Phase Structure and Transport Properties of (Very) Dense QCD Matter

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High Density Quark Matter

Goal: What is the densest (2nd densest, 3rd densest, ...) phase of (three flavor) quark matter?

What are the properties (thermodynamics, transport, ...) of these phases?

Are these properties consistent with observational constraints? Do they provide unique signatures?

Strategy: Weak coupling/effective field theory methods.

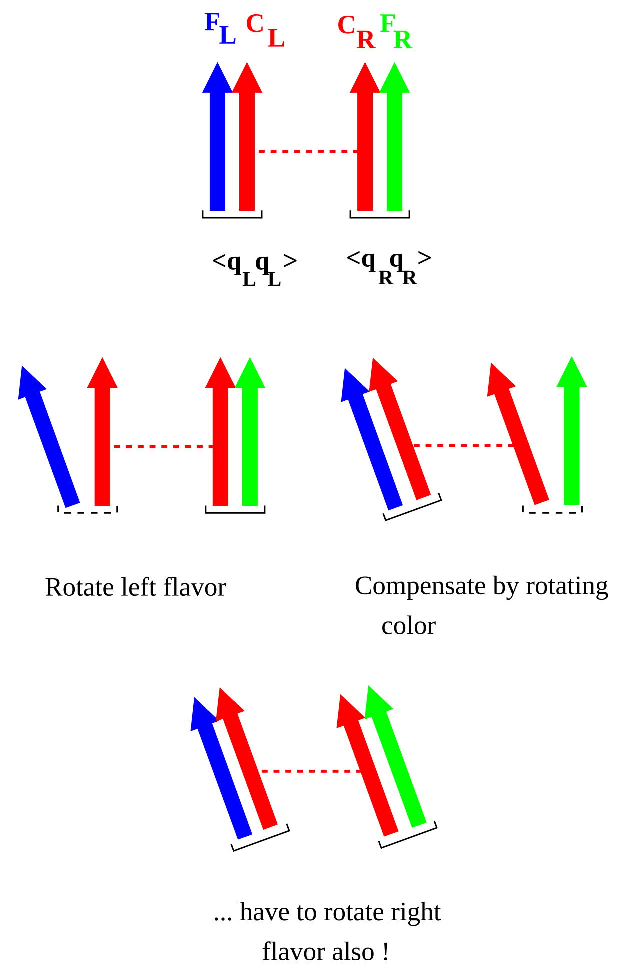
$N_f = 3$: CFL Phase

Consider $N_f = 3$ $(m_i = 0)$

$$\langle q_i^a q_j^b \rangle = \phi \, \epsilon^{abI} \epsilon_{ijI}$$

$$\langle ud \rangle = \langle us \rangle = \langle ds \rangle$$

$$\langle rb \rangle = \langle rg \rangle = \langle bg \rangle$$



Symmetry breaking pattern:

$$SU(3)_L \times SU(3)_R \times [SU(3)]_C \times U(1) \rightarrow SU(3)_{C+F}$$

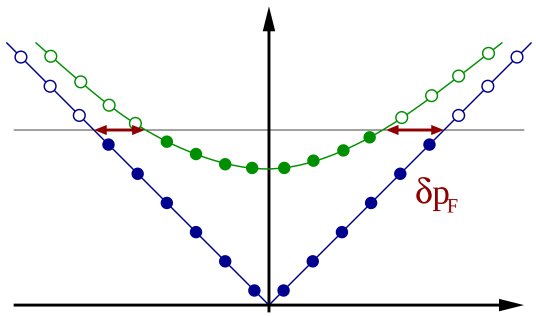
All quarks and gluons acquire a gap

$[8] + [1]$ fermions, Q integer

$$\langle \psi_L \psi_L \rangle = -\langle \psi_R \psi_R \rangle$$

Towards the real world: Non-zero strange quark mass

Have $m_s > m_u, m_d$: Unequal Fermi surfaces



$$\delta p_F \simeq \frac{m_s^2}{2p_F}$$

Also: If $p_F^s < p_F^{u,d}$ have unequal densities

Charge neutrality not automatic

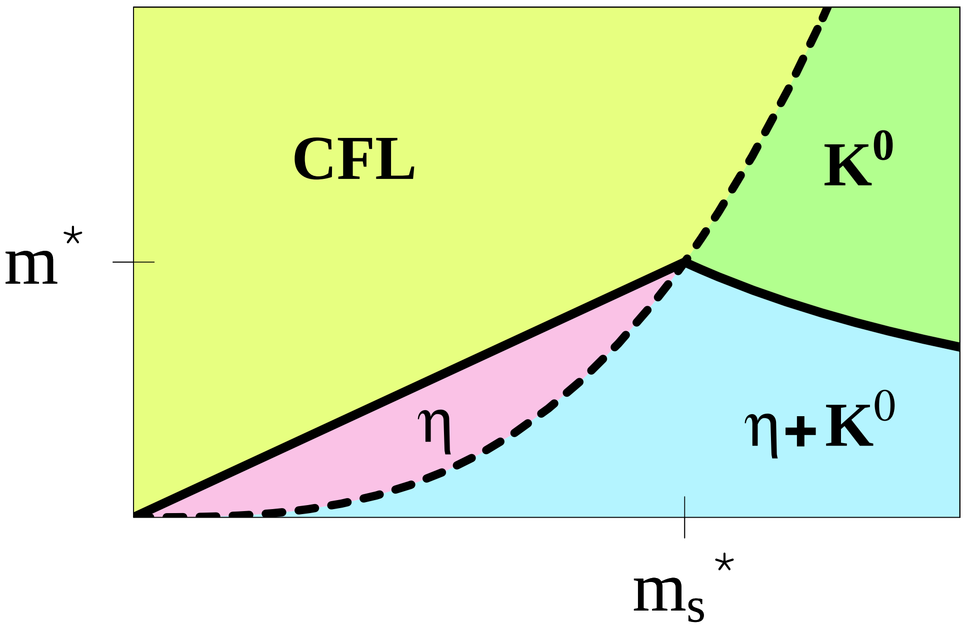
Strategy

Consider $N_f = 3$ at $\mu \gg \Lambda_{QCD}$ (CFL phase)

Study response to $m_s \neq 0$

Constrained by chiral symmetry

Phase Structure of CFL Phase



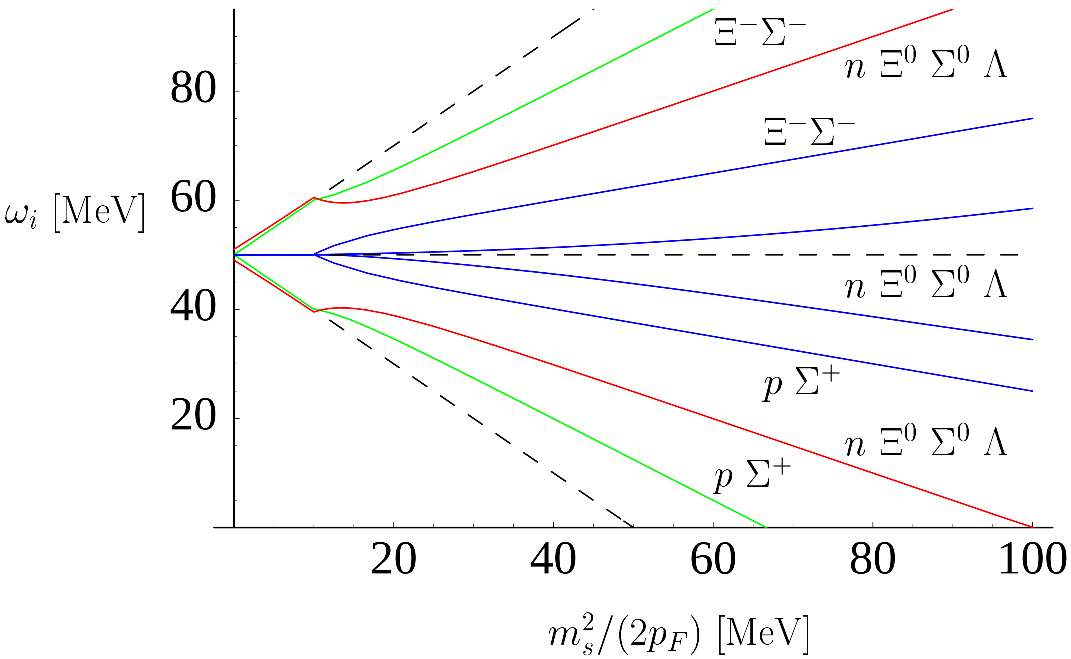
$$m_s^{crit} \sim 3.03\, m_d^{1/3} \Delta^{2/3}$$

$$m^* \sim 0.017\, \alpha_s^{4/3} \Delta$$

QCD realization of s-wave meson condensation

Driven by strangeness oversaturation of CFL state

Fermion Spectrum

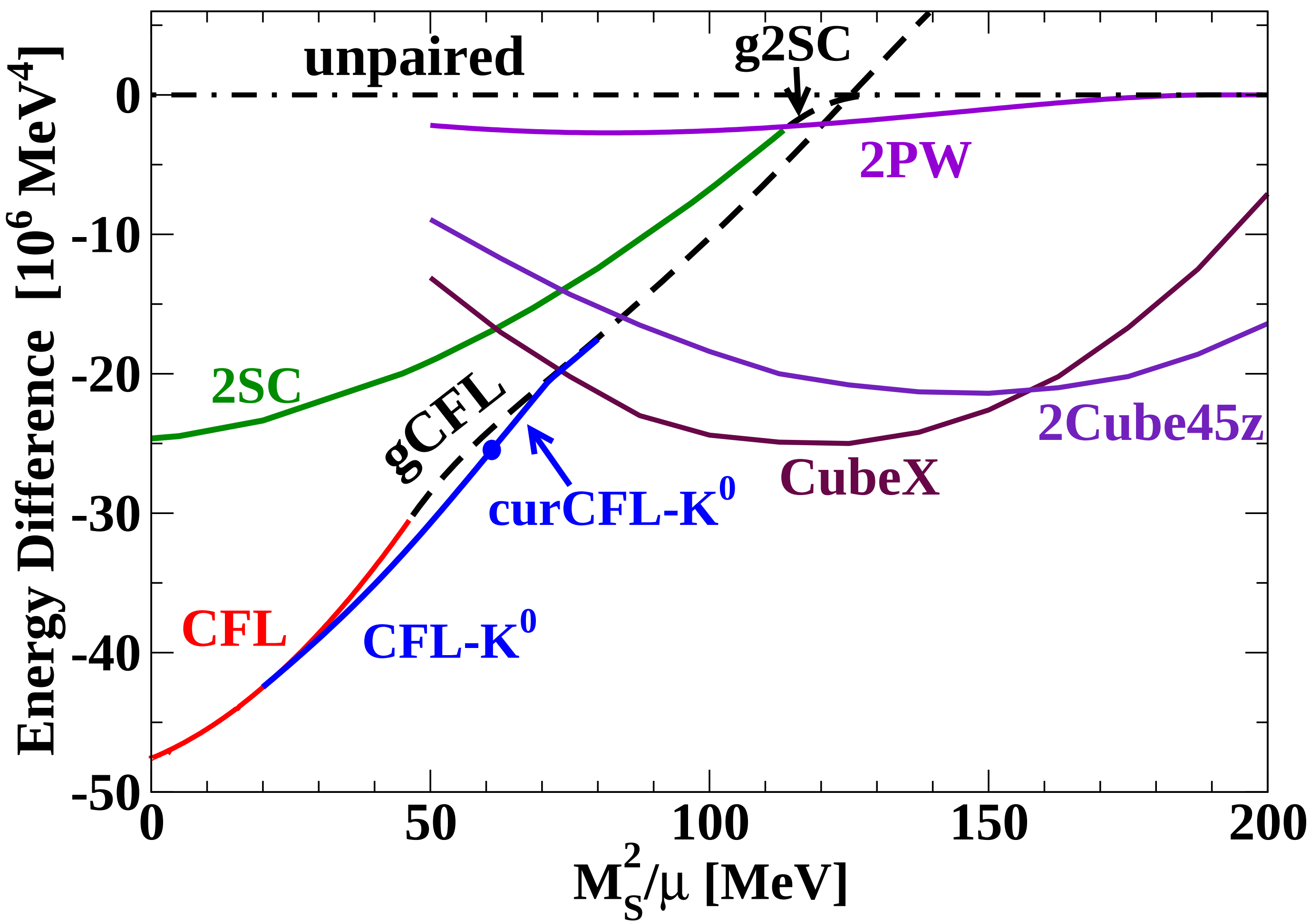


$$m_s^{crit} \sim (8\mu\Delta/3)^{1/2}$$

gapless fermion modes (gCFLK)

(chromomagnetic) instabilities ?

Competition between phases



CFL $\rightarrow$ CFLK $\rightarrow$ curCFLK $\rightarrow$ crystCFL

Transport Properties

Dissipative Terms (v^i, v_s^i normal, superfluid velocity; $w^i = v_s^i - v^i$)

$$\dot{E} = -\frac{\eta}{2}\int d^3x \left(\partial_i v_j + \partial_j v_i - \frac{2}{3}\delta_{ij}\partial_k v_k\right)^2 - \frac{\kappa}{T}\int d^3x \left(\partial_i T\right)^2$$

$$-\int d^3x \left[\zeta_2\left(\partial_i v_i\right)^2 + 2\zeta_1\left(\partial_k v_k\right)\nabla_j\left(\rho_s w_j\right) + \zeta_3\left(\partial_k\left(\rho_s w_k\right)\right)^2\right]$$

Relevant to r-mode damping

Neutrino emissivity

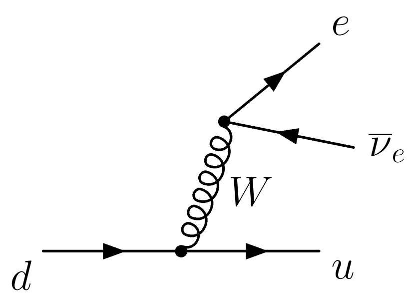
$$\epsilon_\nu = \frac{dE_\nu}{dt d^3x}$$

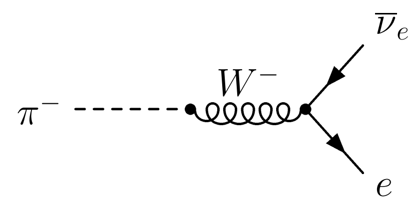
Relevant to cooling (together with κ, c_v)

Kinetics: Quasi-particles

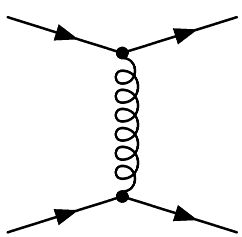
Quasi-particles control transport of flavor, energy, and momentum.

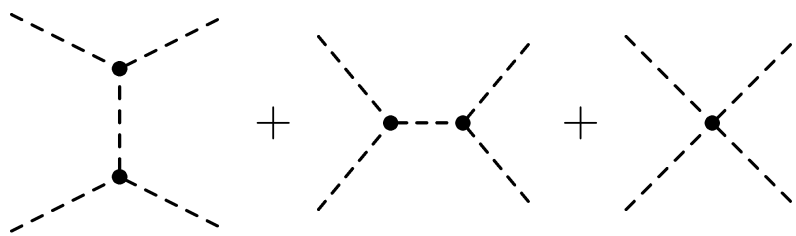
Neutrino emissivity, neutrino mean free path:



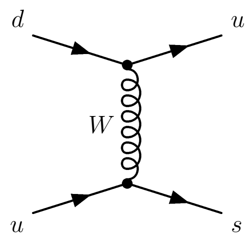


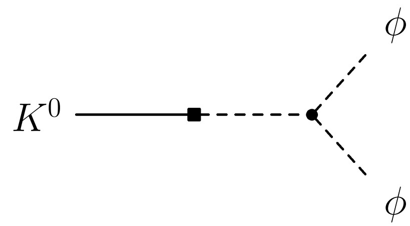
Shear viscosity, thermal conductivity



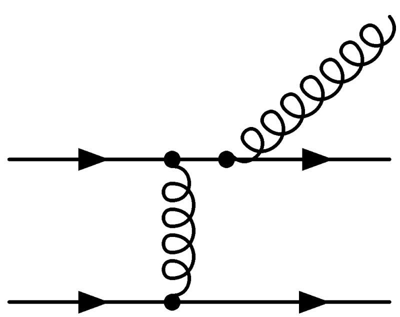


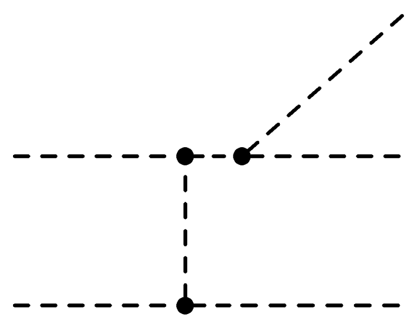
Bulk viscosity: Weak interaction





Bulk viscosity: Strong interaction





Umpaired Quark Matter

$\kappa \simeq 0.5 \frac{m_D^2}{\alpha_s^2}$	Non-FLT
$\eta \simeq 4.4 \times 10^{-3} \frac{\mu^4 m_D^{2/3}}{\alpha_s^2 T^{5/3}}$	Non-FLT
$\zeta \simeq \frac{\alpha T^2}{\omega^2 + \beta T^4} \quad (\alpha, \beta^{1/2} \sim G_F^2)$	QURCA
$\epsilon_\nu \simeq \frac{457}{630} \alpha_s G_F^2 T^6 \mu_e \mu_u \mu_d$	FLT, Non-FLT

CFL Quark Matter

$$\eta = 1.3 \times 10^{-4} \, \frac{\mu^8}{T^5}$$ phonons

$$\zeta_2 = 0.011 \frac{m_s^4}{T}$$ phonons

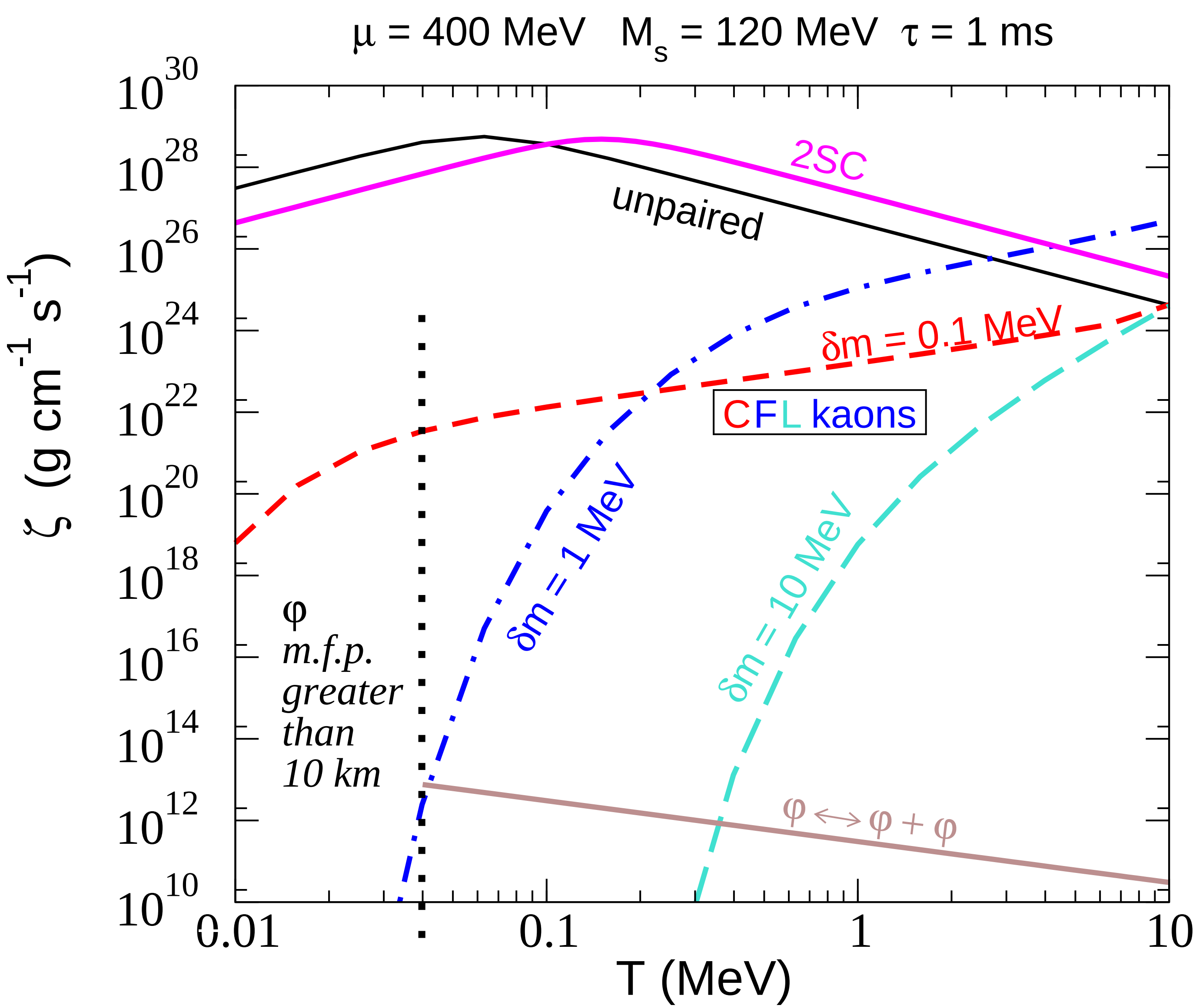
$$\zeta_2 = \frac{C\gamma_K}{\omega^2 + \gamma_K^2} \quad (\gamma_K \sim G_F^2 f_K^2)$$ weak kaon decay

$$\epsilon_\pi \sim A G_F^2 f_\pi^2 m_\pi^2 n_\pi$$ pion (kaon) decay

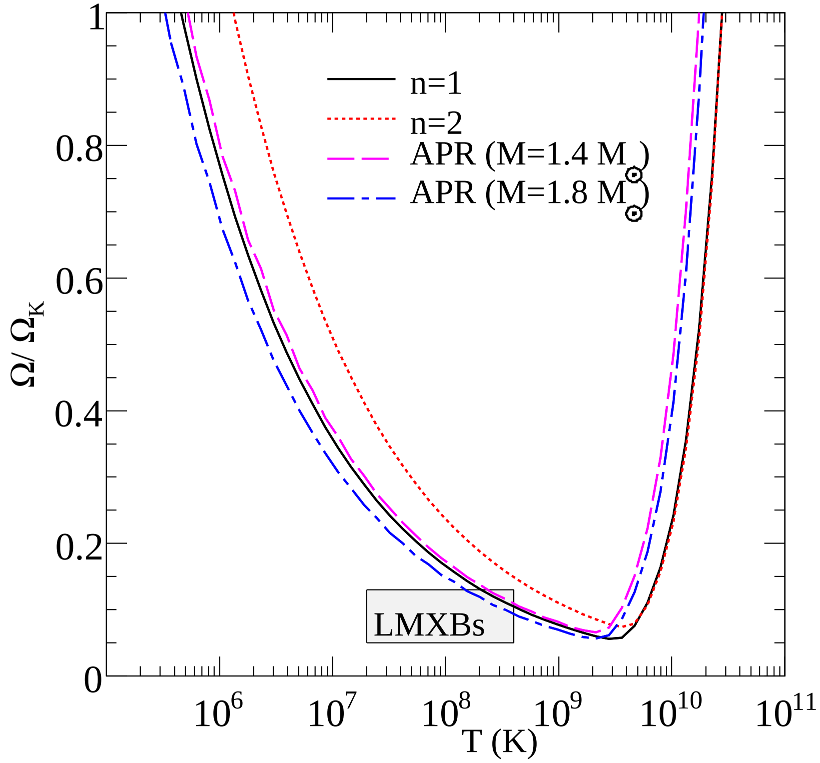
$$\kappa \simeq 4.01 \times 10^{-2} \, \frac{\mu^8}{\Delta^6} \, \mathrm{MeV}^2 \, .$$ phonons, kaons

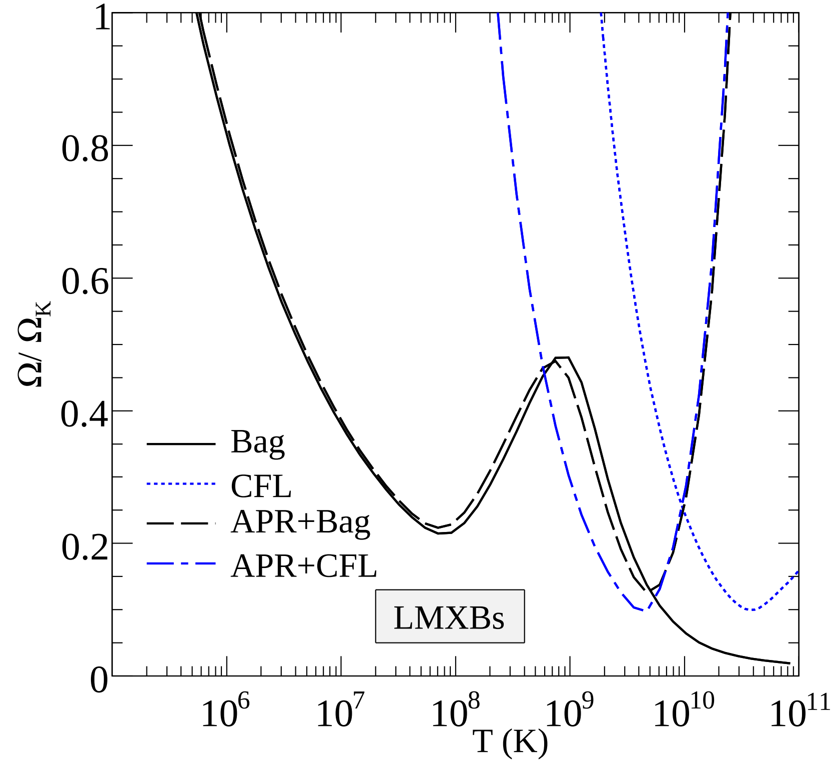
Also $\zeta_1 \sim m_s^2/(\mu T)$ and $\zeta_3 \sim 1/(\mu^2 T)$.

Bulk viscosity: CFL vs unpaired quark matter



R-mode stability





Jaikumar, Rupak, Steiner (2010)

Summary

Order of phases (going down in density): CFL, CFLK, curCFL, ...

Transport coefficients available for unpaired quark matter, CFL, some CFLK.

Questions: Multi-fluid hydro, other mechanisms (friction at interfaces, mutual friction), R-mode profiles in hybrid stars with very inhomogeneous dissipation, dissipation in non-linear regime.