Transport of unpaired quark matter in neutron star densities

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Holographic perspectives on chiral transport

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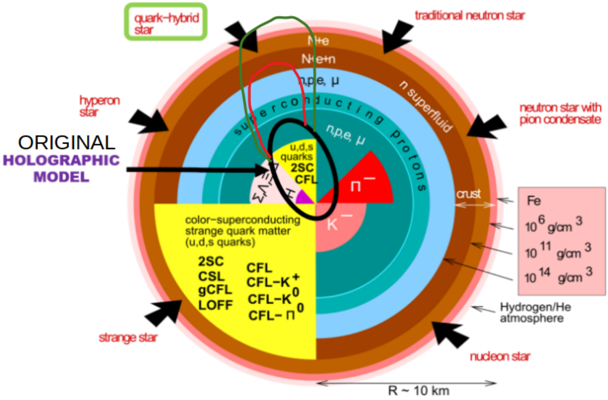
Motivation

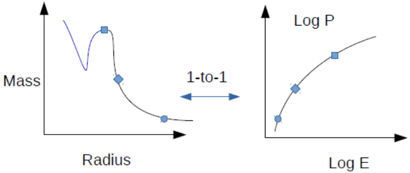
- Can holography be useful in studying quark/nuclear matter relevant for neutron stars?
  [reviews: Järvinen 2110.08281, Hoyos-NJ-Vuorinen 2112.08422]



- Does deconfined matter exist in Nature?

Motivation

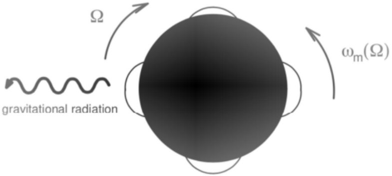
- EoS (pressure$\leftrightarrow$energy density) determines most important properties of stars,



  but alone is insufficient to address if $\exists$ quark matter.
- No symmetry arguments (quark-hadron continuity).
- Sharp deconfinement (Occam's razor?) phase transition may lead to distinct signals
- Root for transport: quarks are relativistic unlike hadrons

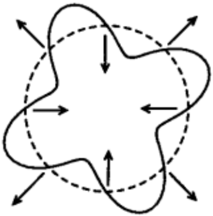
r-mode instability window

- Non-radial modes are driven unstable if the star rotates fast enough.
- These modes are strongly sheared and damped.
- $\nexists$full GR study, estimate: [Andersson-Kokkotas gr-qc/0010102]



[Figure:Bratton et al.'22]

$$\frac{dE}{dt} = -2\frac{E}{\tau}$$
$$\propto \exp\left(i\omega_m(\Omega)t + im\phi - t/\tau_m(\Omega)\right)$$

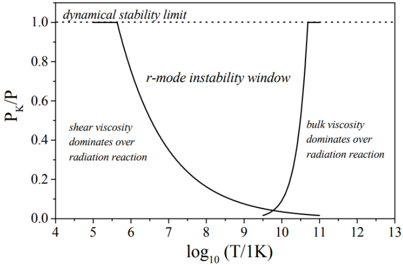


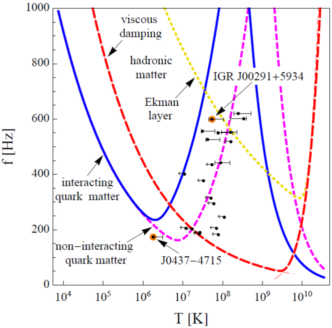
- Maximum stable frequency for the star:

$$0 = 1/\tau_m(\Omega) = -1/\tau_{\mathrm{GW}} + 1/\tau_\eta + 1/\tau_\zeta$$

[Figure: Lindblom'98]

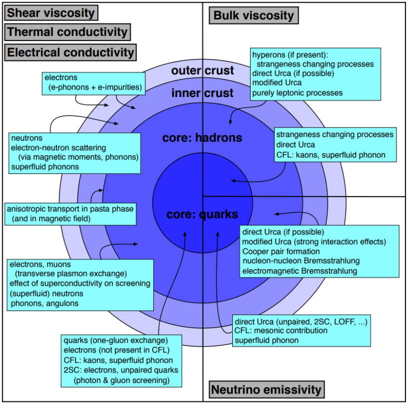
- Indirect evidence for quark matter?
  [Figures: Andersson-Kokkotas gr-qc/0010102,Alford-Schwenzer 1310.3524]





- Bulk viscocity ζ seems interesting

Relevance of transport in stars



[Schmitt-Shternin 1711.06520]

- Damping of oscillations: shear η and bulk ζ viscosities
- Cooling: thermal conductivity κ, neutrino emissivities
- Magnetic fields: electric σ and thermal conductivities
- Mergers: viscosities, conductivities, evolution far from equilibrium

Caution...

- Computing conductivities need care since spatial homogeneity
  - Lorentz invariance: only one hydro transport coeff σ
  - No force condition:

$$\rho_i E - s\nabla_i T = 0$$

  - Conductivities

$$J^i = \sigma^{ij} E_j \quad , \quad \sigma^{ij} = \sigma \frac{\epsilon + p}{Ts} \delta^{ij}$$

$$Q^i = -\kappa^{ij} \nabla_j T \quad , \quad \kappa^{ij} = \frac{\mu}{T} \sigma \frac{\epsilon + p}{\rho} \delta^{ij}$$

- Quiescent stars
  - Local charge neutrality: $\frac{2}{3} n_u - \frac{1}{3} n_d - \frac{1}{3} n_s - n_e = 0$
  - Beta equilibrium: $\mu_s = \mu_d$, $\mu_u = \mu_d - \mu_e$

Holographic models encompassed

Action $S = S_{\text{glue}} + S_{\text{flavor}}$ w/ $\kappa_5^2 \sim 1/N_c^2, \mathcal{T}_b \sim N_f/N_c$:

$$S_{\text{glue}} = \frac{1}{2\kappa_5^2} \int d^5x \sqrt{-g} \left(R - \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - V(\phi, \chi) \right)$$

$$S_{\text{flavor}} = -\frac{\mathcal{T}_b}{2\kappa_5^2} \int d^5x \mathcal{Z}(\phi, \chi) \sqrt{-\det(g_{\mu\nu} + \kappa(\phi, \chi)\partial_\mu \chi \partial_\nu \chi + \mathcal{W}(\phi, \chi) F_{\mu\nu})}$$

- metric $g_{\mu\nu} \leftrightarrow$ energy-momentum tensor
- flavor gauge field $A_\mu \leftrightarrow$ baryon charge
- "dilaton" $\phi \leftrightarrow$ gauge coupling
- "tachyon" $\leftrightarrow$ quark masses

Our examples include:

- bottom-up V-QCD model
- top-down D3-D7 model in the quenched approximation

Transport for flavor independent masses

- Transport determined at the black hole horizon
[Hoyos-NJ-Järvinen-Subils-Tarrio-Vuorinen 2005.14205,2109.12122]

$$T(\text{surface gravity}) \ , \ s(\text{area}) \ , \ \rho(\text{electric flux})$$
$$\phi_H = \phi(r_H) \ , \ \chi_H = \chi(r_H)$$

- Boundary values determine thermo: ϵ, p, μ
- Thermal and electric conductivities

$$\sigma = \frac{\mathcal{W}_H}{2\kappa_5^2 g_{xx}^H}\sqrt{(2\kappa_5^2\rho)^2 + (g_{xx}^H)^3\mathcal{T}_b^2\mathcal{W}_H^2\mathcal{Z}_H^2}$$

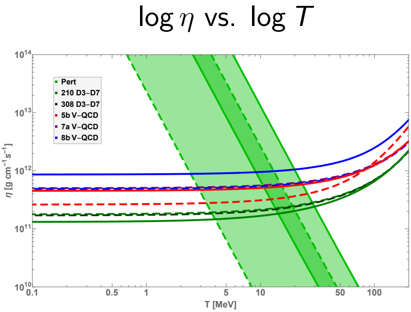
- Shear viscosity

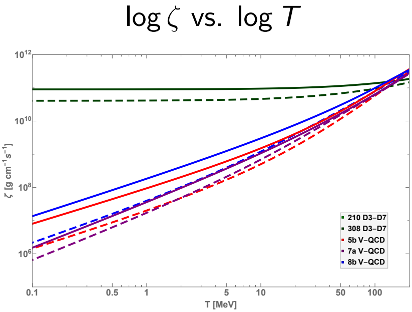
$$\eta = \frac{s}{4\pi} = \frac{(g_{xx}^H)^{3/2}}{2\kappa_5^2} + \frac{s_{\text{flavor}}}{4\pi}$$

- Bulk viscosity

$$\frac{\zeta}{\eta} = (s\partial_s\phi_H + \rho\partial_\rho\phi_H)^2 + \frac{2\kappa_5^2}{(g_{xx}^H)^{1/2}}\frac{\kappa_H}{\mathcal{W}_H^2}(s\partial_s\chi_H + \rho\partial_\rho\chi_H)^2$$

Transport of cool quark matter



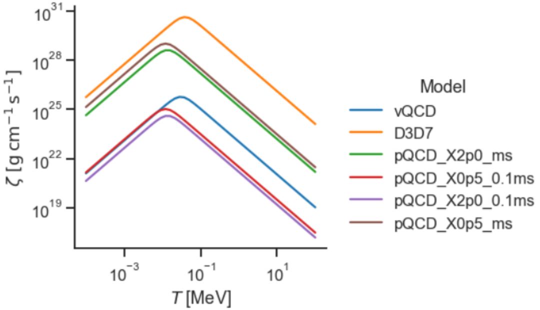


- Predictions for viscosities for unpaired quark matter (dashed $\mu = 450$ MeV, solid $\mu = 600$ MeV)
- Large deviation from perturbative QCD results [Heiselberg-Pethick'93,Arnold-Dogan-Moore'06]
- Small results due "idealized" case. Flavor-independent masses so get only QCD contributions, no weak interactions or electrons

- Bulk viscosity can be enhanced by resonant EW processes [Alford-Mahmoodifar-Schwenzer '12]

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

- Relevant for unequal, flavor-dependent, quark masses [Gorda-Hoyos-NJ-Järvinen-Kurkela-Paatelainen-Rojas-Säppi-Vuorinen]



$$\zeta_{\text{D3-D7}}\Big|_{T=0} = \frac{4\lambda_1 \mu_d^6 \left(m_s^2 - m_d^2\right)}{\pi^4 \lambda_1^2 \left(-6\mu_d^2 + m_d^2 + m_s^2\right)^2 + \omega^2 \left(m_d^2 - 3\mu_d^2\right)^2 \left(m_s^2 - 3\mu_d^2\right)^2}$$

$$\lambda_1 = \frac{64 G_F^2 \sin^2(\theta_c) \cos^2(\theta_c)}{5\pi^3} \mu_d^5 T^2$$

Outlook

- Observable effects in neutron star physics?
- Extensions:
  - neutrino emissivity
  - magnetic field
  - anisotropic equation of state
  - inhomogeneous phases
  - quark pairing (color "superconductivity")

Grazie a tutti!