QUARKS 2018
Valday 5/27 – 6/02

SOUND in QUARK MATTER
(Why should we listen to it?)

Boris Kerbikov ITEP

- Quark Matter: History. Concepts vs. Observations
- Sound mode in hydrodynamic fluid
- Sources of sound. Manifestations of sound
- Speed of sound and EoS
- Bounds on c_s^2. Speed calculations. SU(3) gluodynamics
- Sound near T_c: bulk viscosity divergence
- Aslamazov-Larkin model

1. Terminology in Historical Retrospective

Quark Matter: N. Itoch, 1970, neutron stars.

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

QCD Phase Diagram: N. Cabibbo and G. Parisi, 1975;

Gordon Baym famous plot (1976) + the idea to scan it in HIC (Fig. 1)

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

The Berelac (LBL), AGS (BNL), SPS (CERN). SPS: Maurice Jacob:

"There is no doubt that a new state of matter, with a density of at least an order of magnitude higher than hadronic matter" (1994).

RHIC (BNL), proposed 1984, first beams 1990, operation 2000 – present

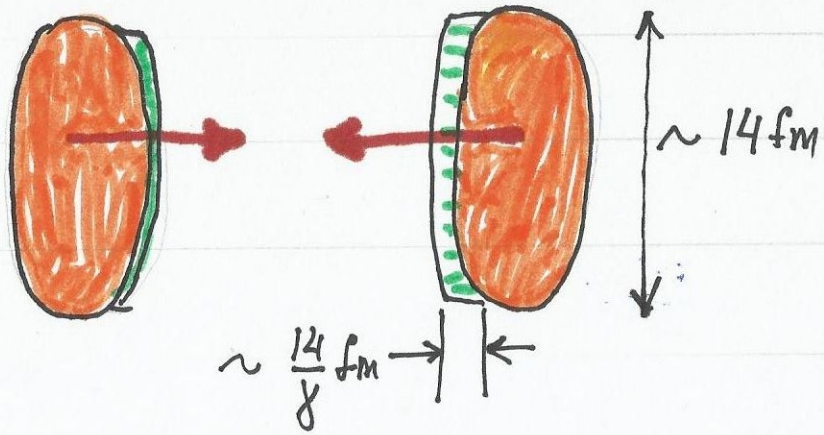
Au–Au $\sqrt{s_{NN}} = 200$ GeV

LHC (CERN), 2009 – present, $\sqrt{s_{NN}} = 2.76$ TeV, Pb–Pb.

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

3. Heavy ion collisions: phenomenology and dynamics

Lorentz contracted discs



$$\gamma = (1-z_2^2)^{-1/2} = \begin{cases} 100 & \text{RHIC} \\ 2500 & \text{LHC} \end{cases}$$

Fig. 2

Incident nuclei – highly complex system of partons

Energy density $\varepsilon \simeq 12\,\text{GeV/fm}^3$ at $\tau \simeq 1\,\text{fm/c}$ (LHC)

$\varepsilon \simeq 500\,\text{MeV/fm}^3$ inside a hadron

Hydrodynamization and Thermalization

↳ hydro at $\begin{cases} 0.2\text{–}0.6\,\text{fm/c} & \text{LHC} \\ 0.4\text{–}1.0\,\text{fm/c} & \text{RHIC} \end{cases}$

↳ $\tau \sim 1\,\text{fm/c}$

3. Heavy Ion Collisions: phenomenology and dynamics

The two (maybe four) discoveries of RHIC later confirmed at LHC with better statistics and a much larger kinematical range

1. Azimuthal asymmetry known as elliptic flow v_2

$$\frac{dN}{d\varphi} \propto 1 + 2v_2(p_T)\cos 2(\varphi - \Psi_{RP})$$ (Fig. 3)

2. Strong suppression of high energy jets and heavy quarks

(3.) The strongest magnetic field in the Universe $eB \sim 10^{19} - 10^{20}$ G created in peripheral HIC

(4.) Collective phenomena in small systems, p+Pb, even p+p.

QCD Phase Diagram. Sound Mode

- A wealth of novel QCD phases
  A complicated (T, μ_B) phase diagram
  Lattice calculations. Critical point?
- Quarks and gluons produced in HIC —
  — a collective medium that expands and
  and flows as a relativistic hydrodynamic fluid
  with low $\eta/s \approx 1/4\pi$
- Sound is the only long-lived propagating mode in a near-ideal fluid

Sources of Sound. Manifestations 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:

a) Sound modes behind the v_2 flow

b) Periodic oscillations in p_T distributions

EoS

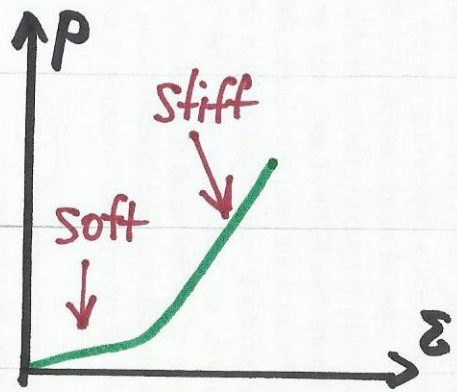
EoS: $p = p(\varepsilon, n_B)$, $p = p(T, \mu_B)$

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

■ Neutron Stars (NS) Mass-Radius relation

EoS $\to M_{max}$ $\forall R$. The higher p for given ε – the larger is M_{max}

Recently NS-rs $M \simeq 2 M_\odot$ – very stiff EoS



Stiff – hard to compress, cold nuclear matter, NS

Soft – very compressive, quark matter $\sim T_c$

Fundamental quantity

$$c_s^2 = \left.\frac{\partial p}{\partial \varepsilon}\right|_s$$ the speed of sound

Newton – isothermal, $\lambda \sim l_{mfp}$

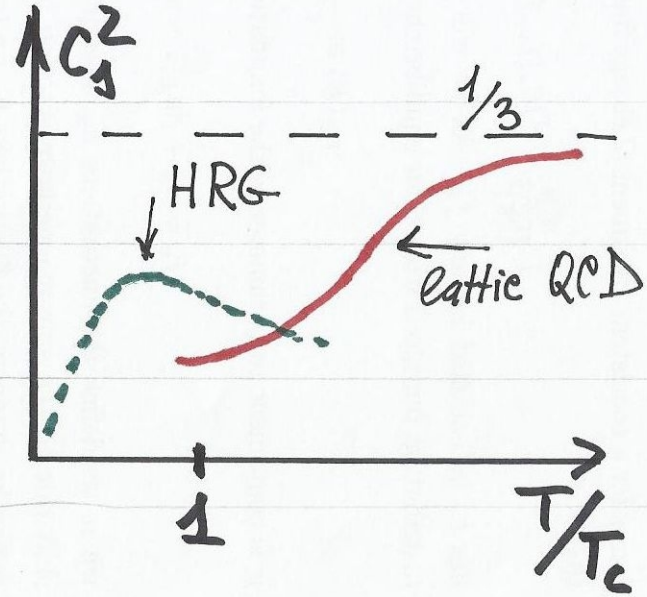
Laplace – adiabatic, $\lambda \gg l_{mfp}$

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

Sound velocity Bounds and EoS

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

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



Deviation from conformality

$\propto \left(1 - 3c_s^2(T)\right)^2$

Violation of $c_s^2 < 1/3$

– very stiff EoS

$c_s = 1$ Zeldovich 1962

$c_s > 1/3$ AdS/QFT 2016

c_s^2 Bounds

Fig McLerran

$c_s \rightarrow$
- 0, $T=0$ HRG (including glueball gas)
- 0 (or discontinuity) $T=T_c$ pure SU(3) glue 1-st order phase transition
- min – the softest point of EoS
- $\rightarrow 1$ very stiff hadronic/quark matter NS $M \simeq 2 M_\odot$

Fig 6 0912.2541

- Very recent development (May 25, Simonov, Khaidukov, Lukashov), SU(3) Yang-Mills, weak 1-st order $T_c \approx 270$ MeV, gas of glueballs at $T < T_c$, magnetic confinement at $T > T_c$

Zakharov

- To accomodate $2M_\odot$ NS description in terms of nuclear matter should be abandoned

Fig 1 1801.01923

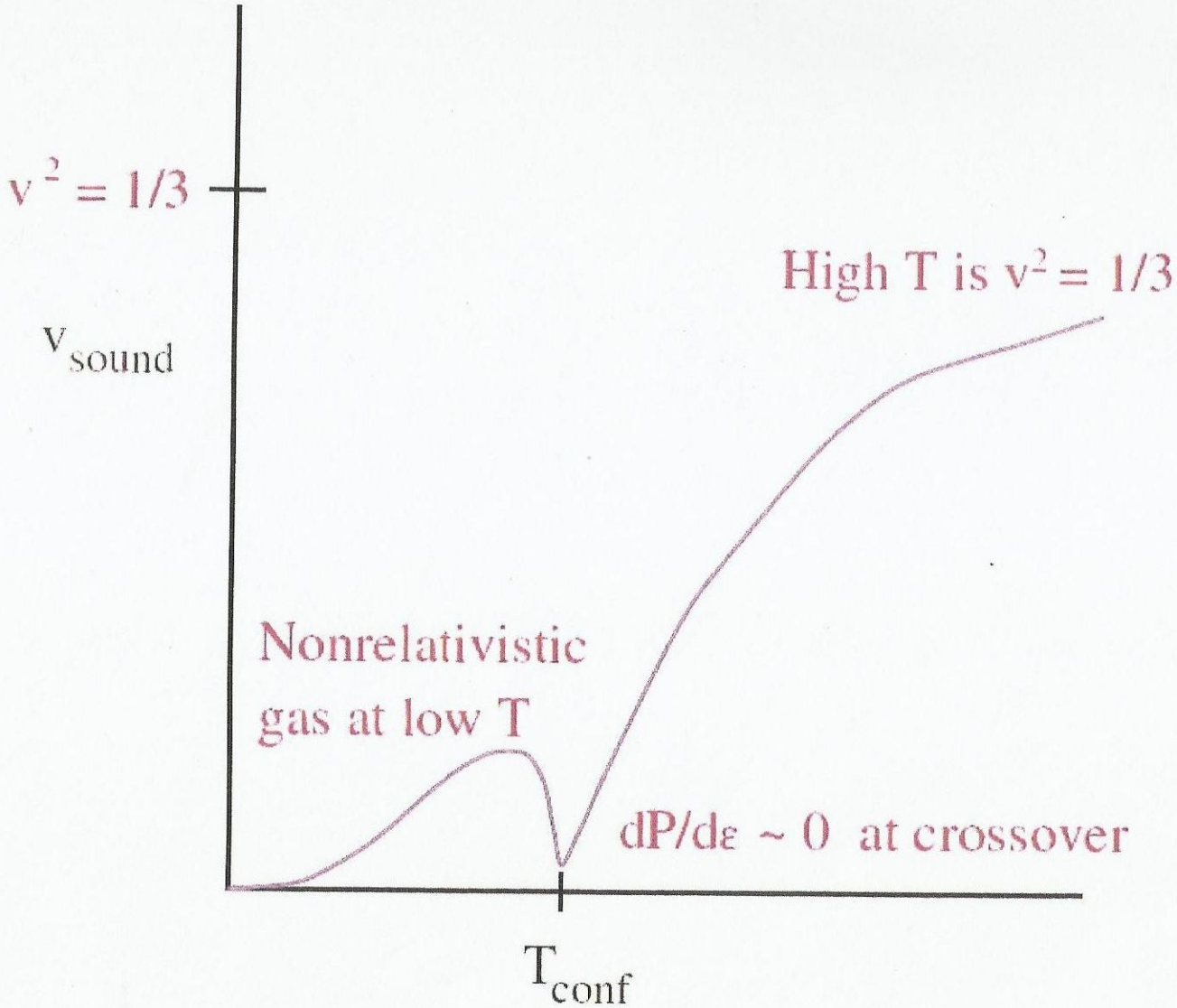


Fig. 6: The sound velocity as a function of temperature

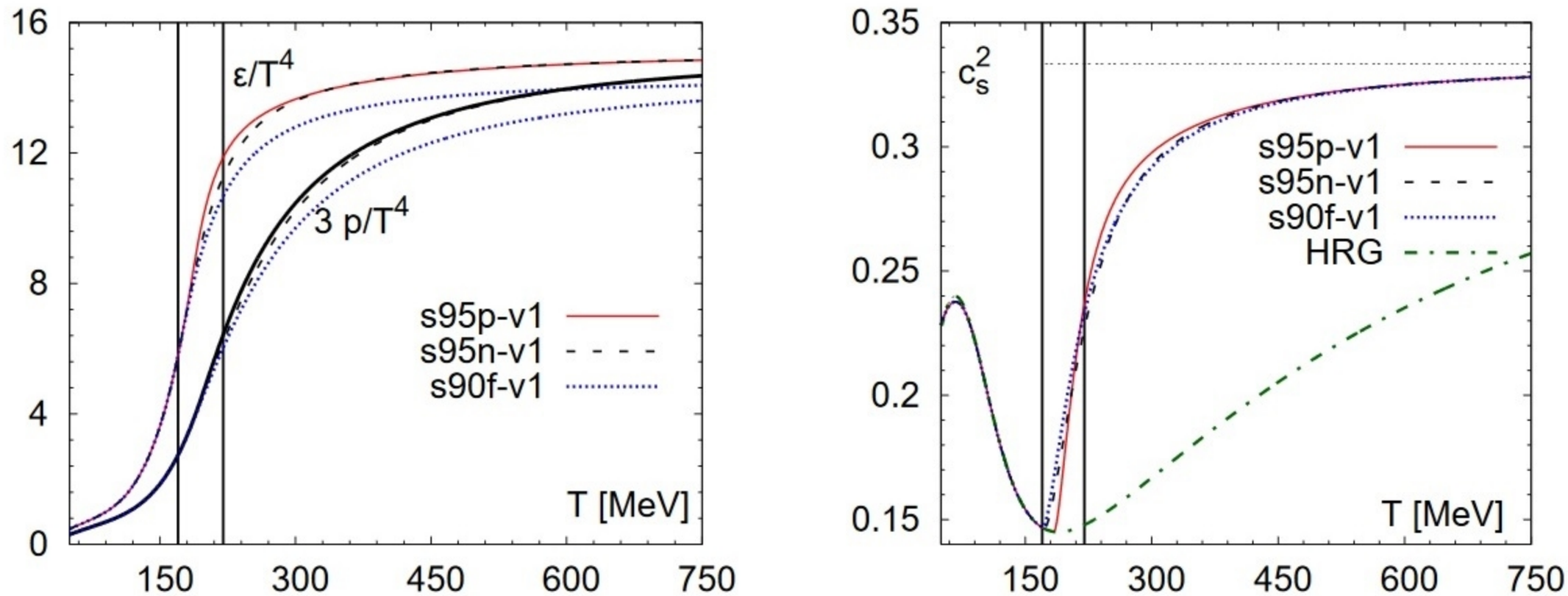
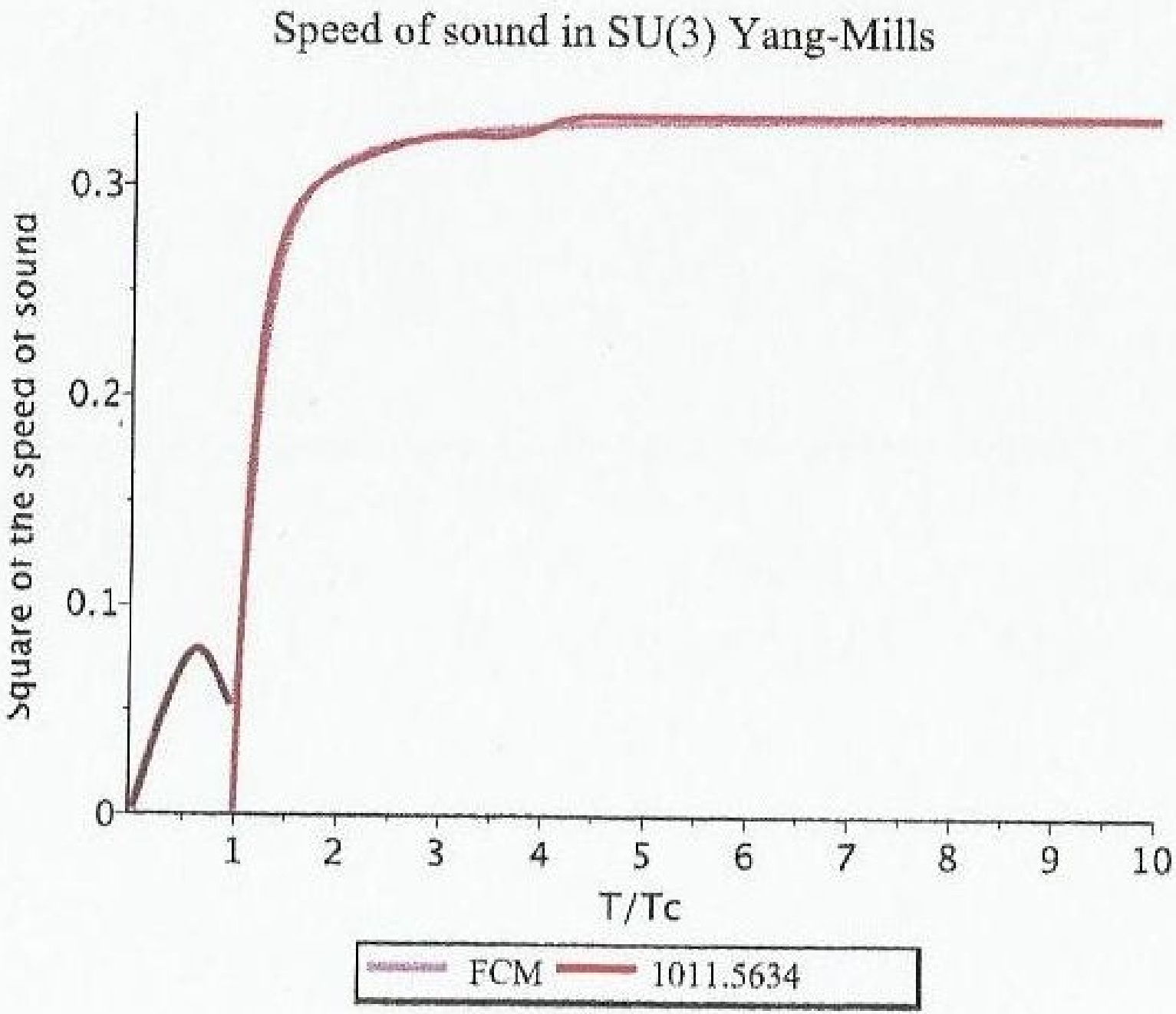


FIG. 6: The pressure, energy density (left panel) and speed of sound (right panel) in the equations of state obtained from Eqs. (4.2) and (4.3). The vertical lines indicate the transition region (see text). In the right panel we also show the speed of sound for the HRG EoS and EoS with first order phase transition (thin dotted) line, the EoS Q


Speed of sound in SU(3) Yang-Mills
Square of the speed of sound
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
9
10
T/Tc
FCM
1011.5634

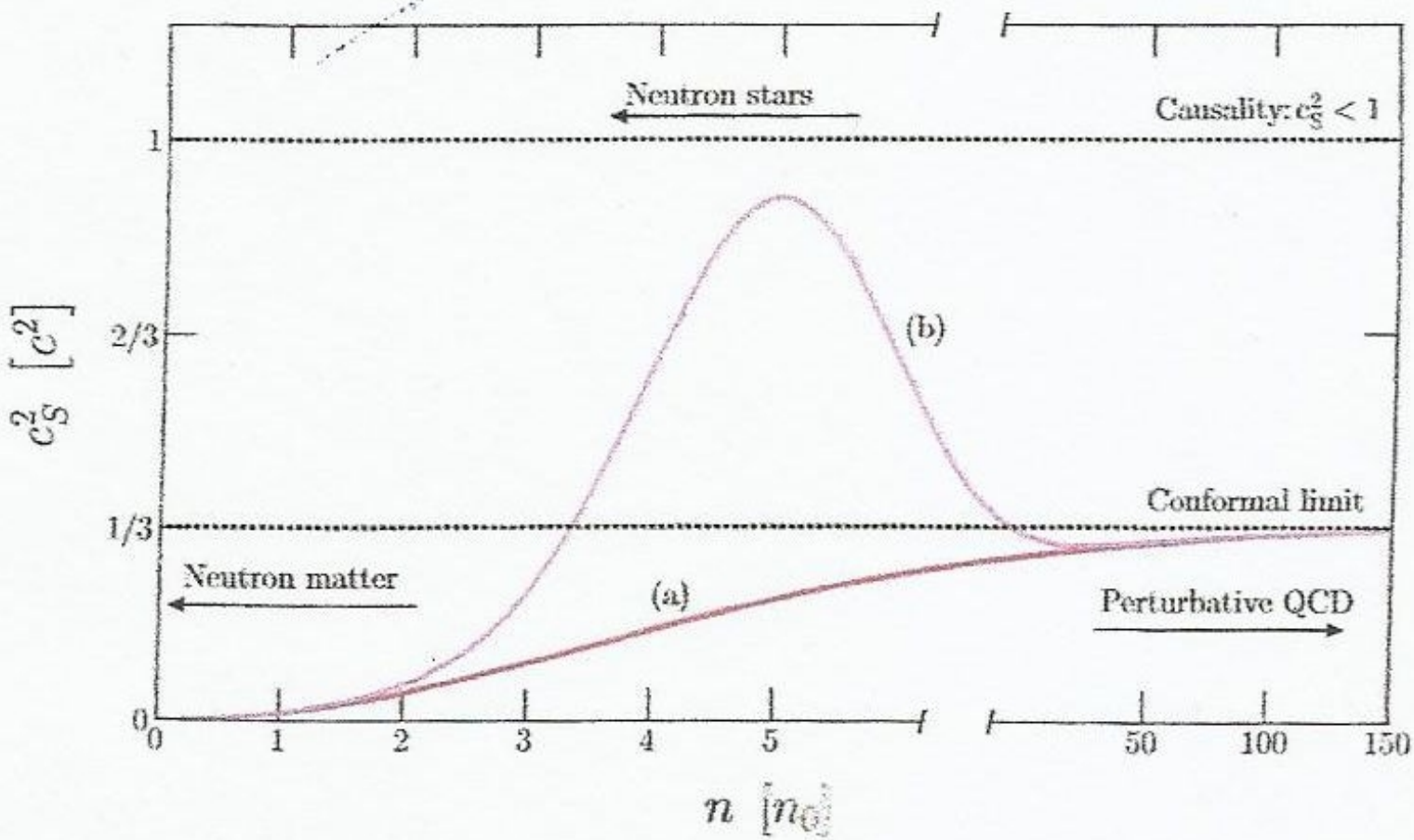


Figure 1. Two possible scenarios for the evolution of the speed of sound in dense matter.

QCD Fluid near T_c: slow relaxation, anomalous sound attenuation, divergent bulk viscosity

Fig 1
Fig 2
1610.02028

From Stokes-Kirchoff to Mandelshtam-Leontovich to critical exponents, mode coupling theory, 4-ε, Aslamazov-Larkin.

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

In some liquids Stokes-Kirchoff fails

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

A possible way out: $\gamma_{exp} - \gamma_{th} \sim \varsigma$ + critical slowing down, Mandelshtam-Leontovich 1937, slow relaxation theory, see Landau Hydro

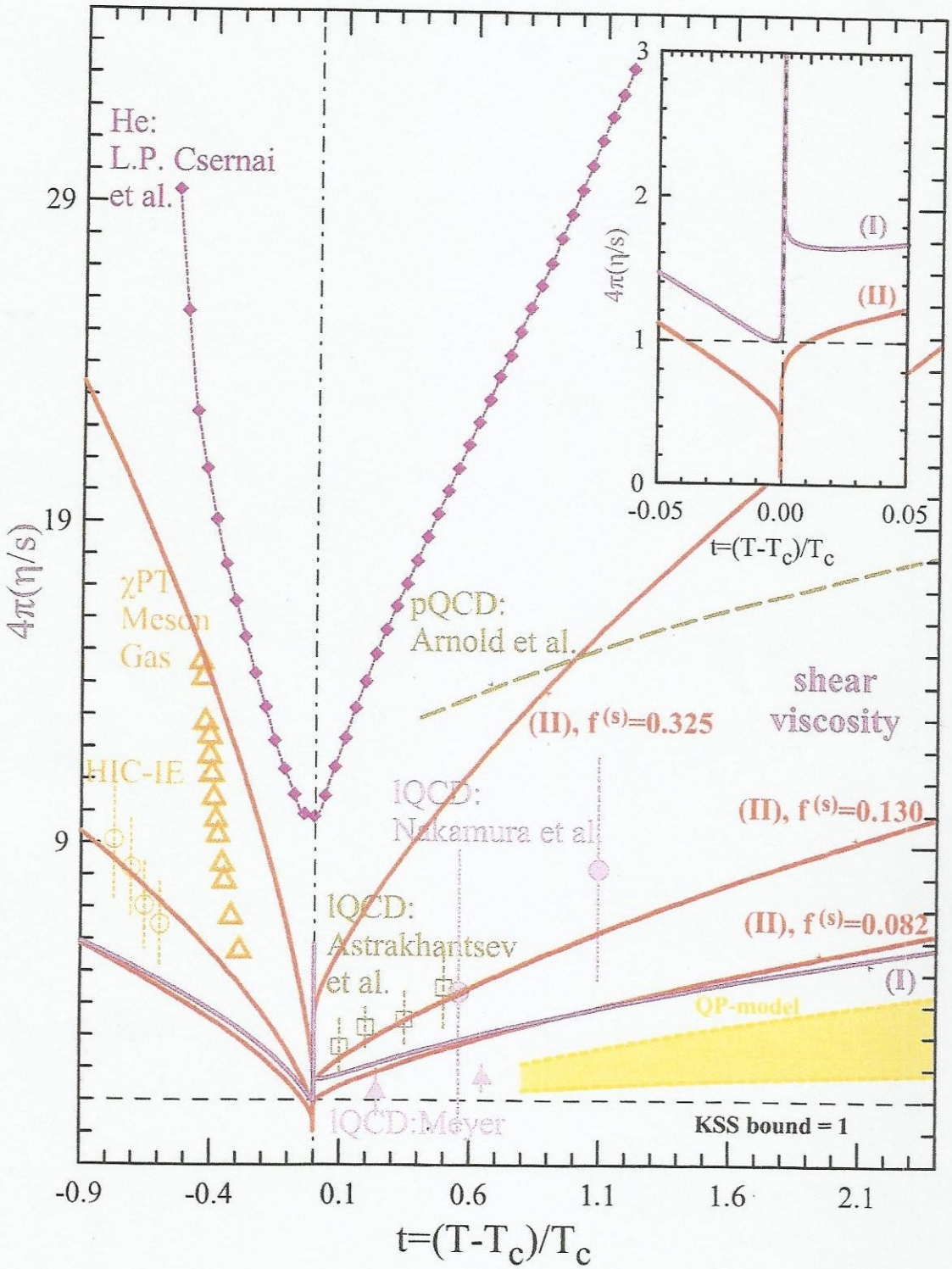


FIG. 1: Our solution of type I (continuous dark line) for the shear viscosity compared with the findings of [5] (empty triangles), [23] (empty circles), [24] (solid circles and solid triangles), [25] (empty rectangles), [26] (dashed line), a quasi-particle model [27] (band) and [6] (dotted line with 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.

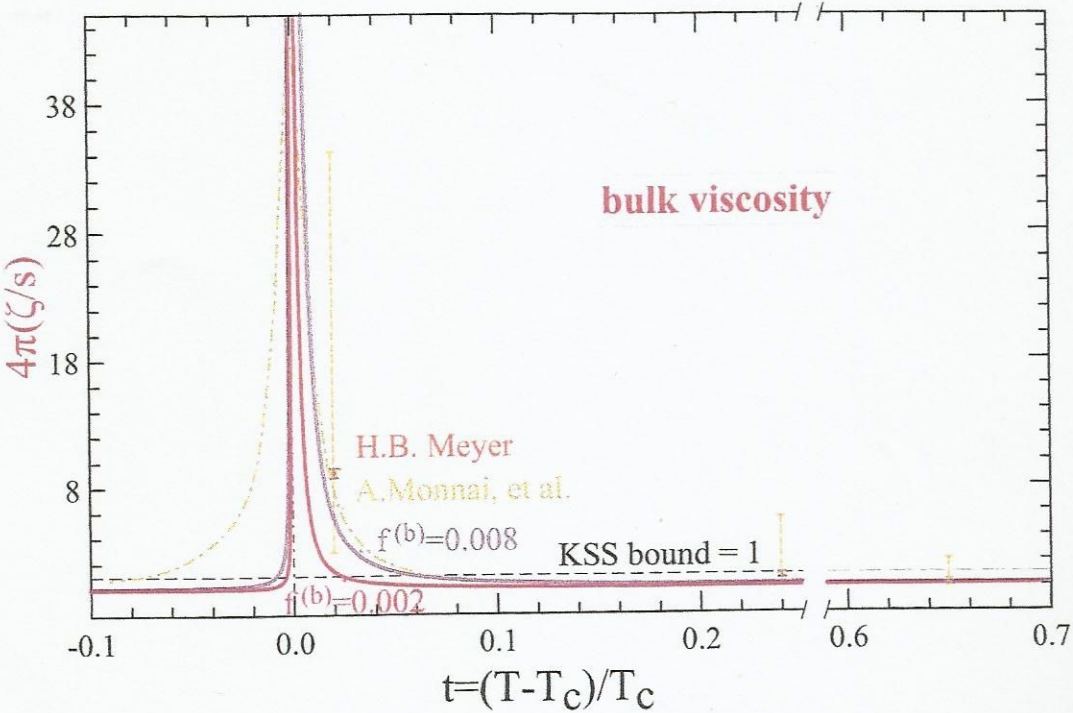


FIG. 2: Solutions for the bulk viscosity (continuous lines) compared with the findings of [11] (dot-dashed line) and [28] (solid rectangles) with systematic (large) and statistical (small) uncertainties.

Slow (Soft) Mode

Sound wave: $p+\delta p$, $T+\delta T$ – deviation from equilibrium

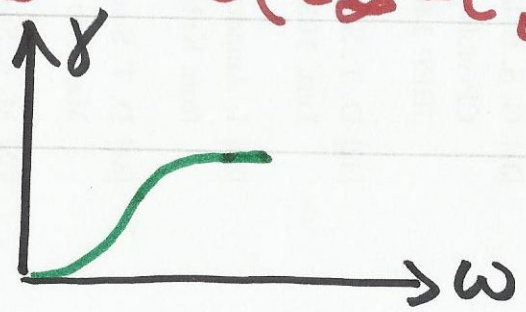
Fluctuations of the order parameter φ near T_c have large relaxation time τ – slow mode

Slow φ fluctuations can not keep up with sound wave compression/expansion. Entropy increases $\rightarrow$ $\rightarrow$ anomalous sound absorption, $\gamma(\omega) \sim \omega, \omega^{1+\alpha}$, const

$\omega\tau \ll 1 \rightarrow \frac{1}{\omega} \gg \tau \rightarrow c_0^2 = \left(\frac{\partial p}{\partial \varepsilon}\right)_{eq}$ $\rightarrow$ enough time for relaxation

$\omega\tau \gg 1 \rightarrow \frac{1}{\omega} \ll \tau \rightarrow c_\infty^2 = \left(\frac{\partial p}{\partial \varepsilon}\right)_{\varphi}$ $\rightarrow$ no time for φ relaxation

$\gamma = \tau\varepsilon(c_\infty^2 - c_0^2)$ Mandelshtam – Leontovich
Landau-Khalatnikov



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 Lin

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

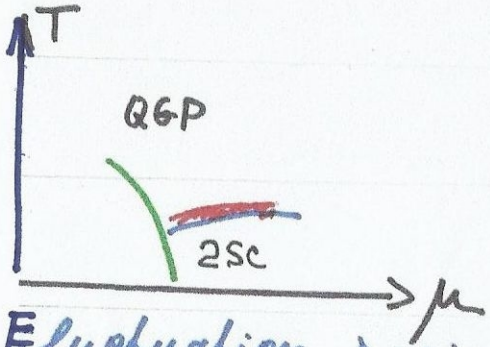
ξ → correlation length — the length scale near T_c

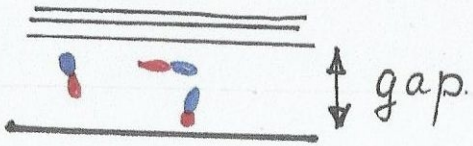
$$t = \frac{T - T_c}{T_c}$$

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

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

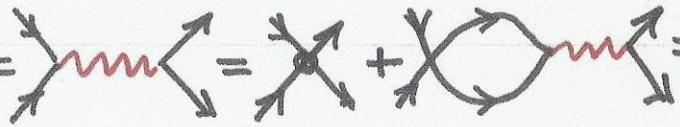
$\tau \sim \frac{\pi}{8(T-T_c)}$

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

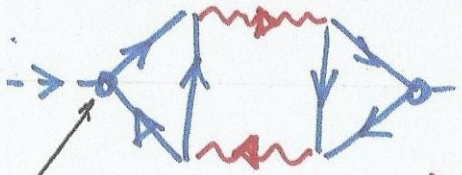
Fluctuation propagator. Aslamazov-Larkin diagram

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

$\nu = \frac{\mu p_F}{2\pi^2}$ $\mathcal{D}$ – 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

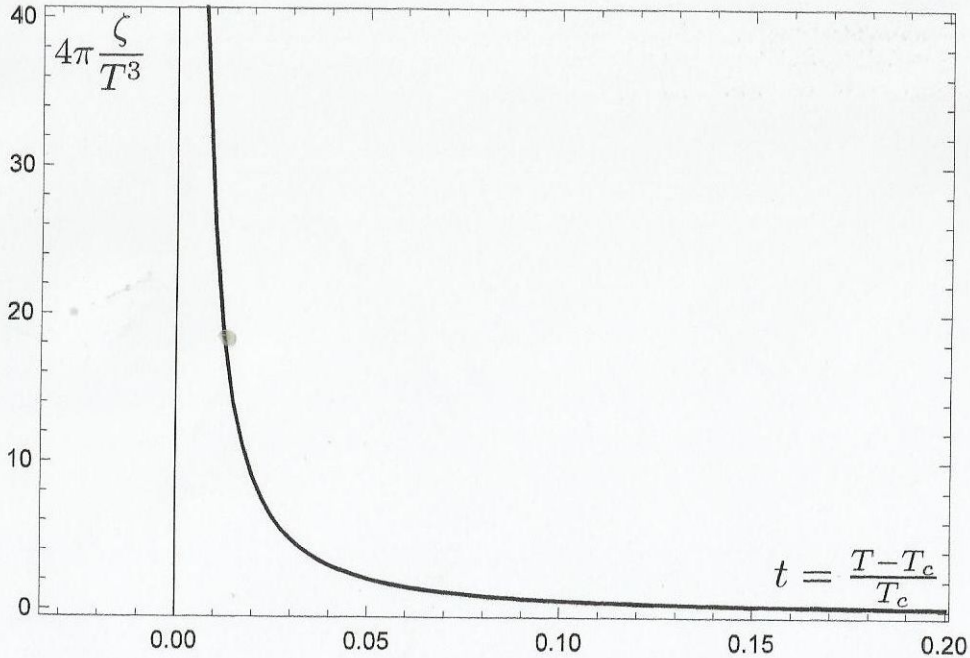


Figure 2.

CONCLUSIONS

- Acoustic perturbations, sound, is an important phenomena in quark matter physics
- Sound speed and sound absorption are among the fundamental characteristics of quark matter
- A dynamic model is proposed for sound absorption and divergent bulk viscosity near T_c

Thank you for attention!