Critical slowing down and bulk viscosity in binary neutron star mergers

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Introduction

In binary neutron star mergers, it is typically safe to assume that weak Urca interactions set the bulk viscous damping scale. However, if a low-temperature upper or lower critical endpoint is present in the QCD phase diagram, the QCD bulk viscosity is enhanced as $\zeta^{z-\alpha/\nu}$, where in Model H $z-\alpha/\nu \approx 2.8$. We perform an order of magnitude calculation to determine whether this critical slowing down can be sufficient to compete with the electroweak background.

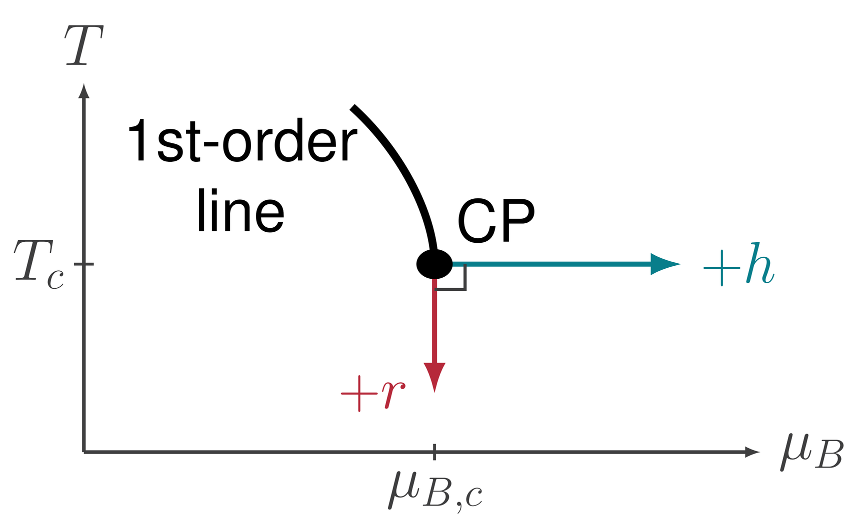
Hohenberg and Halperin, Rev. Mod. Phys. 49, 435 (1977).

Mapping Ising criticality onto the QCD phase diagram

We suppose a low-temperature QCD critical point exists and is in the Model H dynamical universality class. We further assume an Ising model mapping

$$\frac{T-T_c}{\mu_{B,c}} = -\rho w r, \qquad \frac{\mu_B-\mu_{B,c}}{\mu_{B,c}} = wh.$$

As $T_c \to 0$, the r and μ_B axes must be orthogonal to satisfy Clausius-Clapeyron, and we take the r and h axes to be orthogonal for convenience.



cf. Parotto et al., Phys. Rev. C 101, 034901 (2020), arXiv:1805.05249.

Finite merger time caps the correlation length

The growth of the correlation length is bounded:

constraint	analytic bound	estimate
finite size	$\xi \lesssim L_{\text{remnant}}$	$\sim$ km
temperature gradients	$\xi \lesssim \xi_0 \left(\frac{\rho w \mu_{B,c}}{\xi_0 \lvert\nabla T\rvert}\right)^{\nu/(1+\nu)}$	$\sim 100\,\text{nm}$
finite time	$\xi \lesssim \xi_0 \left(\frac{\tau}{\tau_0}\right)^{1/z}$	$\sim 10\,\text{nm}$

For timescales $\tau \sim 1\,\text{ms}$ and gradients $\lvert\nabla T\rvert \sim 5\,\text{MeV/km}$, finite time is probably the strictest constraint.

QCD bulk viscosity near a critical point

Using linear response theory for our chosen mapping,

$$\zeta_{\text{CSD}}(\omega) = \left(\frac{\rho w \gamma_{\pm}^{R}}{\pi}\right)^2 T^3(\tau_0^2\xi_0^3)\left(\frac{e+P}{T}\right)^2 \frac{I_K(\omega)}{\Gamma_\xi}\left(\frac{\xi}{\xi_0}\right)^{-\alpha/\nu}$$

where the relaxation rate of the order parameter is

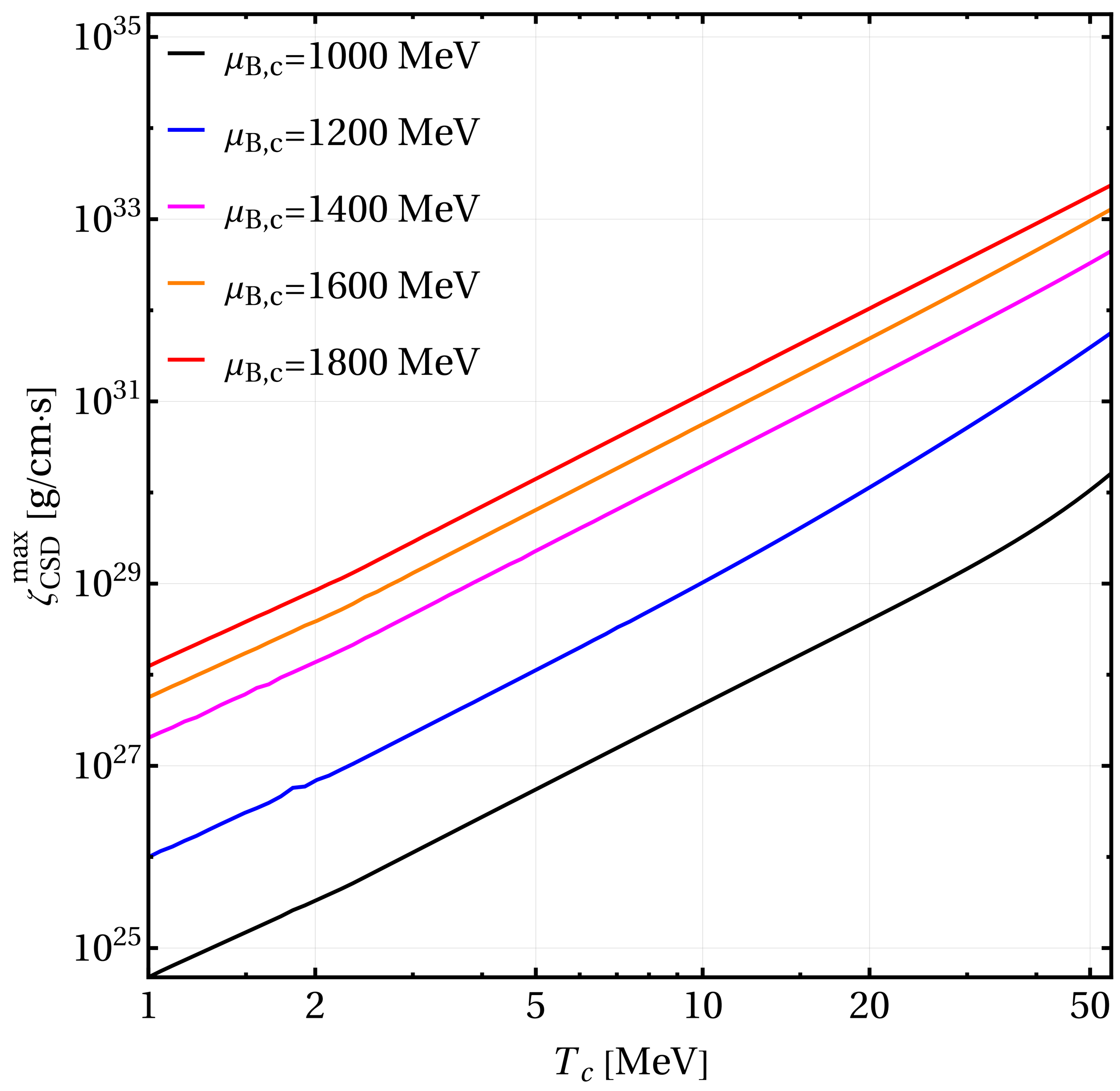
$$\Gamma_\xi = \frac{T}{3\pi\eta_0\xi^z}$$

and $\omega I_K/\Gamma_\xi$ has a resonant peak at $\Gamma_\xi \sim \omega$. We use $\omega = 1\,\text{kHz}$, $\xi_0 \sim \tau_0 \sim 1\,\text{fm}$, and an excluded-volume hadron resonance gas for the non-critical equation of state and shear viscosity.

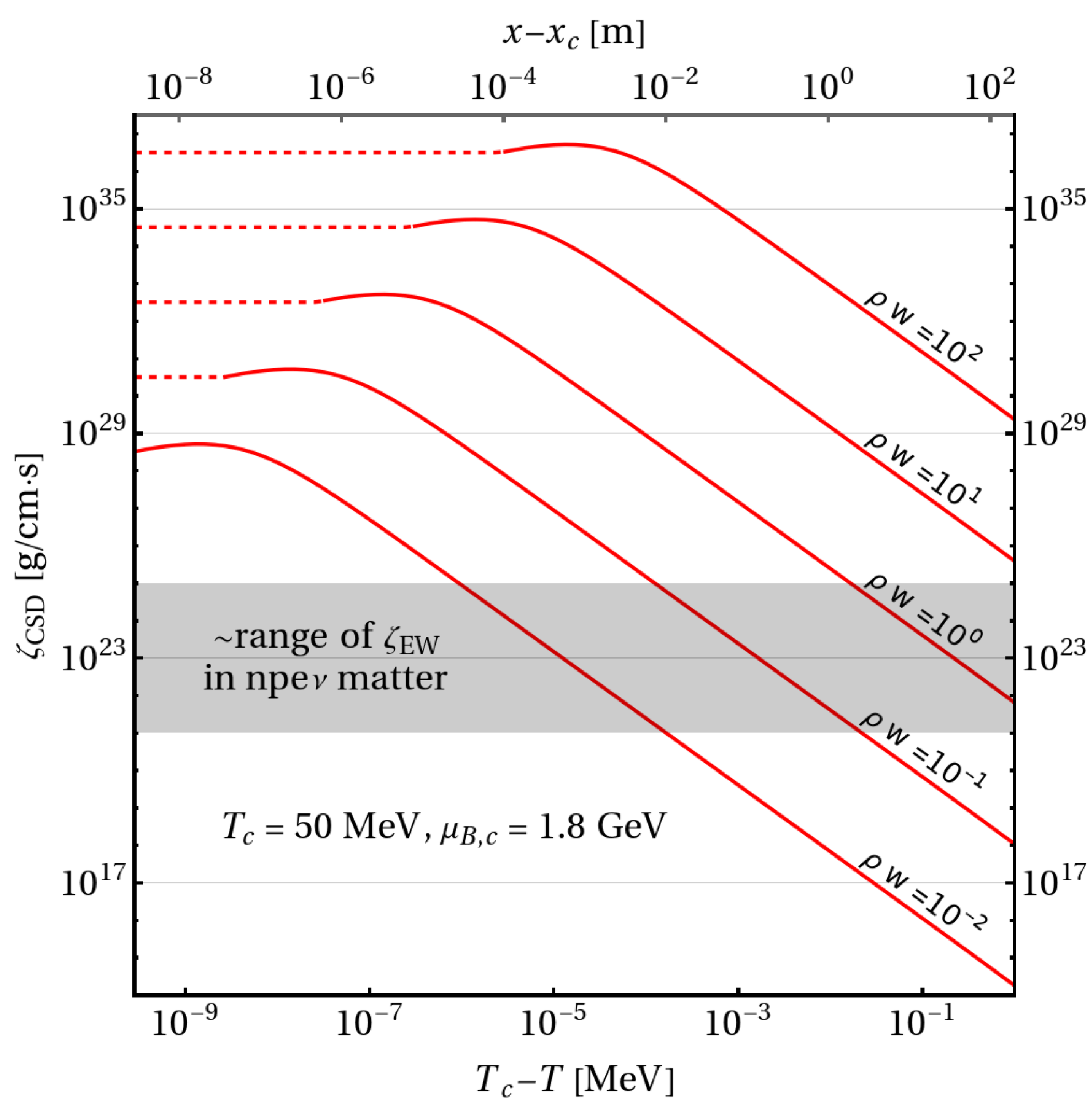
Martinez, Schäfer, and Skokov, Phys. Rev. D 100, 074017 (2019), arXiv:1906.11306.

Estimated maximum critical bulk viscosity (with $\rho w = 1$)

At $\xi = \xi_{\text{max}}$, our order-of-magnitude estimate for the value of ζ_{CSD} can be many orders of magnitude higher than typically estimated bulk viscosity due to Urca processes.



Enhancement away from the critical point



For $\rho w \gtrsim \mathcal{O}(1)$, the critical contribution can match or exceed electroweak dissipation across tens to hundreds of meters while hydrodynamics remains valid.

Outlook

To determine whether a significant local enhancement of bulk viscosity would be measurable through a gravitational wave signal, the next step is to incorporate critical dynamics into merger simulations using a realistic finite-μ_I non-critical equation of state. Additionally, we hope to study other promising critical effects such as enhanced scattering of neutrinos, which could affect cooling rates.

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