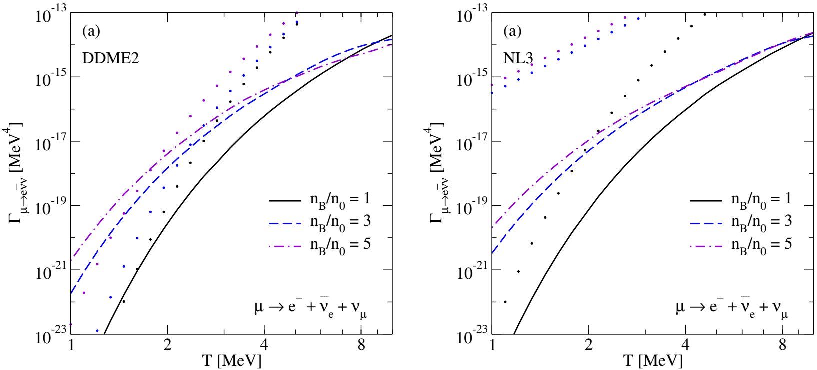
- NL3 has **direct Urca thresholds** at $n_B \simeq 1.3 n_0$ (electron) and $n_B \simeq 1.6 n_0$ (muon)
- DDME2 has **no threshold** up to densities $n_B = 5 n_0$
- For u, d quarks in β-equilibrium $p_{Fu} + p_{Fe} \simeq p_{Fd} \quad \Rightarrow$ phase space for direct Urca process opens only due to thermal blurring of the Fermi surfaces at $T \geq 1$ MeV
- s-quark Urca channel is always open with $p_{Fu} + p_{Fe} - p_{Fs} \geq 70$ MeV

Electron capture rates in baryonic matter



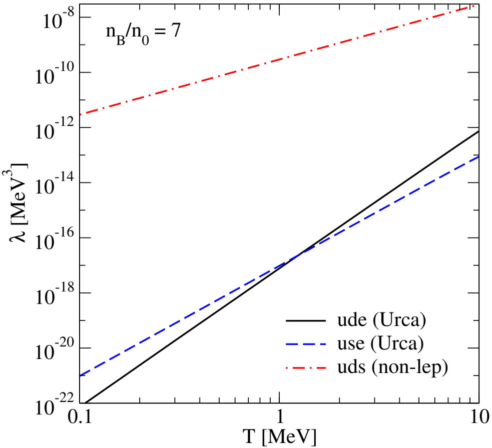
- Fast increase of direct Urca process rates with temperature
- Boltzmann suppressed rates at low temperatures below the threshold density
- Qualitatively and quantitatively similar electron and muon capture rates
- Significant relativistic corrections to baryon spectrum at $n_B/n_0 \geq 3$

Muon capture and muon decay rates



- Boltzmann suppressed muon decay rates at low temperatures
- Comparable muon capture rates at $T \leq 3$ MeV below the threshold density
- Electron capture rates are much larger than muon decay rates
  $\Rightarrow$ slow lepton equilibration limit, e-Urca and μ-Urca processes are independent

Weak process rates in quark matter



- Comparable rates of *d*-Urca and *s*-Urca processes for $0.1 \leq T \leq 10$ MeV
- Much larger rates of non-leptonic processes than Urca processes
  $\Rightarrow \quad \mu_s = \mu_d \neq n_p + n_e$ in the regime where Urca processes are important

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Bulk viscosity of baryonic matter

- Consider small-amplitude **density oscillations** in baryonic matter with frequency ω

$$n_j(t) = n_{j0} + \delta n_j(t), \quad \delta n_j(t) \sim e^{i\omega t}, \qquad j = \{B, n, p, e, \mu\}$$

- Particle production equations due to **Urca processes** ($\theta = \mathrm{div}\boldsymbol{v}$)

$$\frac{\partial n_p}{\partial t} + \theta n_{p0} = \lambda_e \delta\mu_e + \lambda_\mu \delta\mu_\mu, \qquad \frac{\partial n_e}{\partial t} + \theta n_{e0} = \lambda_e \delta\mu_e$$

- Due to δn_j, pressure $p = p(n_{j0} + \delta n_j)$ obtains a **non-equilibrium part**

$$\delta p = \sum_j \frac{\partial p}{\partial n_j} \delta n_j = -\zeta\theta$$

- Two degrees of freedom contributing to the **bulk viscosity**; if muons are neglected

$$\boxed{\zeta = \frac{C^2}{A} \frac{\gamma_e}{\omega^2 + \gamma_e^2}} \qquad A = \frac{\delta\mu_e}{\delta n_n}\bigg|_{n_B} \quad C = n_B \frac{\delta\mu_e}{\delta n_B}\bigg|_{Y_n} \quad \gamma_e = \lambda_e A$$

- **Maximum bulk viscosity** at temperature where the relaxation rate $\gamma_e(T) = \omega$
- **Vanishing bulk viscosity** in limits of **slow** ($\gamma_e \ll \omega$) and **fast** ($\gamma_e \gg \omega$) equilibration

Bulk viscosity of quark matter

- Next consider **density oscillations** in quark matter with frequency ω

$$n_j(t) = n_{j0} + \delta n_j(t), \quad \delta n_j(t) \sim e^{i\omega t}, \qquad j = \{u, d, s, e\}$$

- Particle production equations due to **semi-leptonic (Urca)** and **non-leptonic** reactions

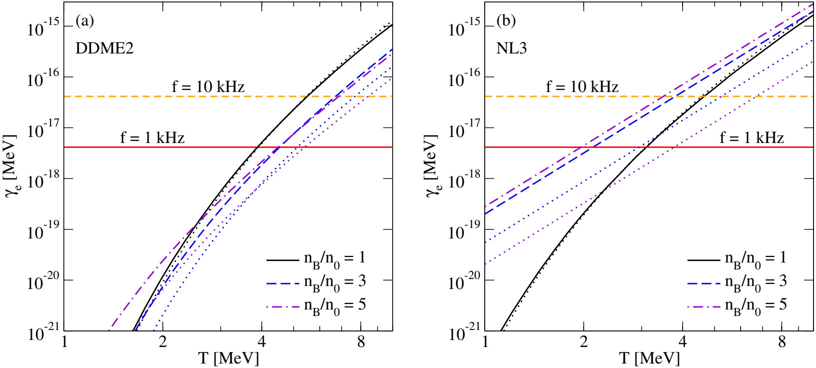
$$\begin{aligned}
\frac{\partial n_d}{\partial t} + \theta n_{d0} &= -\lambda_d \delta\mu - I_{ud\to us} \\
\frac{\partial n_s}{\partial t} + \theta n_{s0} &= -\lambda_s \delta\mu + I_{ud\to us} \\
\frac{\partial n_u}{\partial t} + \theta n_{u0} &= (\lambda_d + \lambda_s)\delta\mu \\
\frac{\partial n_e}{\partial t} + \theta n_{e0} &= (\lambda_d + \lambda_s)\delta\mu
\end{aligned}$$

- **Bulk viscosity** from Urca processes (assuming $\mu_s = \mu_d$)

$$\boxed{\zeta = \frac{C^2}{A}\frac{\gamma}{\omega^2 + \gamma^2}} \qquad A = \frac{\delta\mu}{\delta n_u}\bigg|_{n_B} \quad C = n_B \frac{\delta\mu}{\delta n_B}\bigg|_{Y_u} \quad \gamma = (\lambda_d + \lambda_s)A$$

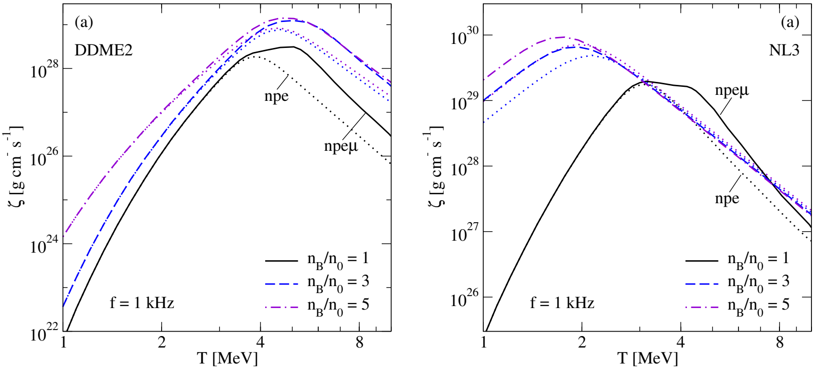
- **Maximum bulk viscosity** at temperature where the relaxation rate $\gamma(T) = \omega$
- **Vanishing bulk viscosity** in limits of **slow** $(\gamma \ll \omega)$ and **fast** $(\gamma \gg \omega)$ equilibration

Relaxation rates in baryonic matter



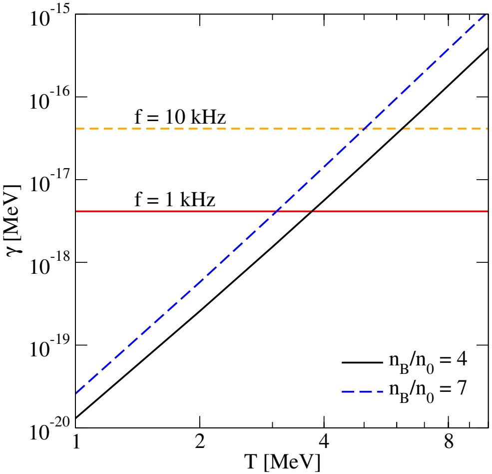
- Relaxation rate $\gamma_e(T)$ increases rapidly with temperature
- Relaxation rate **resonates** with typical **post-merger oscillation frequencies** $f \sim 1$ kHz at $2 \leq T \leq 4$ MeV and $f \sim 10$ kHz at $4 \leq T \leq 6$ MeV
- The **resonance point** shifts to lower temperatures above the direct Urca threshold

Bulk viscosity of baryonic matter ($f = 1$ kHz)



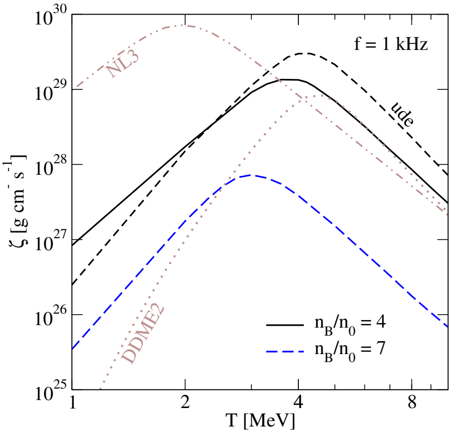
- **Bulk viscosity** attains **maximum** at $T \simeq 3 \div 5$ MeV below direct Urca threshold and $T \simeq 2$ MeV above threshold
- Muons enhance the bulk viscosity in the right side of the maximum at densities below threshold and to the left side of the maximum at densities above threshold
- **Stiffer** model NL3 predicts **larger maximum bulk viscosity** than softer DDME2

Relaxation rates in quark matter



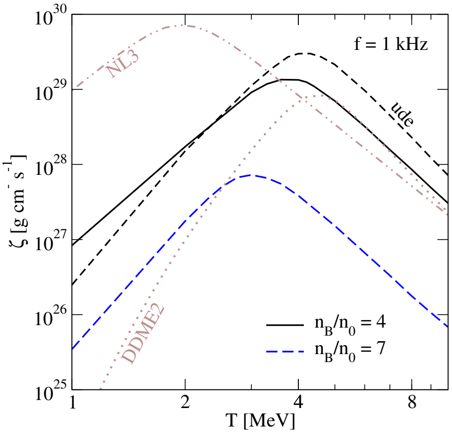
- Urca relaxation rate of quark matter is similar to that of baryonic matter
- **Resonance** around $T \simeq 3-4$ MeV at $f = 1$ kHz and $T \simeq 5-6$ MeV at $f = 10$ kHz

Bulk viscosity of 2SC quark matter



- Maximum bulk viscosity arises at $T \simeq 3 \div 4$ MeV – temperatures typical to mergers
- At $T \leq 4$ MeV bulk viscosity of quark matter lies between results of 2 baryonic models
- At $T \geq 4$ MeV bulk viscosities of baryonic and quark matter are very similar

Bulk viscosity of 2SC quark matter



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Will these bulk viscosities affect the merger dynamics?

Outline

- Introduction
- Weak interactions in dense matter
    - Baryonic matter
    - Quark matter (2SC phase)
- Models of neutron star matter
- Bulk viscosity from weak interactions
- Damping of density oscillations
- Conclusions

Estimation of density oscillation damping timescale

- Density oscillations with amplitude δn_B have the energy density

$$\epsilon = \frac{K}{18} \frac{(\delta n_B)^2}{n_B}$$

- K is the coefficient of matter incompressibility

$$K = 9 n_B \frac{\partial^2 \varepsilon}{\partial n_B^2}$$

- Energy dissipation rate per volume by bulk viscosity

$$\frac{d\epsilon}{dt} = \frac{\omega^2 \zeta}{2} \left(\frac{\delta n_B}{n_B} \right)^2$$

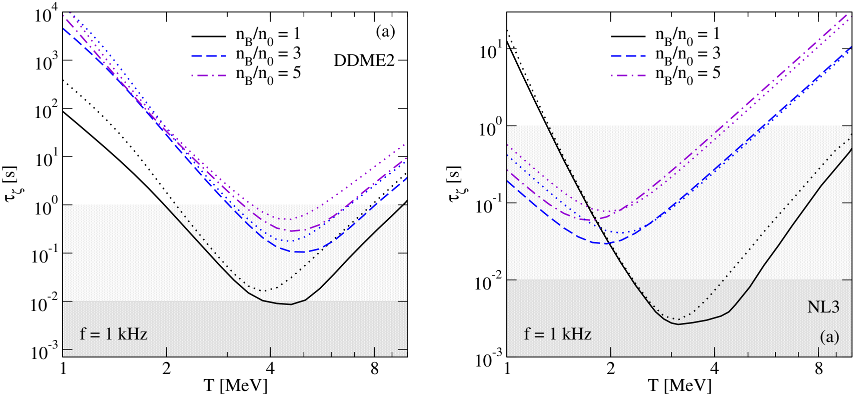
- Characteristic timescale of dissipation $\tau_\zeta = \frac{\epsilon}{d\epsilon/dt}$

$$\boxed{\tau_\zeta = \frac{K n_B}{9 \omega^2 \zeta}}$$

- For maximum bulk viscosity damping timescale is the shortest

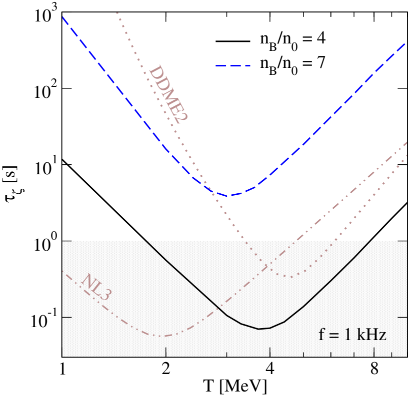
$$\tau_{\min} = \frac{2}{9\omega} \frac{K n_B}{C^2/A} \sim \frac{1}{\omega}$$

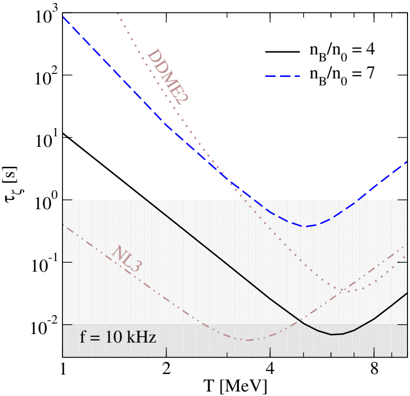
Oscillation damping timescales in baryonic matter ($f = 1$ kHz)



- Fast damping $\tau_\zeta \le 10$ ms at temperatures $T \simeq 3 \div 5$ MeV and densities $n_B \le 3n_0$
  $\Rightarrow$ **significant impact on merger dynamics**
- Stronger damping for stiffer models with direct Urca threshold
  $\Rightarrow$ **potential imprint of stiffness of EoS on observational signatures**

Oscillation damping timescales in quark matter





- Noticeable damping of low-frequency oscillations only in long-lived remnants
- Strong damping in short-lived remnants at high-frequencies $f \sim 10$ kHz
- Similar damping rates for NL3 and NJL with different critical temperatures
  $\Rightarrow$ **possible information on core composition from observational data**

Conclusions

- Urca process rates in baryonic/quark matter resonate with density oscillations of mergers
- Bulk viscosity from Urca processes has maximum at $T \simeq 2 \div 6$ MeV typical to mergers
- At its maximum bulk viscosity is strong enough to damp density oscillations in mergers
- Damping patterns may contain useful information on properties of neutron star matter

THANK YOU FOR ATTENTION!