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SOUND in QUARK MATTER

- Why should we listen to it?

Paradigm shift — from QGP via sQGP towards to an ALMOST IDEAL FLUID

Sound is the only long-lived propagating mode in a near-ideal fluid

PLAN of the TALK

- Quark Matter: History. Concepts. Observations
- Sound Mode. Sources of sound
- The speed of sound and EoS
- Breaking the sound barrier in Neutron Stars
- Sound attenuation and bulk viscosity
- Critical slowing down
- Very close to T_c
- Fluctuation-dissipation theorem
- Speed of sound in SU(3) gluodynamics → 1806.09407

① Terminology in Historical Retrospective

Quark Matter: N. Itoch, 1970, neutron stars

Quark Gluon Plasma (QGP): Ed. Shuryak, 1978

QCD Phase Diagram: N. Cabibbo, Parisi 1975;

Gordon Baym famous plot 1976 + HIC idea → Fig 1 →

② Heavy Ion Collisions (HIC): from early days onwards to FAIR and NICA

The Bevelac (LBL), AGS (BNL), SPS (CERN).

SPS - Maurice Jacob "There is no doubt that a new state of matter..."

CERN Press Release Feb 2000: "new state of matter created at CERN" 1994

RHIC (BNL), proposed 1984, first beams 1990, operation 2000 – present, Au-Au. LHC (CERN) 2009 – present

Future machines: FAIR (GSI), NICA (Dubna)

Fig. 1

PHASE DIAGRAM OF NUCLEAR MATTER

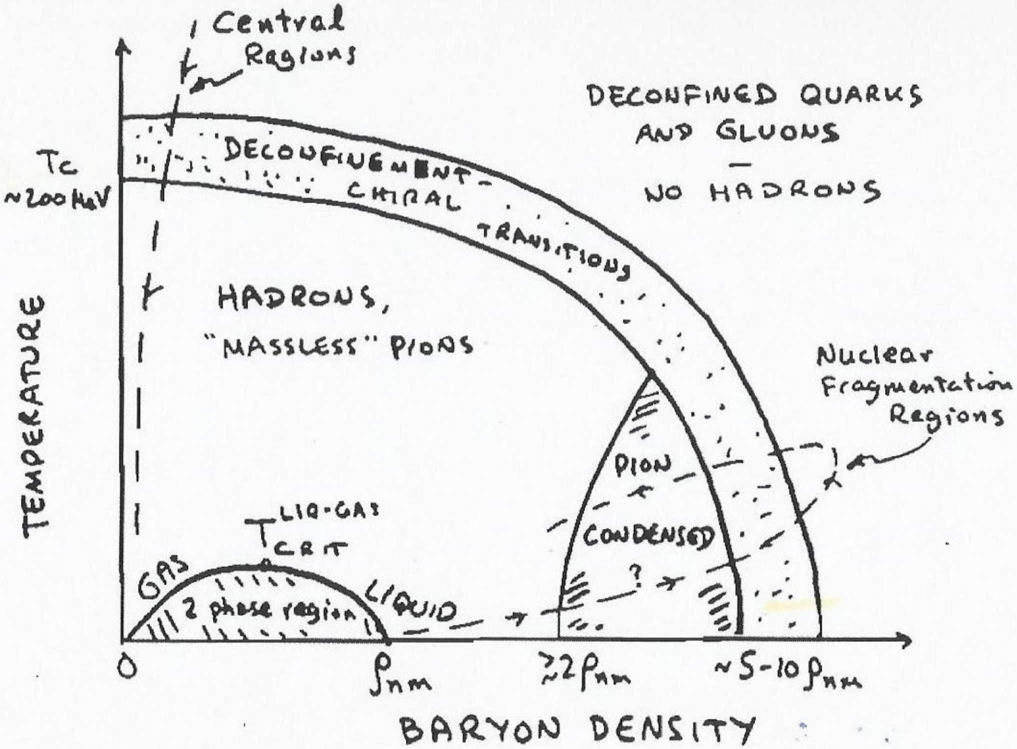


Fig. II.9-A. Expected phases of nuclear matter at various temperatures and baryon (or nucleon) densities, showing the "hadronic phase" including a gas-liquid phase transition region, and the transition region to deconfined quarks and gluons. The dashed lines illustrate trajectories in this phase diagram that can be explored in ultra-relativistic heavy ion collisions.

A light-touch list of the principal RHIC and LHC discoveries

- Azimuthal asymmetry known as elliptic flow v_2

$$dN/d\varphi \propto 1+2v_2(p_T)\cos(\varphi-\Psi_{RP})$$

- Strong suppression of high energy jets and heavy quarks
- The strongest (?) magnetic field in the Universe created in peripheral HIC, $eB \sim 10^{19}-10^{20}$ G
- Collective phenomena in small systems, p+Pb, even p+p
- Rapid Hydronamization $\begin{cases} 0.2-0.6\ \mathrm{fm}/c & \text{LHC} \\ 0.4-1.0\ \mathrm{fm}/c & \text{RHIC} \end{cases}$

→ almost ideal fluid → sound mode

SOURCES of SOUND

Sound is produced and propagates from QGP era through T_c till the chemical freeze out

The sources of sound

(a) Quantum fluctuations in the wavefunctions of colliding nuclei

(b) Jet propagating through the medium

(c) Sound from the phase transition near T_c (boiling tea pot)

Sound manifestations (possible)

(a) Sound modes behind v_2 flow

(b) Periodic oscillations in p_T distributions

- Sound velocity – an insight into EoS
- Conformal value $c_s^2 = 1/3$
- Breaking the sound barrier in two-solar-mass neutron stars

$$c_s^2 = \frac{\partial p}{\partial \varepsilon} = \frac{\partial p/\partial T}{\partial \varepsilon/\partial T} = \frac{s}{c_V} \begin{cases} \leq 1 & \text{causality} \\ > 0 & \text{thermodynamic stability} \end{cases}$$

$$c_s^2 = \frac{1}{3} \rightarrow \begin{cases} \text{conformal symmetry, } \varepsilon = 3p \\ \text{high } T \text{ and high } \mu \text{ limits of asymptotically} \\ \text{free QCD} \end{cases}$$

Deviation from conformality $\propto (1 - 3c_s^2(T))^2$

Classical gas $PV^\gamma = \text{const}$, $c_s^2 = \frac{\gamma}{3} \langle v^2 \rangle$

Nuclear matter near the saturation density $c_s \simeq 0.15$.

$c_s = 1$ Zeldovich model (1962)

$\longrightarrow$ Fig 2

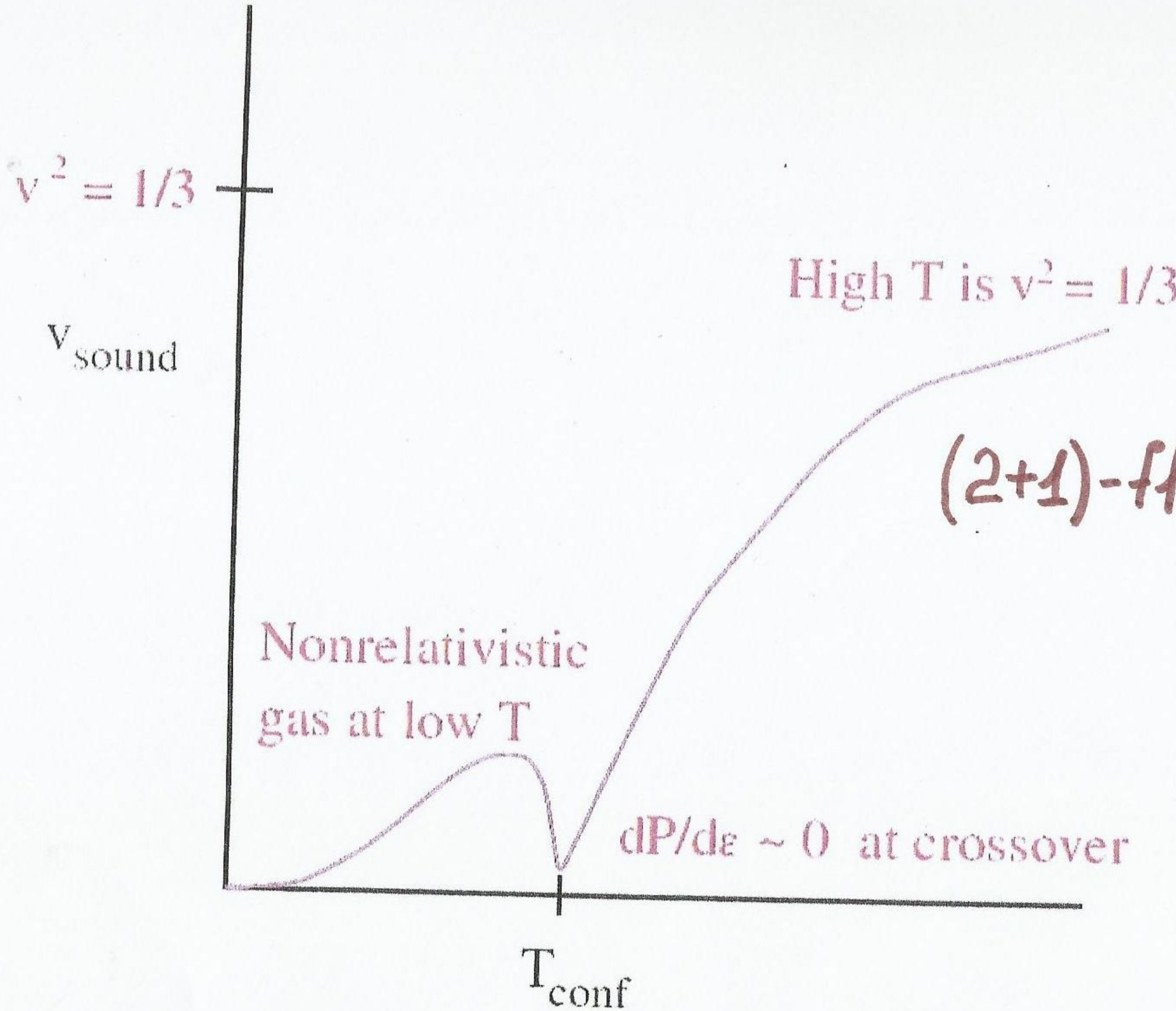


Fig. 6: The sound velocity as a function of temperature

EoS

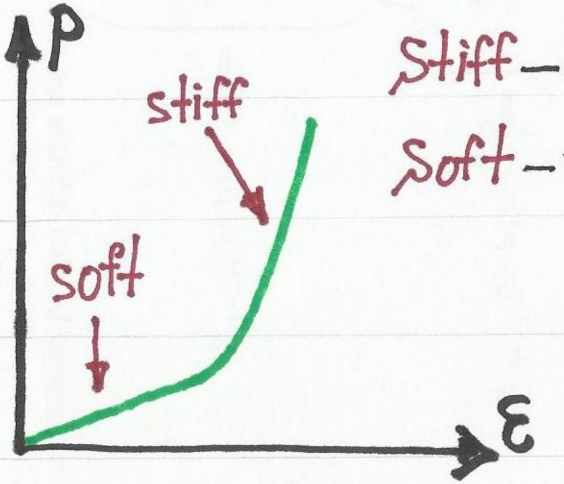
EoS: $p = p(\varepsilon, n_B)$, or $p = p(T, \mu_B)$

EoS: how $\vec{\nabla}\varepsilon \to \vec{\nabla} p$

- Neutron Stars → Mass-Radius relation

EoS → M_{max} ∀R. The higher $\underline{\underline{p}}$ for given $\underline{\underline{\varepsilon}}$ –
– the larger is M_{max}

Recently Neutron Stars $M \simeq 2 M_\odot$ – very stiff EoS



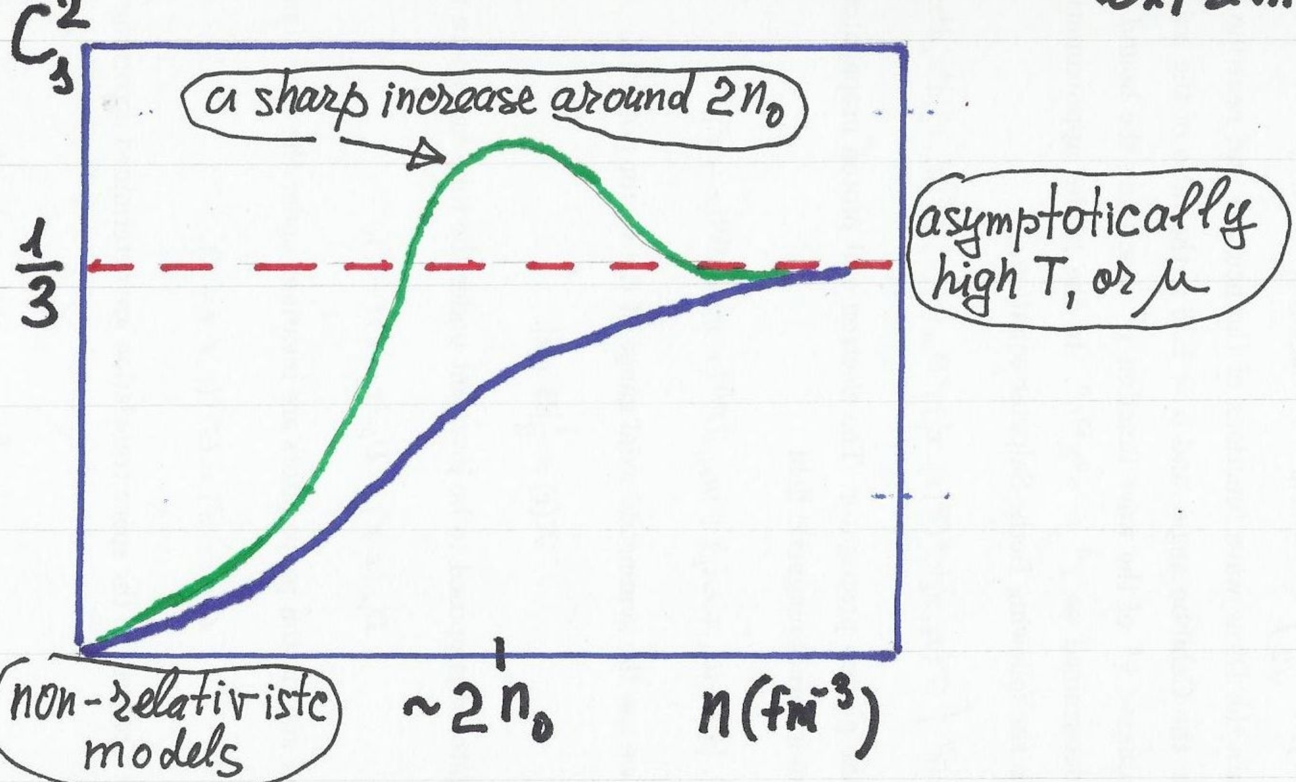
Stiff – hard to compress, cold nuclear matter, NS

Soft – very compressive, quark matter ~ $\underline{\underline{T_c}}$

$$c_s^2 < \frac{1}{3} \to M_{max} \leq 2 M_\odot$$

SOUND VELOCITY BOUND and NEUTRON STARS

possible interpolations between the two extremes



Description interms of nucleons inconsistent with $2M_\odot$ NS?

SOUND ATTENUATION and BULK VISCOSITY

- From Stokes-Kirchoff to Mandelshtam-Leontovich
- Critical slowing down. Slow relaxation theory
- Striking acoustic properties near the phase transition
- Divergent bulk viscosity
- Fluctuation-dissipation theorem (Kramers-Kronig relationship)

Anomalous sound attenuation. Slow mode

From Stokes-Kirchoff to Mandelshtam-Leontovich

$$A(x)=A_0 e^{-\gamma x}\begin{cases}\text{Stokes } \gamma=\dfrac{2\eta\omega^2}{3\rho c^3}, & \zeta=0\to \text{bulk viscosity discarded}\\ \text{Kirchoff } \gamma=\dfrac{\omega^2}{2\rho c^3}\left[\dfrac{4}{3}\eta+\varkappa\left(\dfrac{1}{c_v}-\dfrac{1}{c_p}\right)\right], & \zeta=0\to\text{bulk viscosity discarded}\end{cases}$$

ρ - density (m/v), η - shear viscosity, c - speed of sound, ζ - bulk viscosity, $\varkappa$ - heat conductivity

In some liquids Stokes-Kirchoff equations fail badly

(i) $\gamma_{exp} \gg \gamma_{theor}$, (ii) $\gamma_{exp} \not\propto \omega^2$

A possible way out: $\gamma_{exp}-\gamma_{theor}\sim \zeta$ ← here bulk visc. comes into play

The matter has been clarified by Mandelshtam and Leontovich (1937).

Critical slowing down, Slow relaxation theory

Landau Hydro $\gamma=\dfrac{\omega^2}{2\rho c^3}\left[\left(\dfrac{4}{3}\eta+\zeta\right)+\varkappa\left(\dfrac{1}{c_v}-\dfrac{1}{c_p}\right)\right]\equiv a\omega^2$

Weinberg $\zeta\propto\left(\dfrac{1}{3}-c_s^2\right)^2$, in some theories $\zeta\propto\left(\dfrac{1}{3}-c_s^2\right)$.

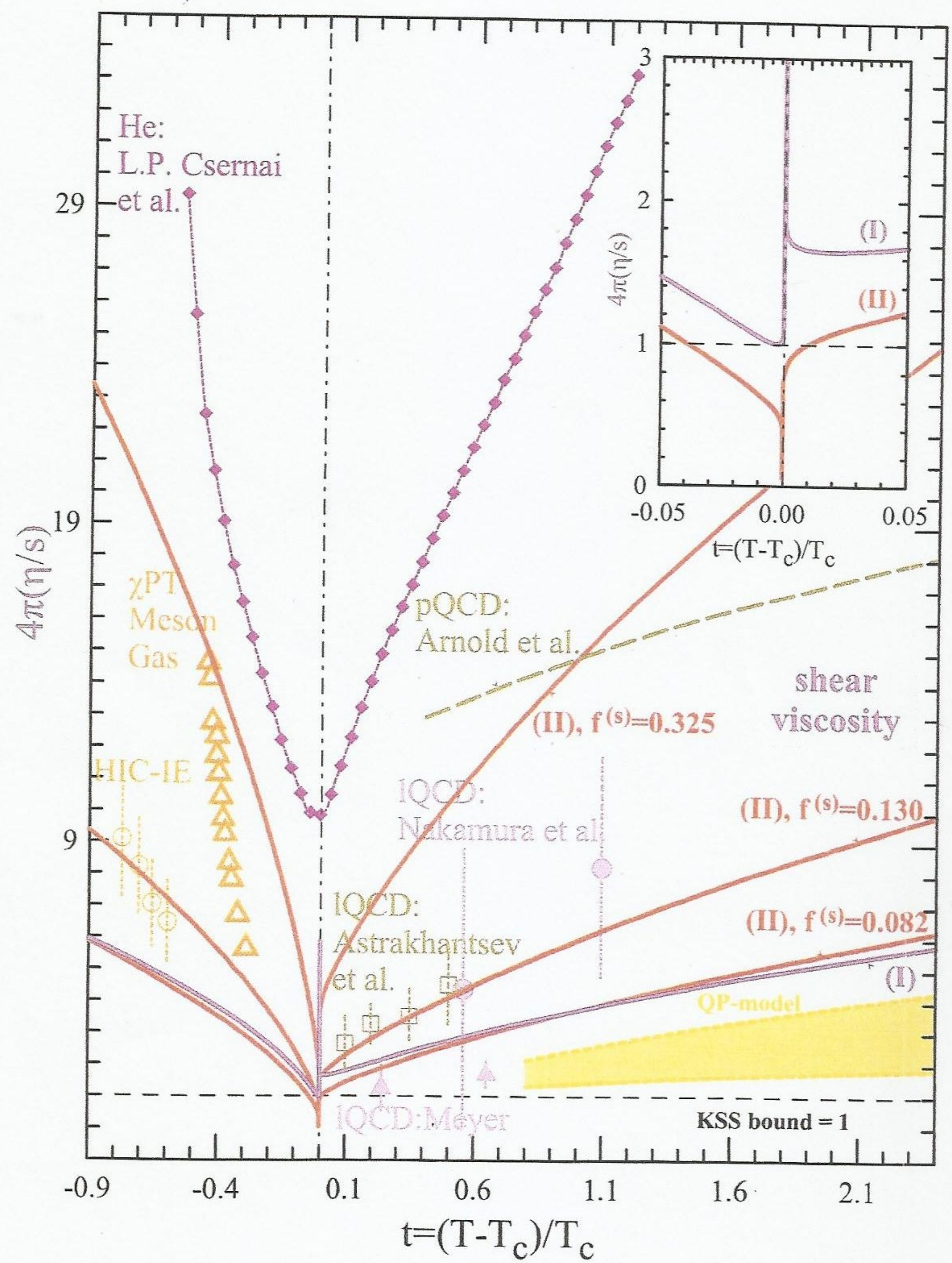


FIG. 1: Our solution of type I (continuous dark line) for the shear viscosity compared with the findings of [5] (empty triangles), [23] (empty circles), [24] (solid circles and solid triangles), [25] (empty rectangles), [26] (dashed line), a quasi-particle model [27] (band) and [6] (dotted line with solid rectangles). In the inset graph we focus on the shape of our solution in the vicinity of the critical temperature. Also solutions of type II (continuous light lines) are shown.

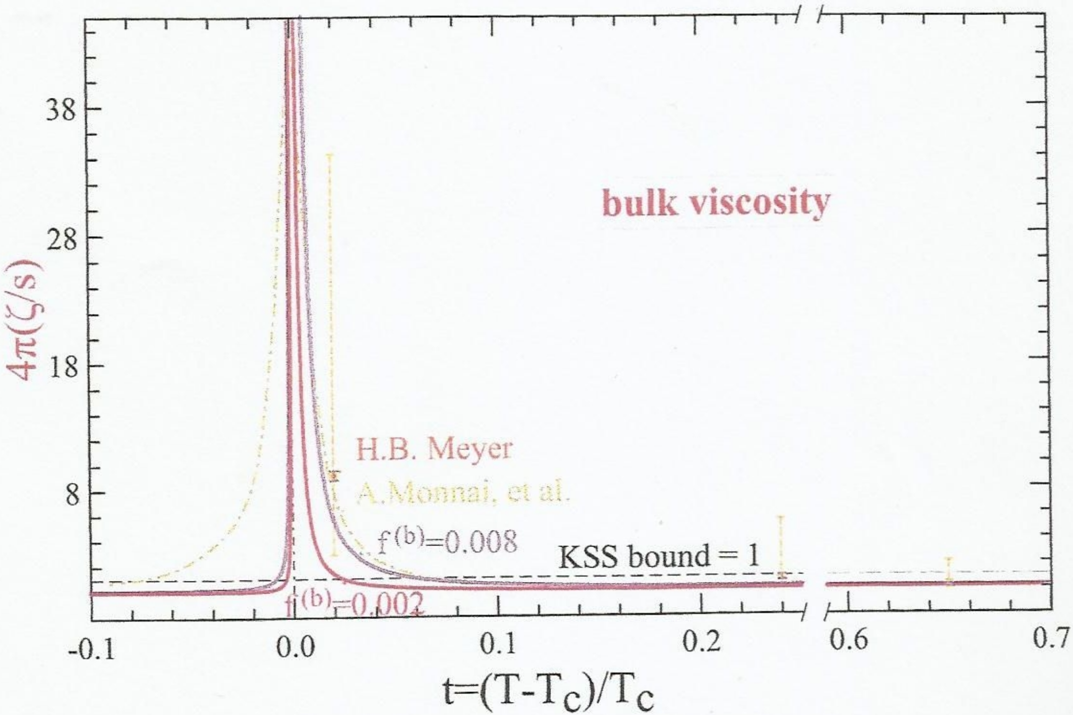


FIG. 2: Solutions for the bulk viscosity (continuous lines) compared with the findings of [11] (dot-dashed line) and [28] (solid rectangles) with systematic (large) and statistical (small) uncertainties.

SLOW (SOFT) MODE (near T_c)

Fluctuations of the order parameter φ near T_c have a large relaxation tim τ - slow mode

Slow φ fluctuations can not keep up with the sound wave compression/expansion. Entropy increases → → anomalous sound absorption,

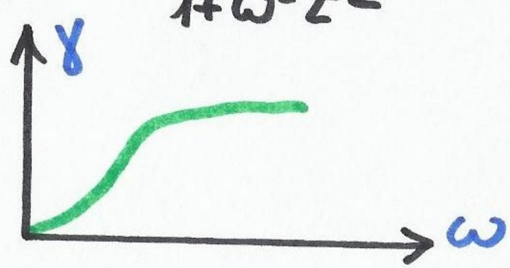
$$\gamma(\omega) \sim \begin{cases} \omega \\ \omega^{1+\alpha} \\ const \end{cases}$$ vs. $\gamma \sim \omega^2$ Stokes-Kirchoff

$\omega\tau \ll 1 \rightarrow c_0^2 = (\partial P/\partial \varepsilon)_{eq}$ enough time for relaxation

$c_\infty > c_0$

$\omega\tau \gg 1 \rightarrow c_\infty^2 = (\partial P/\partial \varepsilon)_\varphi$ not enough time for φ relaxation

$$\gamma(\omega) = \frac{\gamma(0)}{1+\omega^2\tau^2} = \frac{\varepsilon\tau(c_\infty^2 - c_0^2)}{1+\omega^2\tau^2}$$ – Landau-Khalatnikov formula



Not the whole truth!

What happens very close to T_c?

In the immediate vicinity of T_c sound wave interacts directly with the fluctuation mode

Difficult problem. Not yet completely solved.

Ising-like universality, mode coupling theory, renormalization group, $d = 4-\varepsilon$ regularization

Kawasaki, Pokrovsky, Semiz, Khalatnikov, Onuki, Antoniou et al., Stephanov and Yin

$\gamma, \varsigma \sim \xi^{2-\alpha/\nu}$, $\xi = |t|^{-\nu} \simeq |t|^{-0.61} \Rightarrow \gamma, \varsigma \sim |t|^{-1.69}$

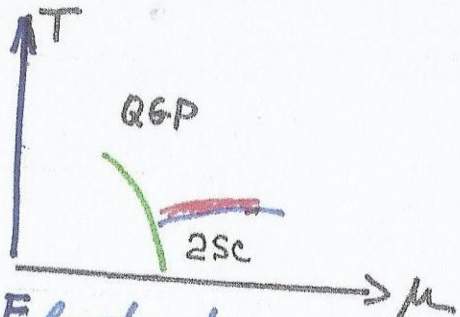
$t = \frac{T-T_c}{T_c}$

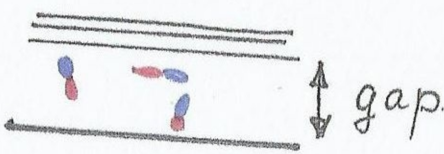
ξ — correlation length — the length scale near T_c

$\varsigma_R(0) \sim \xi^{2.77}$

A Dynamic model for sound attenuation and bulk viscosity near T_c ($\zeta \sim |t|^{-1.69}$ model)

We focuse on the QCD phase diagram region $T \to T_c$ from above at $\mu_q \sim 300-400$ MeV. This is just above the phase transition to 2SC color superconductor.





fluctuating quark pairs

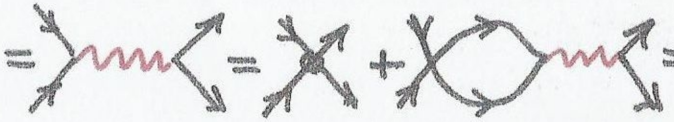
$\tau \sim \frac{\pi}{8(T-T_c)}$

Fluctuation region for quarks is extremely wide.

$$\delta T / T_c \simeq \begin{cases} 10^{-12} & \text{BCS} \\ 10^{-2} & \text{color superconductor} \end{cases}$$

Slow fluctuation mode, $L(\vec{q}, \omega)$ - propagator

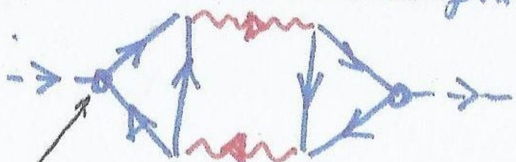
Fluctuation propagator. Aslamazov–Larkin diagram

$L(\vec{q},\omega) =$  $= -\dfrac{1}{\nu_0}\,\dfrac{1}{\dfrac{T-T_c}{T_c} + \dfrac{\pi}{8T}\left(-i\omega + \mathcal{D}\vec{q}^{\,2}\right)}$

$\nu = \dfrac{m p_F}{2\pi^2}$ $\quad\mathcal{D}$ – diffusion

singular at T_c for small $\omega, \vec{q}^{\,2}$

Aslamazov–Larkin diagram



Two $L(\vec{q},\omega)$ – twice singular

k-phonon g

$$\mathrm{Im}\,\Pi_{fi} \propto -\omega g^2 \left(\frac{T}{T-T_c}\right)^{3/2}$$

$\gamma, \rho \sim t^{-3/2}$ vs $t^{-1.69}$ not bad!

Fig. 2

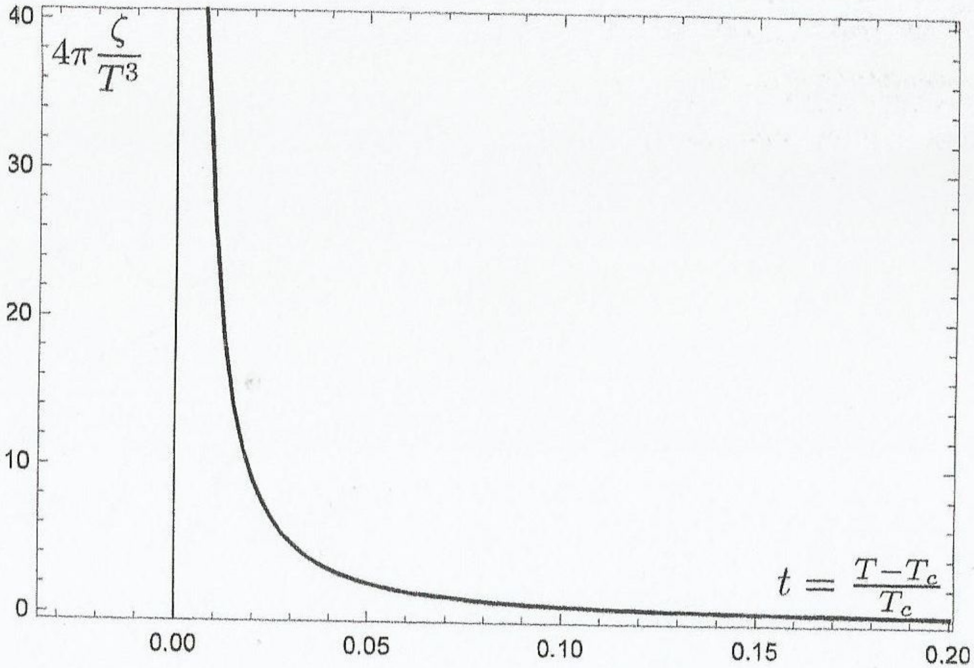


Figure 2.

A marginal remark: In presence of relaxation the sound speed and attenuation are linked by the

Fluctuation - Dissipation Theorem
(Kramers - Kronig relationship)

$$A \sim e^{i(kx-\omega t)} = e^{-\gamma x} \exp\left\{ i\left(\frac{\omega x}{c_1(\omega)} - \omega t\right)\right\}$$

$$\rightarrow k = \frac{\omega}{c_1(\omega)} + i\gamma$$

$$\Delta C_1 = C_1(\omega) - C_1(\omega_0) = \frac{2C_1^2(\omega_0)}{\pi} \int_{\omega_0}^{\omega} d\omega' \, \frac{\gamma(\omega')}{\omega'^2}$$

CONCLUSIONS

- Quark Matter displays a hydrodynamic behavior
- Sound is the only long-lived hydrodynamic propagation mode
- The speed of sound is a crucial quantity fo EoS
- The upper bound on c_s^2 constrains the mass of NS
- Anomalous sound attenuation near the phase transition line is in conjunction with divergent bulk viscosity
- A dynamical model is proposed for anomalous sound attenuation and divergent bulk viscosity near T_c
- A new development — c_s^2 in gluodynamic → 1806.09407
  Khaidukov, Lukashov, Simonov

Thank you for attention!