Viscosity of constituent quark matter

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with
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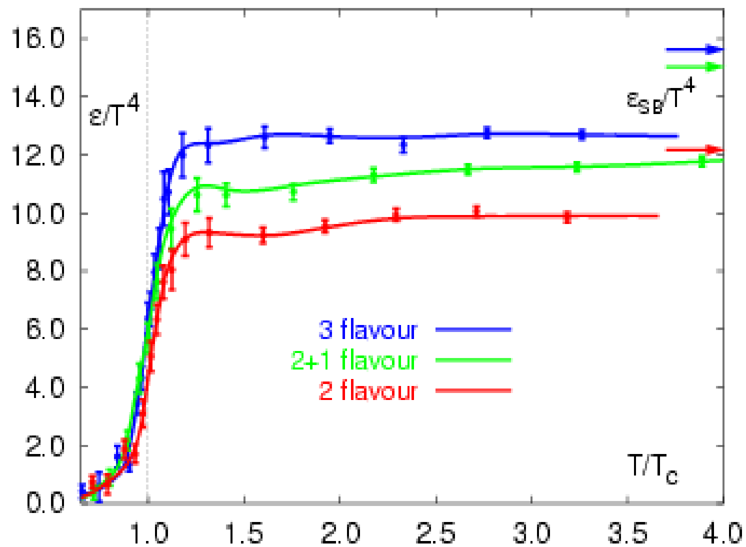
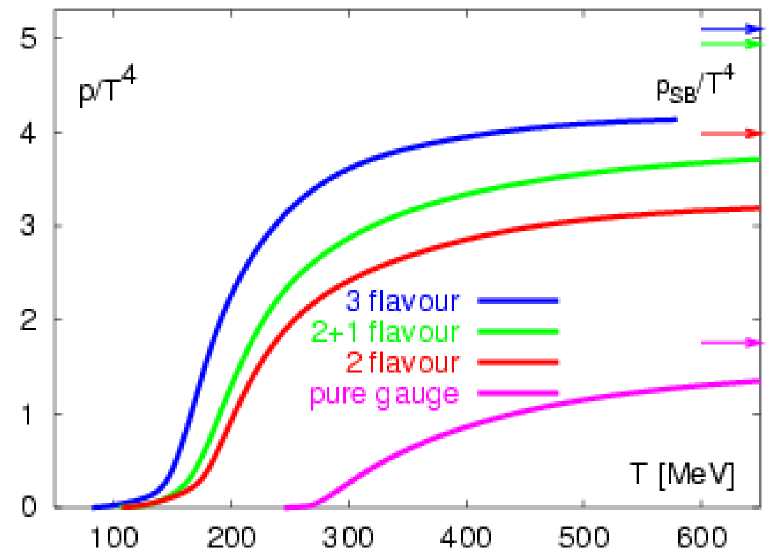
Fundament-1: EOS for strongly interacting matter from lattice-QCD

zero baryon density (1990-2000)

finite baryon densities (2000 -)

➔ $\varepsilon(T, \mu)$, $P(T, \mu)$





LQCD gives realistic EOS for QGP (deconfined matter)

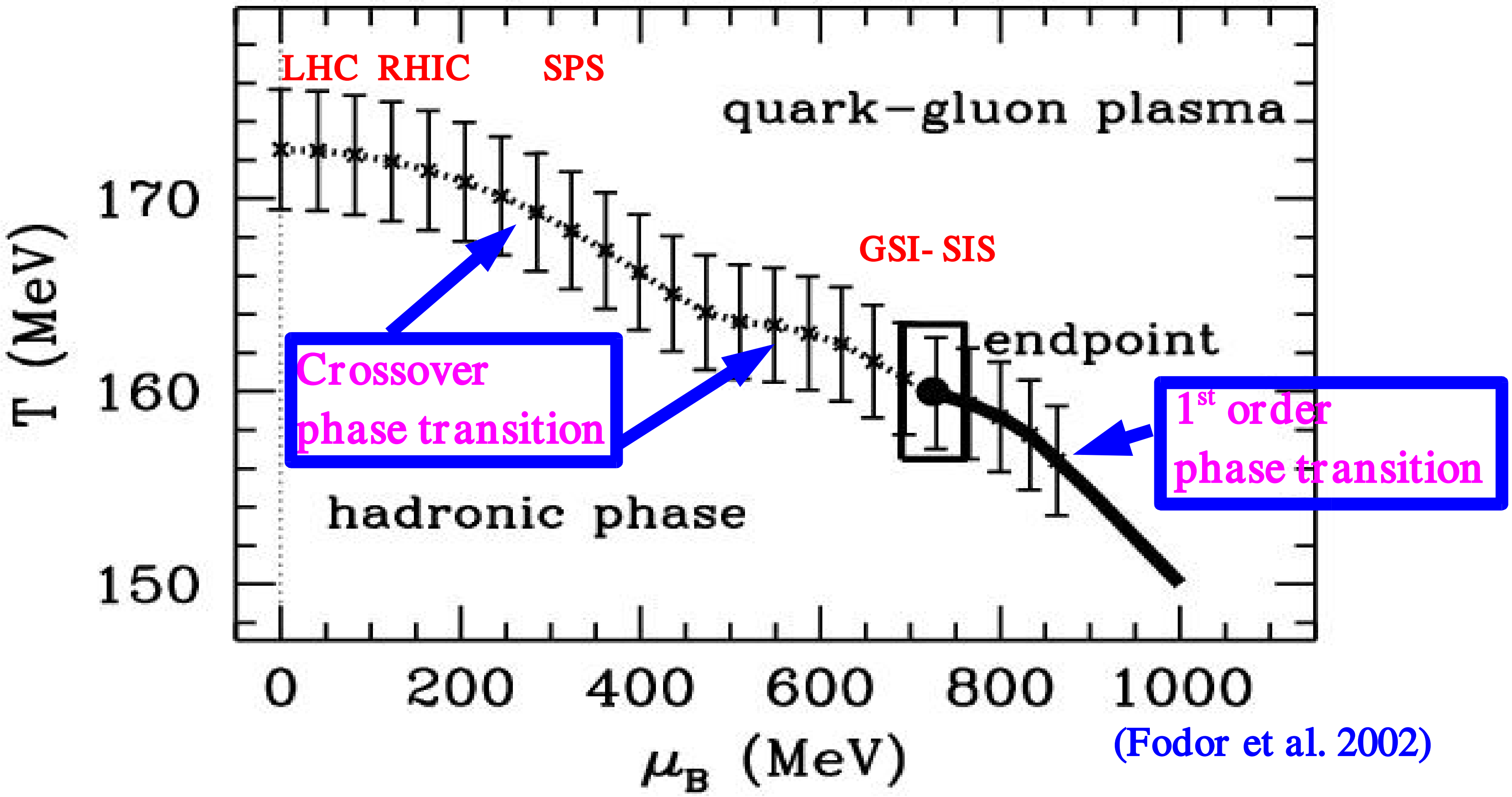
$T_c = 170$ MeV $T/T_c = 1.1\text{-}1.2$ ➣ $\varepsilon =$ 2-3 GeV/fm^3 (SPS ?)

$T/T_c = 1.5\text{-}2.0$ ➣ $\varepsilon =$ 6-20 GeV/fm^3 (RHIC ?)

$T/T_c = 2.0\text{-}3.0$ ➣ $\varepsilon =$ 20-100 GeV/fm^3 (LHC ?)

Fundament-2: order of phase transition from lattice-QCD

Lattice-QCD results at finite density, SU(3), Nf=2 $\mu>0$



(Fodor et al. 2002)

Crossover phase transition at small and intermediate baryon densities:

What is the microscopical mechanism of the hadronization ????

⇒ **QUARK COALESCENCE is one possibility**

Interacting massive quarks around T_c !!

Introducing quasi-particle picture:

SU(3) Gluon EOS with free quasi-gluons + B(T) bag

Fix degrees of freedom (d=16)

$$P(T)=\frac{d}{(2\pi)^3}\int d^3p \; \frac{p^2}{3\sqrt{p^2+M(T)^2}} \left[\exp\frac{\sqrt{p^2+M(T)^2}}{T}-1\right]^{-1} - B(T)$$

$$\varepsilon(T)=\frac{d}{(2\pi)^3}\int d^3p \; \sqrt{p^2+M(T)^2} \left[\exp\frac{\sqrt{p^2+M(T)^2}}{T}-1\right]^{-1} + B(T)$$

$\epsilon(T)$, $P(T)$ ↣ $M(T)$, $B(T)$

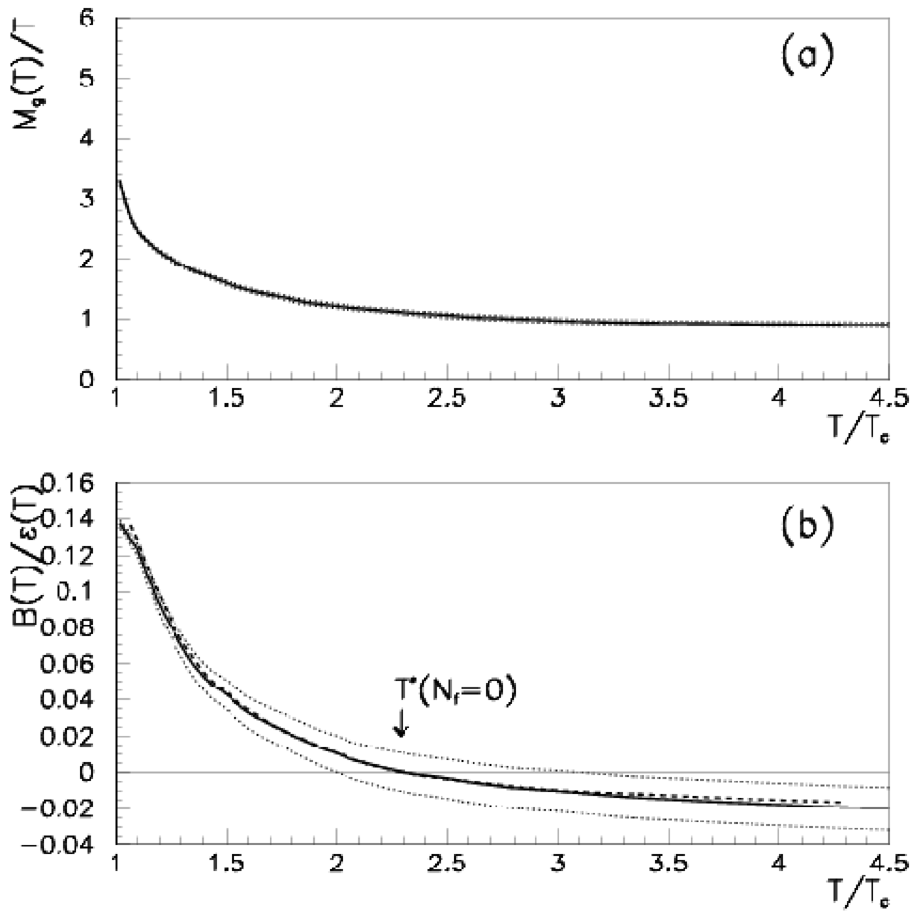
Mass + Interaction

P. Lévai, U. Heinz, 1996, PRC51, 3326.

Extracting g(T) and B(T) from lattice-QCD results:

SU(3) Gluon EOS with free quasi-gluons + B(T) bag

Fix degrees of freedom (d=16)



ϵ(T), P(T) ↣ M(T), B(T)

T > 2 T_c

M(T)/T = c·g(T) [c=1/√2]

T → 5T_c , $\alpha_s = g^2/4\pi \rightarrow 0.15$ ✓

B(T) is small (≈0)

Free quasi-gluons !

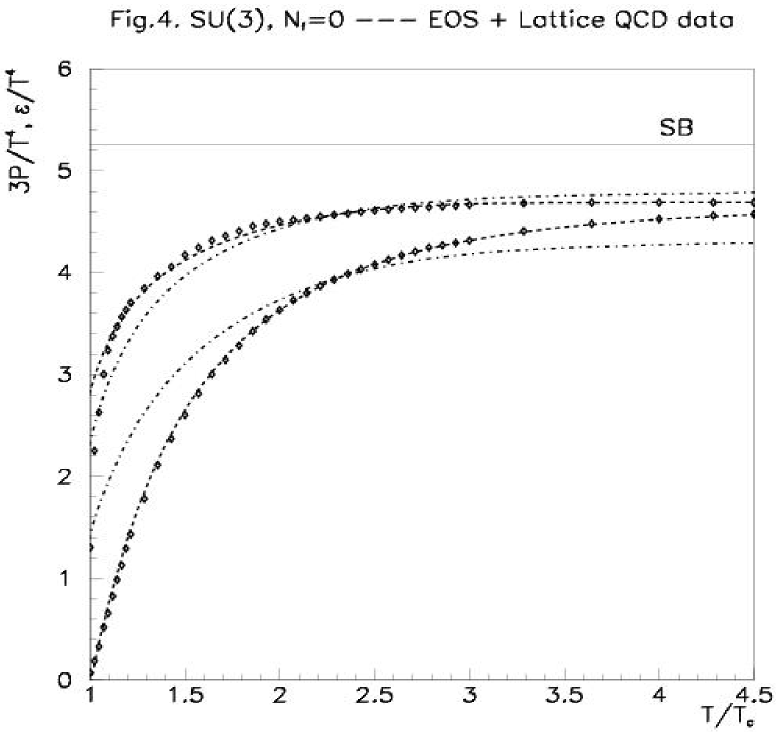
T < 2 T_c

Interacting quasi-gluons or new excitations ?

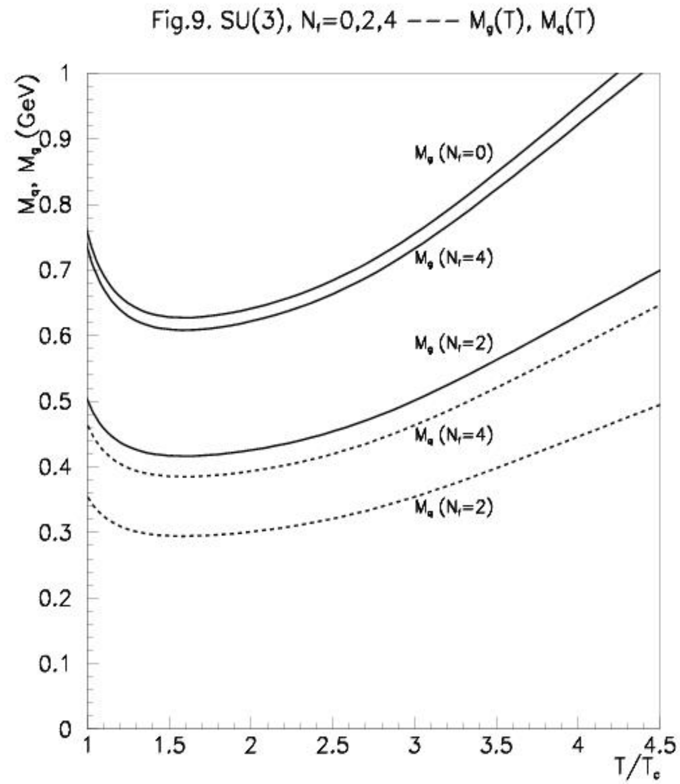
Or both ?

Quark matter formation in heavy ion collisions

Lattice-QCD results around T_c, SU(3), Nf=0,2,4 $\mu=0$ (1990 - ...)



(Karsch et al. 1992)



Understanding in a quasiparticle picture: M(Q) ≃300 MeV, M(G)≃ 500-800 MeV

[L.P, Heinz U., 1996, PRC51,3326]

➔ Quark and antiquark dominated matter (QAP)

HADRONIZATION ⇔ QUARK COALESCENCE (ALCOR '95)

('Cross-over' phase transition) **[T.S. Biro, P.L., J. Zimányi]**

Quark matter formation in heavy ion collisions

Lattice-QCD results around T_c, SU(3), Nf=0,2,4 μ=0

Fig.10. SU(3), N_f=0,2,4 --- n_g/n_g^0, n_q/n_q^0

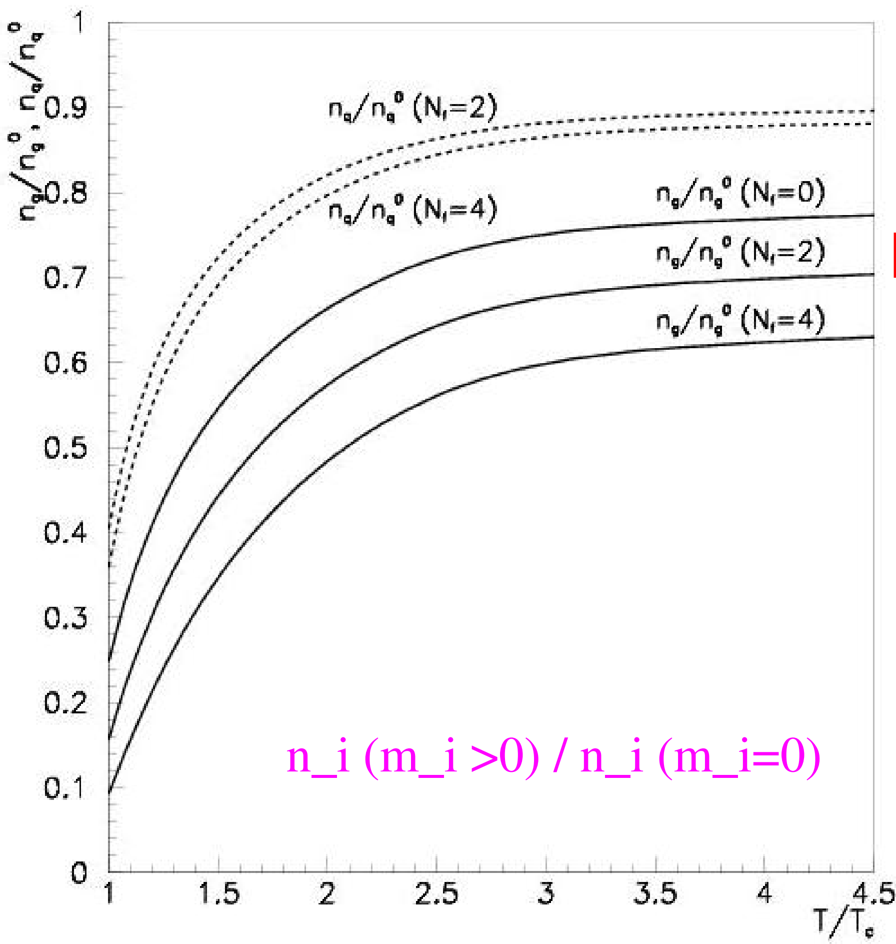
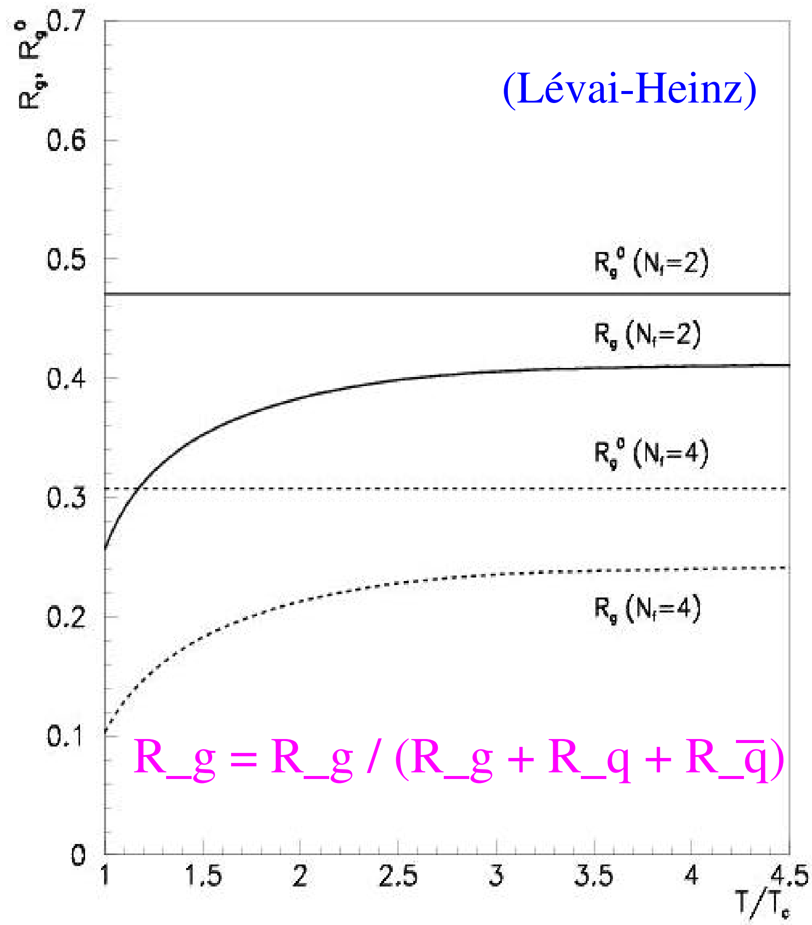


Fig.11. SU(3), N_f=2,4 --- $R_g(T)$, $R_g^0(T)$



➔ GLUON numbers are strongly suppressed at T_c and they will decay

QUARK-ANTIQUARK PLASMA

Model for interacting massive gluonic quasi-particles [SU(3), N_f=0]

B(T) ↔ interaction between gluons

$$P_{tot}(T) = P_{kin}(M(T),T) - B(T)$$

$$\varepsilon_{tot}(T) = \varepsilon_{kin}(M(T),T) + B(T)$$

B(T) ↣ attractive (effective) scalar field

$$B(T) = \frac{1}{2} m_\sigma^2 \sigma^2 = \frac{1}{2} \frac{g^2}{m_\sigma^2} n^2$$

M(T) ↣ effective mass

$$M_0(T) = \frac{1}{\sqrt{2}} g(T) T$$

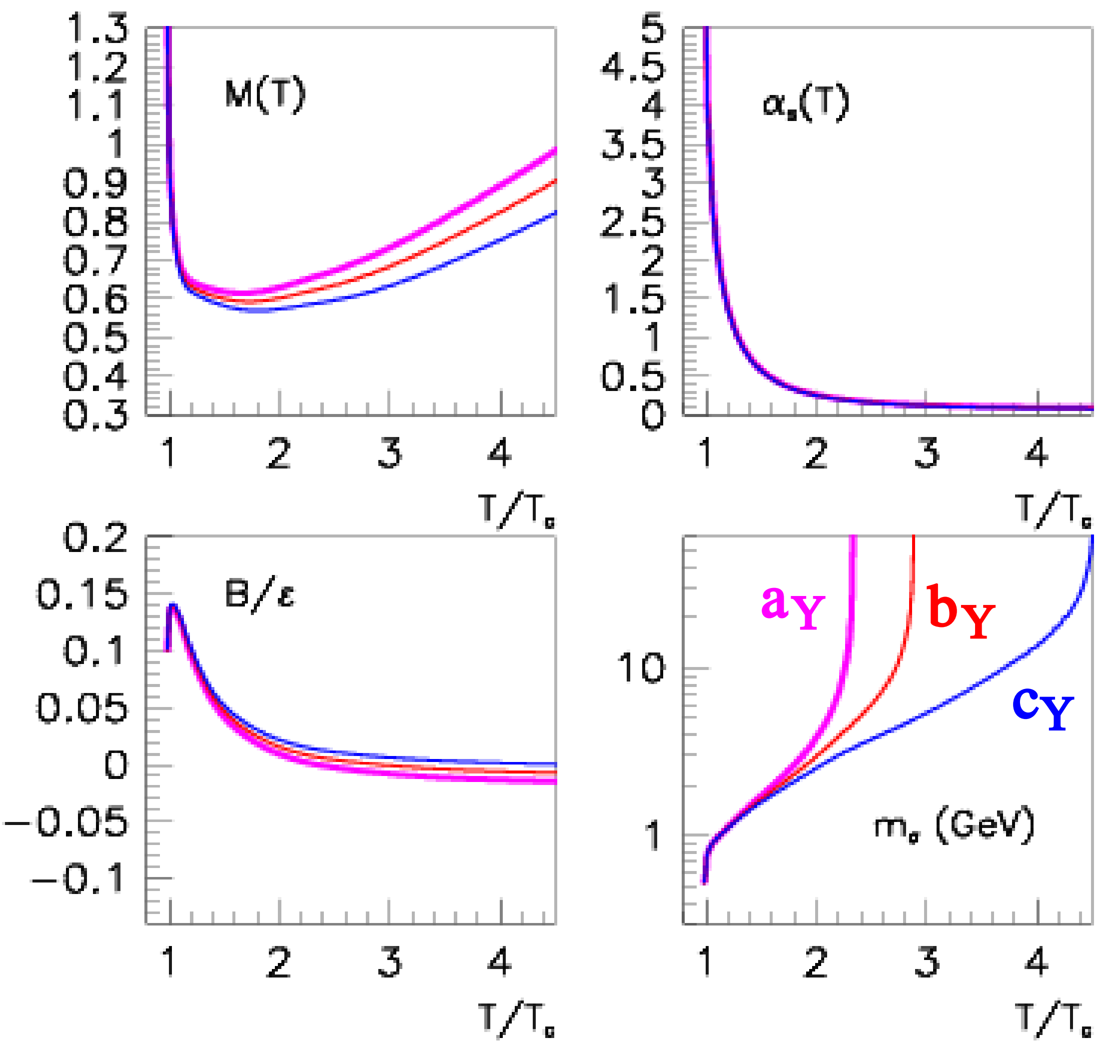
$$M(T) = M_0(T) - g\sigma = M_0(T) - \frac{g^2}{m_\sigma^2} n$$

U(r) ↣ effective potential between octet gluons

$$U(r) = \langle \lambda_i \lambda_j \rangle \alpha_s \frac{e^{-m_\sigma r}}{r} = -\frac{3}{2} \alpha_s \frac{e^{-m_\sigma r}}{r}$$

Numerical results for interacting massive gluonic quasi-particles

$\varepsilon(T)$, $P(T)$ ➤➤➤➤ $M(T)$, $B(T)$ ➤➤➤➤ $\alpha_s(T)$, $m_\sigma(T)$



Uncertanties (0-2-4 %) in the lattice results:

$\alpha_s(T)$ is robust

m_σ (T) is sensitive

[Yukawa-int.]

m_σ (T) is divergent, where B becomes negative

We can compress infinity into a finite T/T_c region.

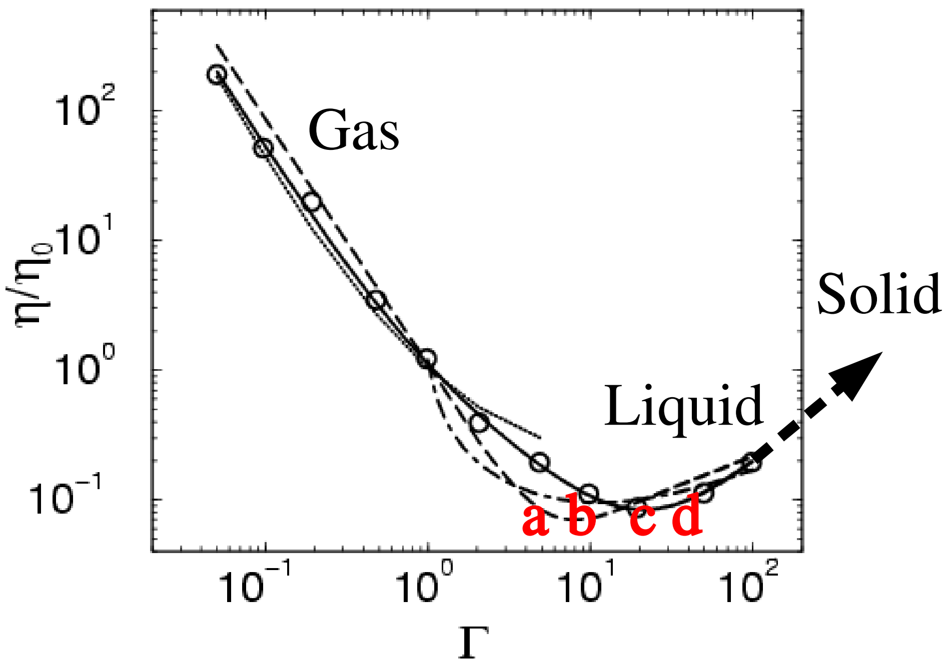
Viscosity of QGP (QAP, ...)

Motivations: - how large is the viscosity in QGP (around T_c) ?

- how can we determine it ?

Binary Ionic Mixture (BIM OCP)

S. Bastea, PRE71,2005,056405



$\eta/\eta_0(\Gamma)$ has an U-shape in Γ !!

What about the shape of η/s(T) ???

What about the properties of sQGP ?

What about sQGP ?

SU(3), N_f=2, d= 16 + 12 + 12

$$\Gamma = \frac{4\pi\alpha_s(T)}{a_{WS}T} = C\alpha_s(T)$$

$$a_{WS}^3 = \frac{3}{4\pi n(T)}$$

$$\eta_0 = \sqrt{\frac{\alpha_s(T)M}{a_{WS}^5}\left(\frac{3}{4\pi}\right)^3}$$

T=200 MeV, SU(3), N_f=2

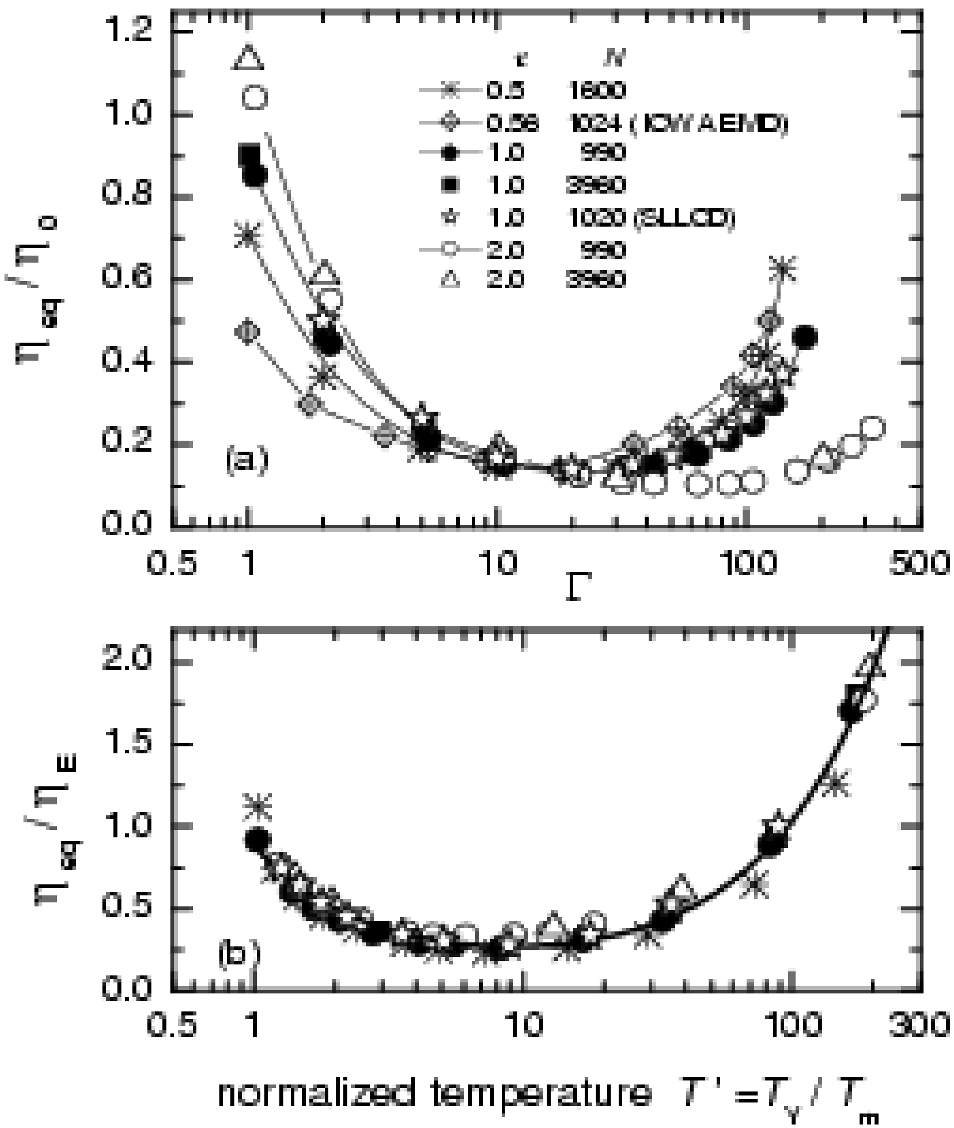
a, $\alpha_s = 0.17$ ↣ $\Gamma = 5.1$

b, $\alpha_s = 0.25$ ↣ $\Gamma = 7.3$

c, $\alpha_s = 1.0$ ↣ $\Gamma = 24$

d, $\alpha_s = 2.0$ ↣ $\Gamma = 40$

<u>Answer in dense plasma physics:</u> η(T) has a U-shape ! η/s ?



Z. Donkó, J. Goree,
P. Hartmann, K. Kutasi:
Shear viscosity in 2D Yukawa-liquid
PRL96(2006)145003

Molecular dynamical simulation with a finite number of particle.

Can we do it in YM case?
How large is the viscosity in other models?

Danielewicz-Gyulassy:
$\eta/s \approx 1$ PRD31(1985)

What about viscosity in QGP?

1. Viscosity in ~free massive quark gas [classical physics]
   in weakly interacting QGP [QCD at high-T]

2. Lattice-QCD results ⤖⤖⤖ sQGP
   --- viscosity in the quasi-particle picture
   --- different models (width, spectral function)

3. Molecular dynamical simulation for
   massive quasi-particles with Yukawa-interaction
   ⤖ ⤖ ⤖ viscosity at $1 < T/T_c < 2$

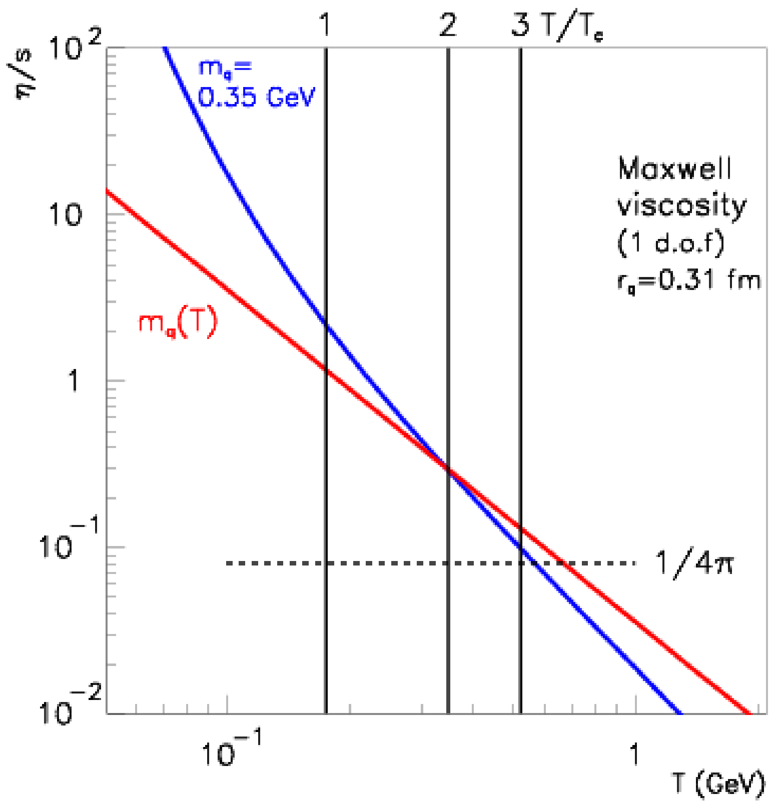
Viscosity of ~free massive fermi (q) gas [1 degree of freedom]

A, constant mass, $m_q = 0.35$ GeV

B, temperature dep. mass, $m_q(T) = g\,T/\sqrt{3}$ [$g=1.77$, $\alpha_s=0.25$]

$\eta(T)$: Maxwell viscosity ➔ $\eta = \frac{m_q}{3\sqrt{2}\pi d^2}\sqrt{\frac{8T}{\pi m_q}}$ $[d=2r_q]$ $[r_q=0.31\,fm, \sigma=3\,mb]$

s(T) = (ε(T) + P(T))/T for free massive fermi gas, s(T) ~T³



NO Minimum (?)

$\eta/s = 1/4\pi$ at $T \approx 3\,T_c$

$\eta/s = 0.2 - 2$ at $2 > T/T_c > 1$

Did we find the wanted "perfect fluid" in the classic description of a free massive gas ???

[Where is the U-shape ??!]

Viscosity of ~free massive fermi (q) gas [1 degree of freedom]

A, constant mass, m_q= 0.35 GeV

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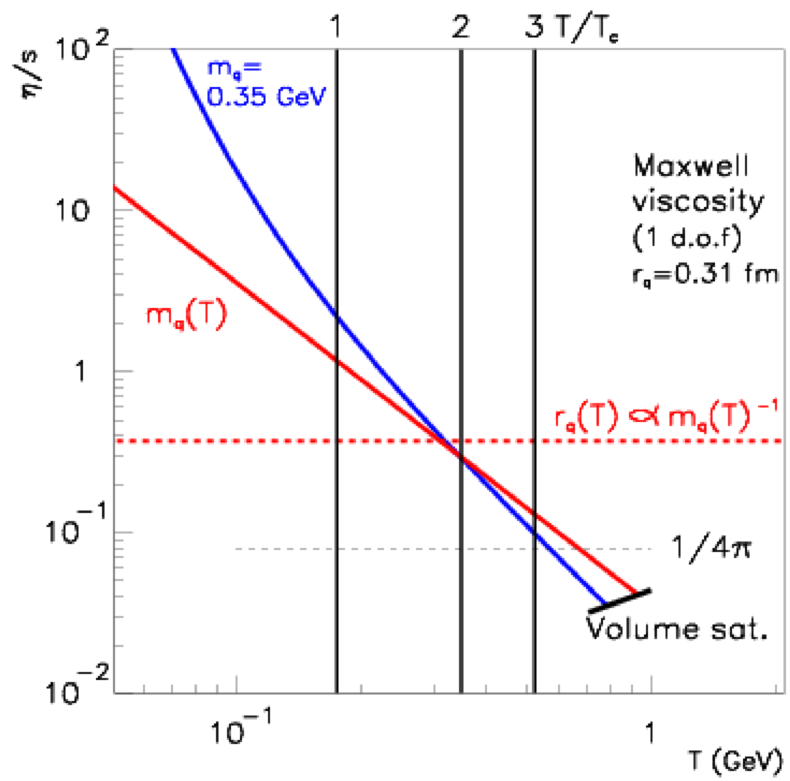
$\eta(T)$: Maxwell viscosity ➔ $\eta = \dfrac{m_q}{3\sqrt{2}\pi d^2}\sqrt{\dfrac{8T}{\pi m_q}}$

$[d = 2 r_q]$

$[\sigma = \pi r_q^2 \sim (g T)^{-2}]$

C, ---------- $r_q(T) = \dfrac{1}{2}\dfrac{\hbar c}{m_q(T)} \sim \dfrac{1}{gT}$



A & B : Constant volume

↣ Volume saturation

$\eta/s \approx (1/4\pi)/2$ at $T \approx 5\, T_c$

C, --------

$\eta \sim T^3, s \sim T^3$

$\dfrac{\eta}{s} = const.$

More T-dependence is needed in η for the U-shape

Viscosity in weakly coupled QGP [SU(3), gluon + $N_f = 2$, g=const.]

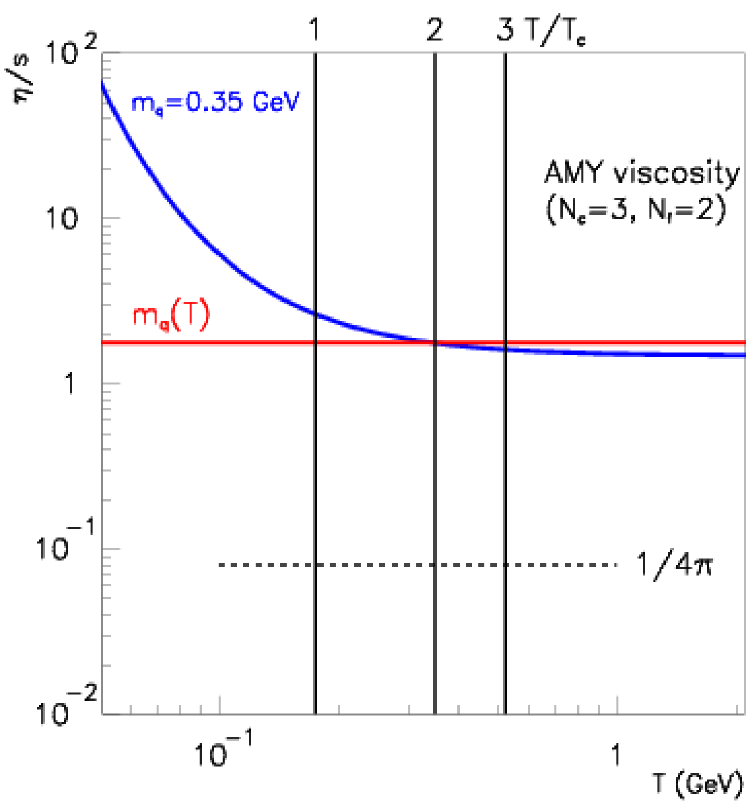
A, constant mass, $m_q = 0.35$ GeV, $m_g = \sqrt{2}\, m_q$

B, temperature dep. mass, $m_q(T) = g\, T/\sqrt{3}$ [$g=1.77$, $\alpha_s=0.25$]

$\eta(T)$: AMY viscosity ➔ $\eta = \kappa \dfrac{T^3}{g^4 \ln g^{-1}}$ $[\kappa = 86.47]$

(Arnold, Moore, Yaffe, JHEP 2003)

$s(T) = (\varepsilon(T) + P(T))/T$ for massive fermi and bose gas, $s(T) \sim T^3$



NO Minimum

If $T \to \infty$ then

$\eta/s \to 20(1/4\pi)$

At $1 < T/T_c < 2$

$\eta/s = 2 - 3$

This matter is not a "perfect fluid" !

Viscosity in weakly coupled QGP [SU(3), gluon + $N_f = 2$, g(T)]

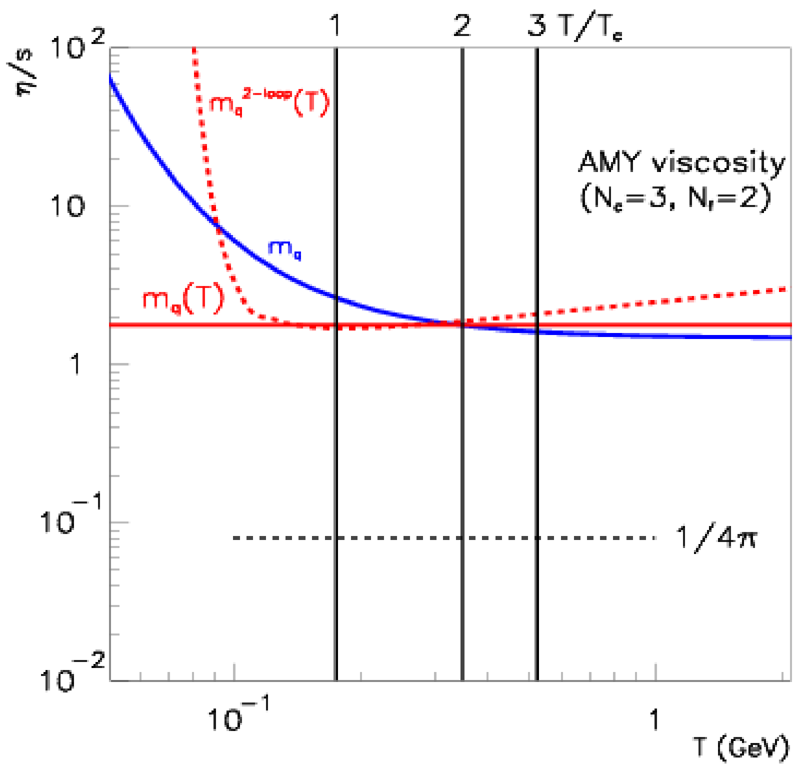
A, constant mass, $m_q = 0.35$ GeV, $m_g = \sqrt{2}\, m_q$

B, temperature dep. mass, $m_q(T) = g\, T/\sqrt{3}$ [$g=1.77$, $\alpha_s=0.25$]

$\eta(T)$: AMY viscosity ➔ $$\eta = \kappa \frac{T^3}{g^4 \ln g^{-1}}$$ $[\kappa = 86.47]$

(Arnold, Moore, Yaffe, JHEP 2003)

C, ---- 2-loop renorm. $$g(T)^{-2} = \frac{9}{8\pi^2} \ln \frac{T}{\mu_0} + \frac{4}{9\pi^2} \ln\left(2 \ln \frac{T}{\mu_0}\right)$$ $[\mu_0 = 0.03\, GeV]$



C: Minimum at

$T \approx T_c$, $\eta/s = 20\ (1/4\pi)$

$1 < T/T_c < 2$, $\eta/s \approx 2$

$T \to \infty$, $\eta/s \sim \ln^2 T$

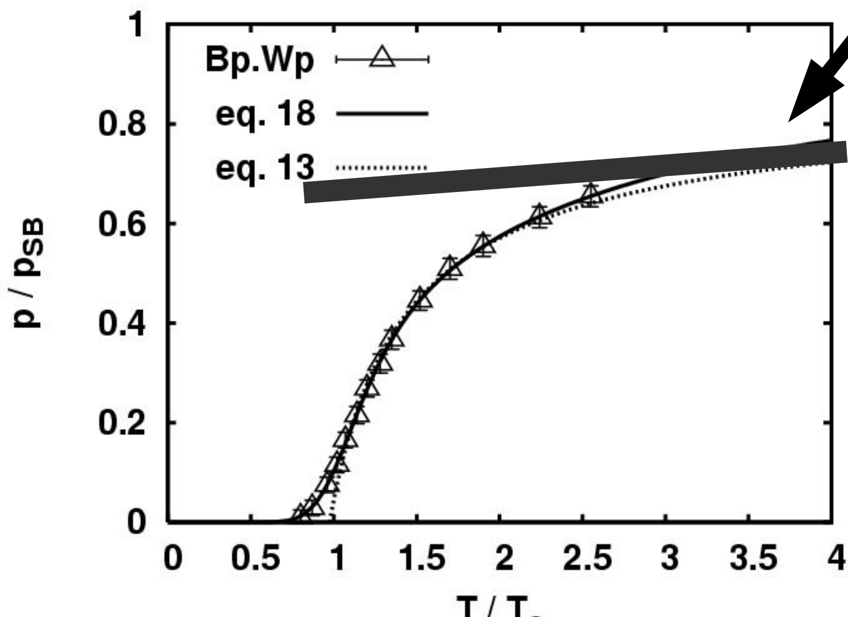
So far this is the best candidate but it is not "perfect fluid".

"Low-viscosity matter"
Csernai, Kapusta, McLerran, PRL97, 152303, 2006

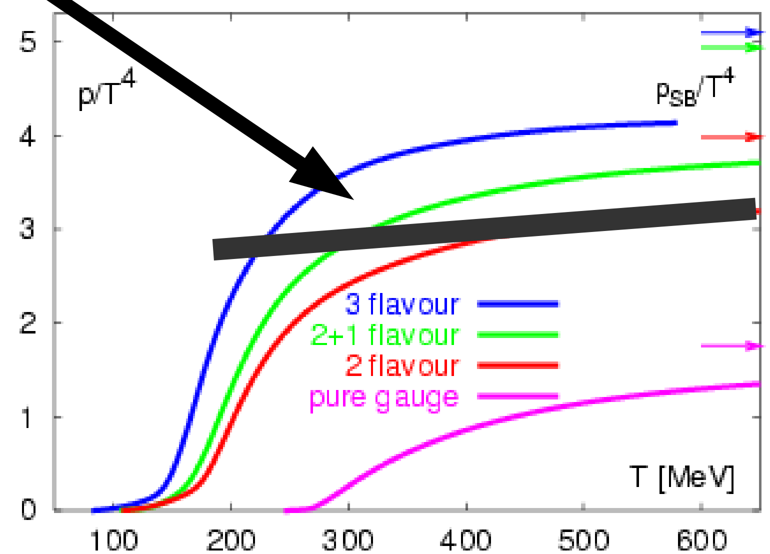
Lattice-QCD results: EOS for strongly interacting QGP

Testing $g^{2\text{-loop}}(T)$ ➔ $\varepsilon(T)$, $P(T)$ in SU(3), $N_f = 2$

$$m_q(T) = g(T)T/\sqrt{3}\,; \quad m_g(T) = \sqrt{2}\, m_q(T)$$



Fodor et al. 2003 - physical quark mass



Karsch et al. 1992

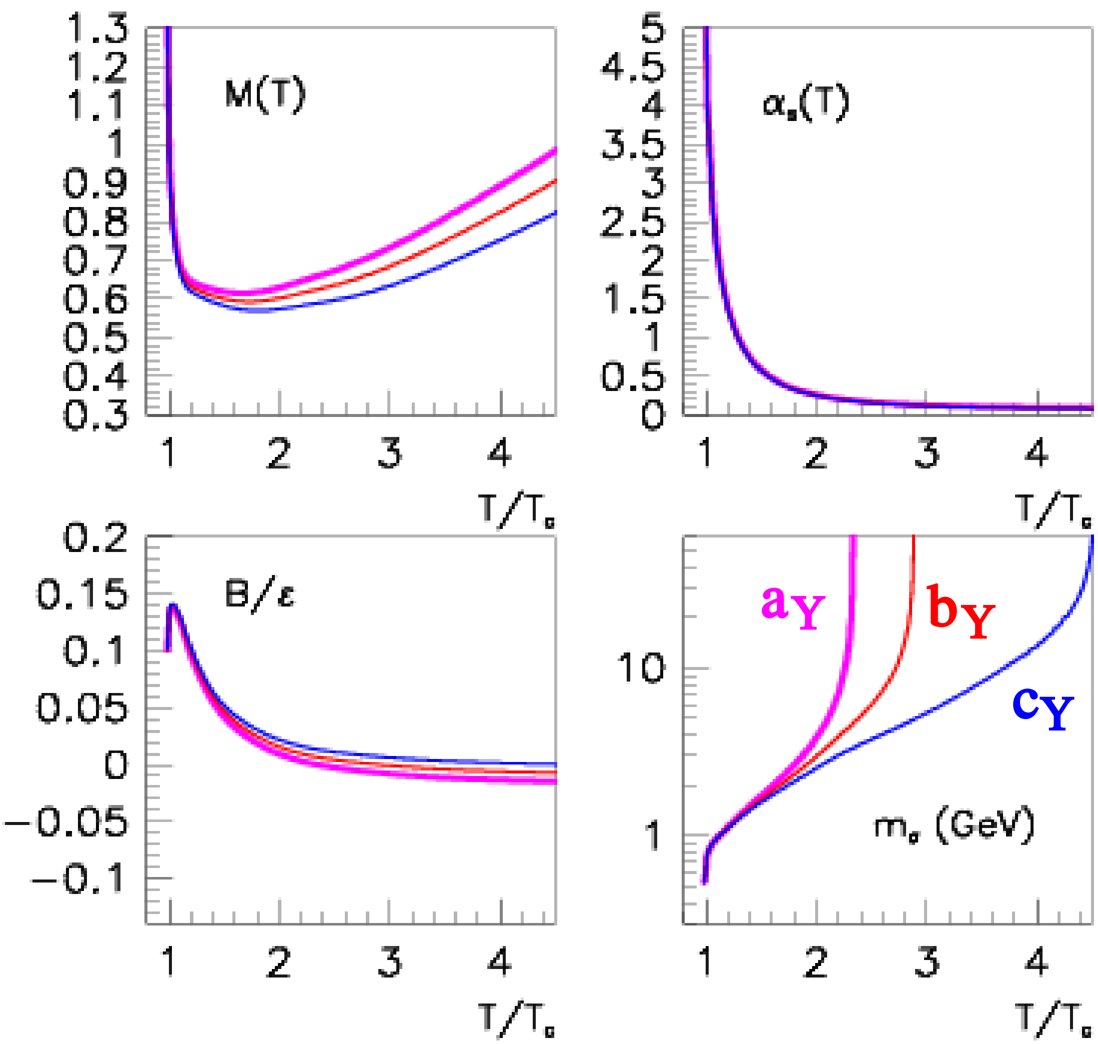
$g^{2\text{-loop}}(T)$ is maybe good asymptotically, but not for $T < 2\,T_c$

Non-ideal EOS ➣ quasi-particle picture of strongly interacting QGP

Can we extract viscosity in the quasi-particle description ???

Numerical results for interacting massive gluonic quasi-particles

$\varepsilon(T)$, $P(T)$ ➤➤➤➤ $M(T)$, $B(T)$ ➤➤➤➤ $\alpha_s(T)$, $m_\sigma(T)$



Uncertanties (0-2-4 %) in the lattice results:

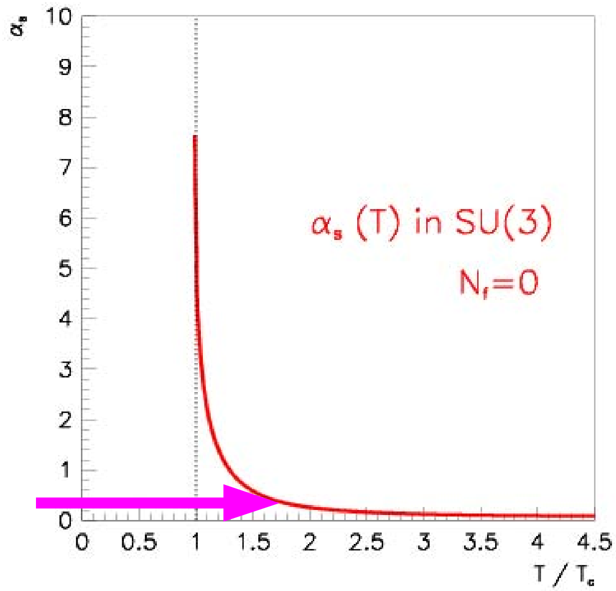
$\alpha_s(T)$ is robust

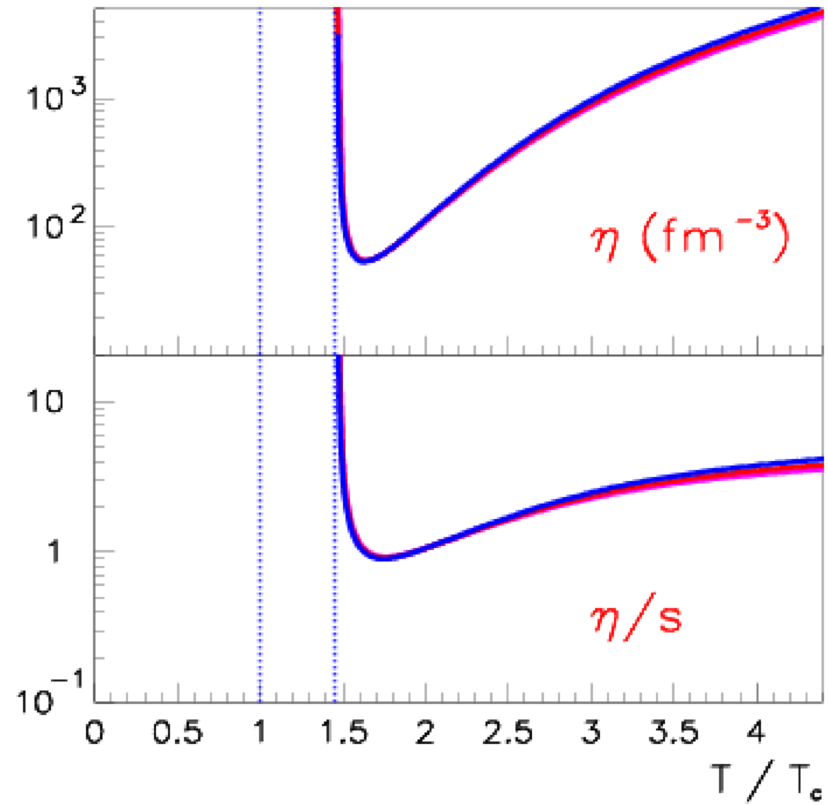
m_σ (T) is sensitive [Yukawa-int.]

m_σ (T) is divergent, where B becomes negative

We can compress infinity into a finite T/T_c region.

AMY formula for the quasi-gluon gas [SU(3) N_f=0]





$$\eta_{NLL} = \frac{27.12\,T^3}{g^4 \ln(2.765/g)}$$

$\eta/s = 0.9$ at $T=1.75\,T_c$

$T \rightarrowtail T_c$ ➤➤➤➤➤ $\alpha_s(T)$ becomes extremely large

If $\alpha_s(T) > 1$, then the simple viscosity formula does not work.

AMY: formula is good for $\alpha_s(T) < 0.3$!!! $T/T_c \geq 1.8$, $\eta/s \geq 0.9$

How to improve quasi particle description, especially in the region $1 < T/T_c < 1.5$

1. Multi-gluon and multi-quark states around T_c

   E.V. Shuryak, I. Zahed, PRC70 (2004) 021901.

   P. Lévai, A. Németh, in preparation [10-15 %]

2. Width of the quasi particles .

   A. Peshier, W. Cassing, PRL94(2005)172301. [Diverg.]

3. Mass distribution of the quasi particles (spectral function)

   T.S. Bíró, P. Lévai, P. Ván, J. Zimányi
   JPG31,2005,711
   hep-ph/0606076 [Interaction in the $F(m_q)$.]

OR: Molecular dynamical simulations for SU(3) quark matter!

P. Hartmann, Z. Donkó, G. Kalman, P. Lévai
Nucl. Phys. A774, 2006, 881

Talks on the QM05 and QM06.

INTERACTION ↣ Multi-gluon states: 2g, 3g, 4g, ...

$$M_0(T) = \frac{1}{\sqrt{2}}\, g(T)\, T$$

Singlet (1) is attractive

Octet (8) is attractive

Decuplet (10) is neutral

Higher multiplets are repulsive

$$M_i(T) = i M_0(T) - g\sigma = i M_0(T) - \frac{g^2}{m_\sigma^2} \sum n_i$$

Multi-gluon states	1	8	10	27	28	35	64	80 ...
8⊗8	1	2	2	1	0	0	0	0
8⊗8⊗8	2	8	8	6	0	4	1	0
8⊗8⊗8⊗8	8	32	40	33	4	30	12	0
8⊗8⊗8⊗8⊗8	32	145	200	180	40	200	94	10
8⊗8⊗8⊗8⊗8⊗8	145	702	1050	999	322	1260	660	140
8⊗8⊗8⊗8⊗8⊗8⊗8	702	3598	5712	5670	2352	7840	4424	1400

Suppression of the multi-gluon states: Γ * (2g, 3g, 4g, ...)

$$P(T)=P_1(M_{1,}T)+C(T)*\sum_2^{\infty} P_i(M_i,T)-B(T)$$

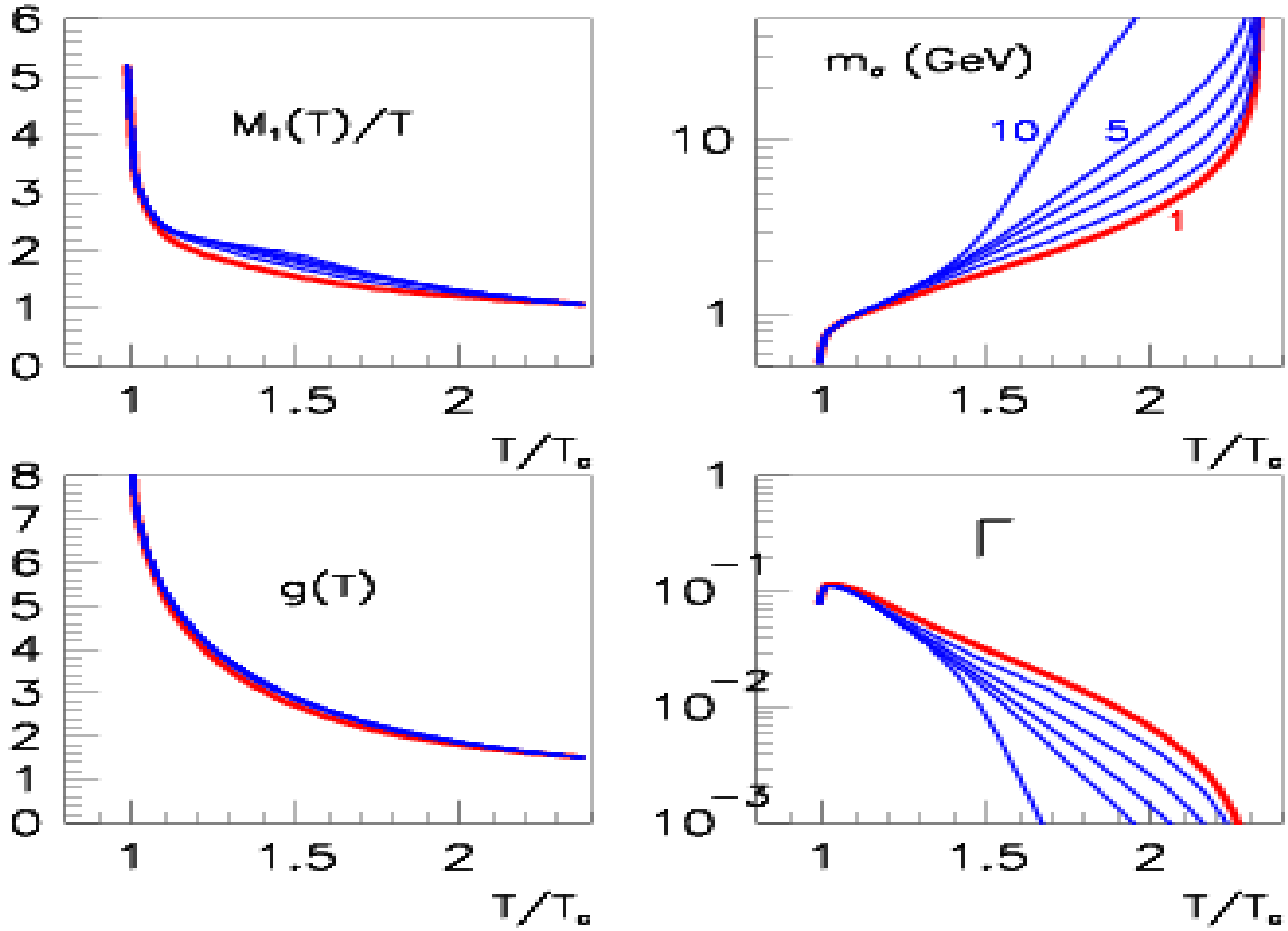
$$\varepsilon(T)=\varepsilon_1(M_{1,}T)+C(T)*\sum_2^{\infty} \varepsilon_i(M_i,T)+B(T)$$

$$n(T)=n_1(M_{1,}T)+C(T)*\sum_2^{\infty} n_i(M_i,T)$$

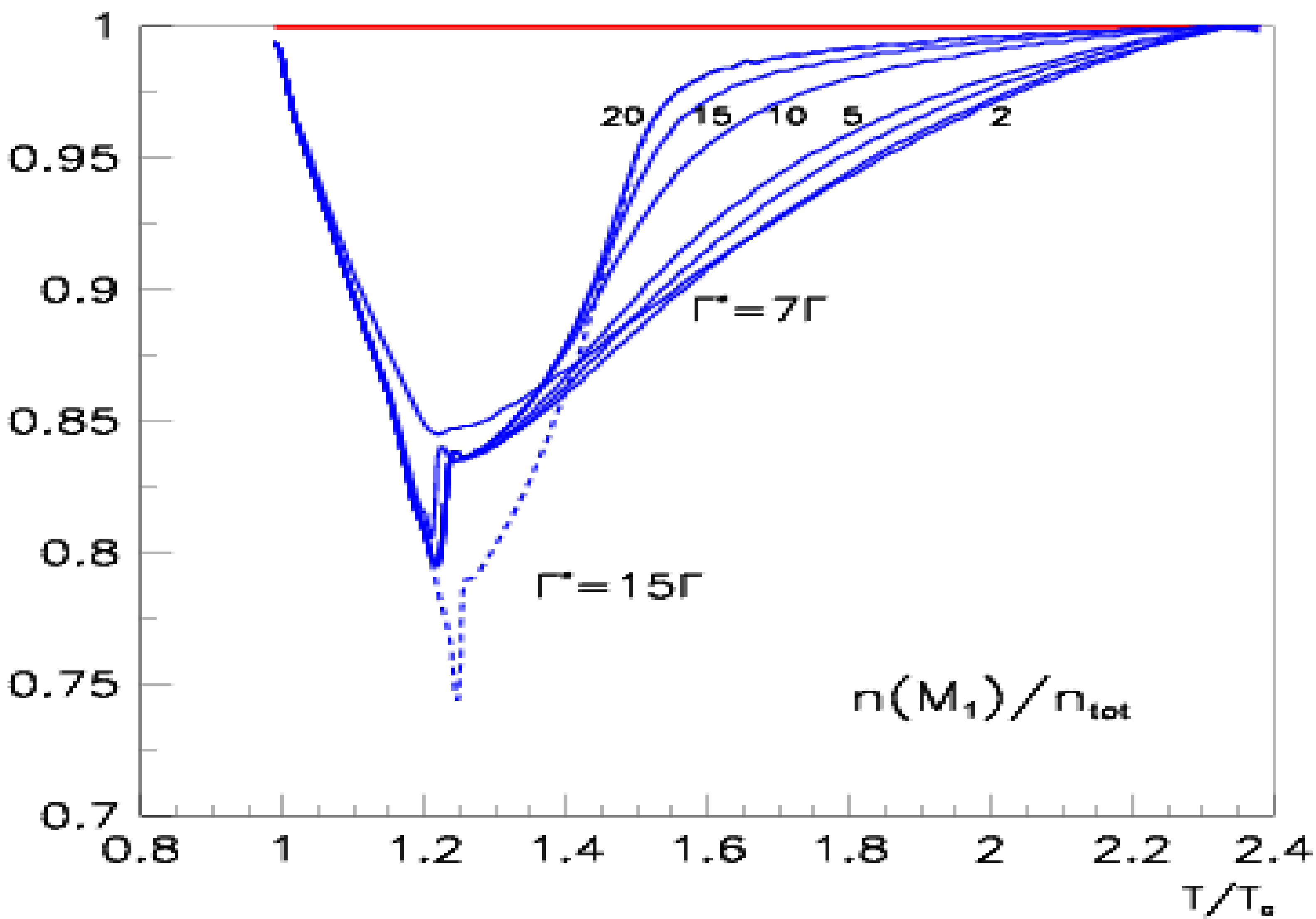
$$C(T) = \kappa * \Gamma(T)$$

$$\Gamma = E_{pot} / E_{kin} = \frac{3}{m_\sigma^2} \frac{n^2}{\varepsilon_{tot}-B}$$

Interacting multi-gluon states (2,3,4,5,...,10) and $\Gamma = E_{pot} / E_{kin}$



Relative density of 1g to the total density (incl. multi-gluon states)



Interpretation:

Multi-gluon states has very small contribution at T_c

Multi-gluon states has contribution at large T,

but Γ(T) -factor cuts this out,

cut-off moving closer to T_c as N_g is increasing

Finally there is a small window ($1.05 < T/T_c < 1.15$)

where multi-gluons can exist – depending on Γ

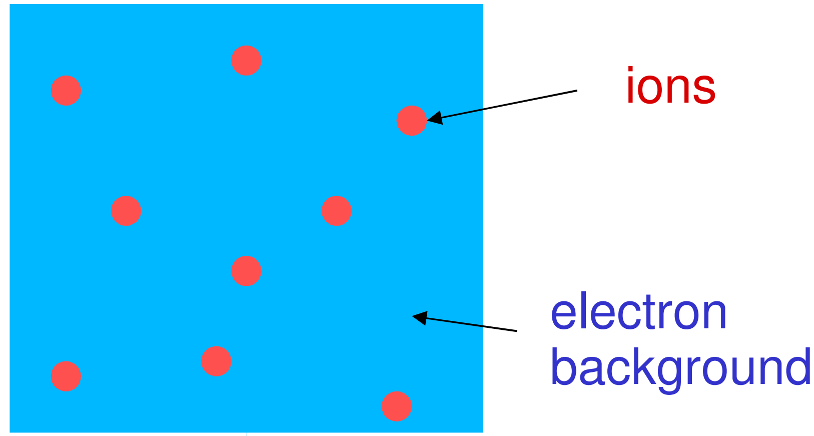
One-gluon states are good degrees of freedom

at T_c and at high temperature

Classical strongly coupled plasmas

The simplest system: classical one-component plasma (OCP).

OCP: charged heavy particles immersed into a homogeneous neutralizing background.



interaction (Coulomb) potential: $V(r)=\frac{Q^2}{r}$

particle density n particle mass m electric charge Q Temperature T	plasma coupling parameter	$\Gamma=Q^2/(a_{WS}k_B T)$
	ion sphere radius	$a_{WS}=\sqrt[3]{3/(4\pi n)}$
	plasma frequency	$\omega_p=\sqrt{4\pi Q^2 n/m}$

investigated properties:

- structure (pair correlation function, static structure function)
- thermodynamics (internal energy, compressibility, equation of state)
- transport phenomena (thermal conductivity, shear viscosity, diffusion)
- collective dynamics (density and current fluctuations, dispersion relations)

Our sQGP model is rooted on the classical OCP model. The links are:

classical OCP		QGP model
ions	$\longrightarrow$	*quarks (massive)*
electron background (neutralizing)	$\longrightarrow$	*gluon background* interacting !!!
$V(r_{ij}) = \frac{Q^2}{r_{ij}}$	$\longrightarrow$	$V(r_{ij}) = \frac{\langle \lambda_i \lambda_j \rangle \alpha_S}{r_{ij}}$
$\Gamma = \frac{Q^2}{a_{WS} k_B T}$	$\longrightarrow$	$\Gamma = \frac{C \;\; S}{a_{WS} k_B T}$

The numerical simulation is based on the classical molecular dynamics scheme:

- calculating the forces acting on each particle due to all other particles
- integrating the equation of motion for all particles in each time-step
- using periodic boundary conditions to handle long range forces
- implementing color rotation due to random gluonic interaction

Potential model for QCD interaction

color dependent interaction potential between quark i and j: $$V = \langle \lambda_i \lambda_j \rangle \frac{\alpha}{r_{ij}}$$

possible two-quark states (***R***, ***G*** and ***B*** are the single-quark color states):

$\|RR\rangle$	$\Psi = \Psi_1(R)\Psi_2(R)$
$\|GG\rangle$	$\Psi = \Psi_1(G)\Psi_2(G)$
$\|BB\rangle$	$\Psi = \Psi_1(B)\Psi_2(B)$
$\|RG\rangle$	$\Psi = \frac{1}{\sqrt{2}}[\Psi_1(R)\Psi_2(G) + \Psi_1(G)\Psi_2(R)]$
$\|RB\rangle$	$\Psi = \frac{1}{\sqrt{2}}[\Psi_1(R)\Psi_2(B) + \Psi_1(B)\Psi_2(R)]$
$\|GB\rangle$	$\Psi = \frac{1}{\sqrt{2}}[\Psi_1(G)\Psi_2(B) + \Psi_1(B)\Psi_2(G)]$
$\|RG\rangle_{Anti}$	$\Psi = \frac{1}{\sqrt{2}}[\Psi_1(R)\Psi_2(G) - \Psi_1(G)\Psi_2(R)]$
$\|RB\rangle_{Anti}$	$\Psi = \frac{1}{\sqrt{2}}[\Psi_1(R)\Psi_2(B) - \Psi_1(B)\Psi_2(R)]$
$\|GB\rangle_{Anti}$	$\Psi = \frac{1}{\sqrt{2}}[\Psi_1(G)\Psi_2(B) - \Psi_1(B)\Psi_2(G)]$

color factor:

$$\langle \lambda_i \lambda_j \rangle = \frac{1}{2}\left[\langle (\lambda_i + \lambda_j)^2 \rangle - \langle \lambda_i^2 \rangle - \langle \lambda_j^2 \rangle\right]$$

$+1/3$ symmetric (6)

$-2/3$ antisymmetric ($\bar{3}$)

The interaction matrix

Consequences:
- equally colored quarks repulse each other
- different colors may repulse or attract each other

⇨

$$V = \langle \lambda_i \lambda_j \rangle \frac{\alpha}{r_{ij}}$$

$\langle \lambda_i \lambda_j \rangle$	$\lvert R\rangle$	$\lvert G\rangle$	$\lvert B\rangle$
$\lvert R\rangle$	$+\frac{1}{3}$	D	D
$\lvert G\rangle$	D	$+\frac{1}{3}$	D
$\lvert B\rangle$	D	D	$+\frac{1}{3}$

where $D = \begin{cases} +1/3 & \text{with 50\% prob.} \\ -2/3 & \text{with 50\% prob.} \end{cases}$

<u>An example:</u>

interaction matrix of a 9-quark system (excluding self-interaction and double counting)

	1_R	2_G	3_B	4_G	5_R	6_R	7_B	8_G	9_B
1_R		D	D	D	$+\frac{1}{3}$	$+\frac{1}{3}$	D	D	D
2_G			D	$+\frac{1}{3}$	D	D	D	$+\frac{1}{3}$	D
3_B				D	D	D	$+\frac{1}{3}$	D	$+\frac{1}{3}$
4_G					D	D	D	$+\frac{1}{3}$	D
5_R						$+\frac{1}{3}$	D	D	D
6_R							D	D	D
7_B								D	$+\frac{1}{3}$
8_G									D
9_B									

quark-gluon interaction:

- redistribution of elements D in the interaction matrix (with a characteristic time: τ_D)
- “color rotation”: exchange of colors of some quark pairs (τ_C)

MD results for pair correlation

In the following we present molecular dynamics results for quark plasma with physical parameters:

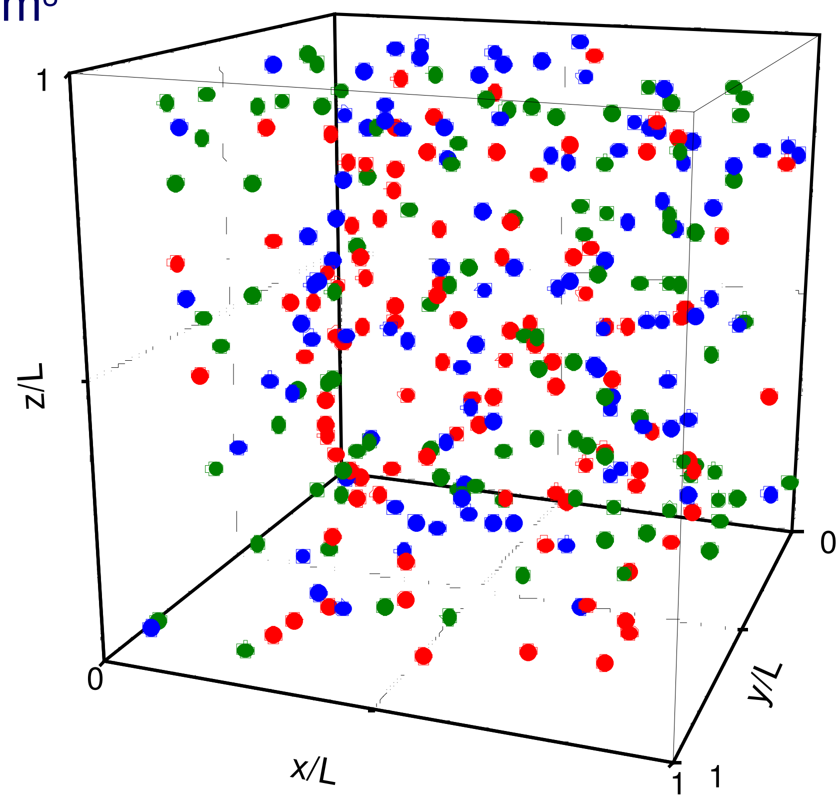
- kinetic temperature, T_0 = 180 - 350 MeV
- particle density, n = 5-100 quarks / fm^3
- interaction strength, α_S = 1-2
- quark mass, m = 300-400 MeV

and technical parameters:

- number of particles, N = 300
- starting positions = random
- initialization time, $t_i = 10^{6+1}\,dt$
- measure time, $t_m = 2\text{x}10^5\,dt$
- time-step, $dt = 5\text{x}10^{-5}$ fm

measured parameters are:

- kinetic temperature, $T(t)$
- pair correlation function, $g(r)$
- viscosity, η

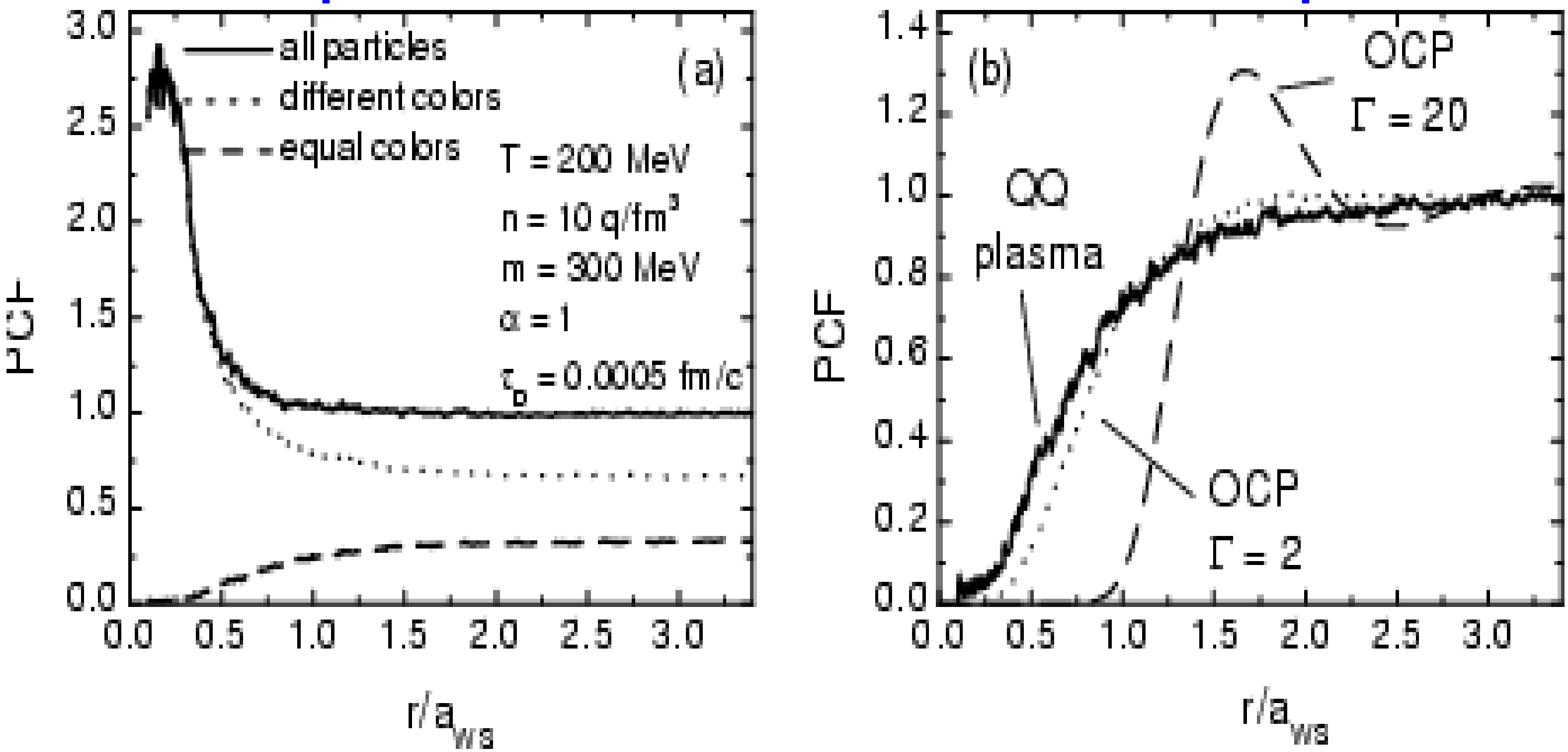


Correlations

g(r) pair-correlation function: liquid or gas ? ⇒⇒⇒ "gas" !

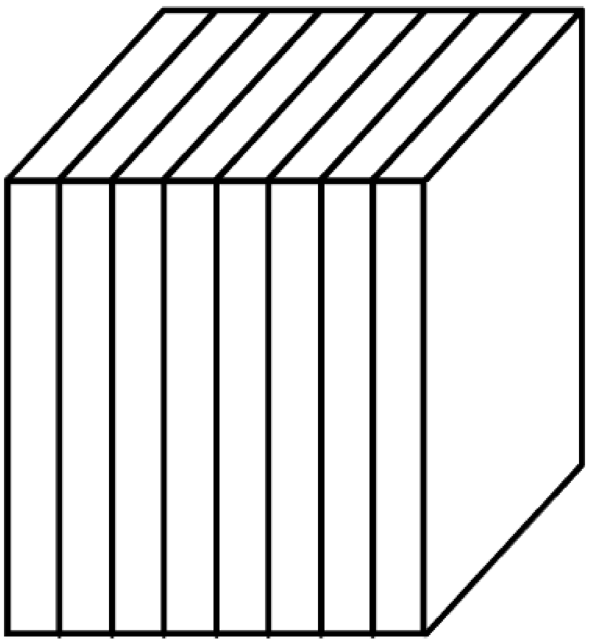
repulsive species: gas-like behaviour
attractive species: strong correlation (clusterization)

QQ plasma **QQ and ee plasma**

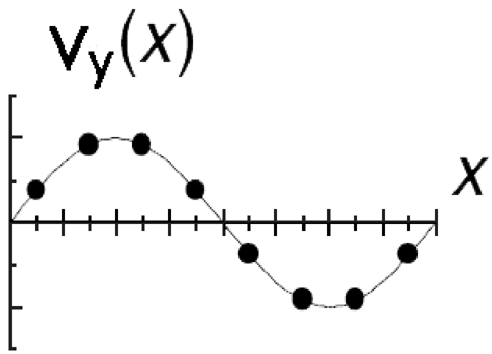


MD measurement for viscosity – 1

Z. Donkó, B. Nyíri, L. Szalai, S. Holló,
Phys. Rev. Lett. 81 (1998) 1622.



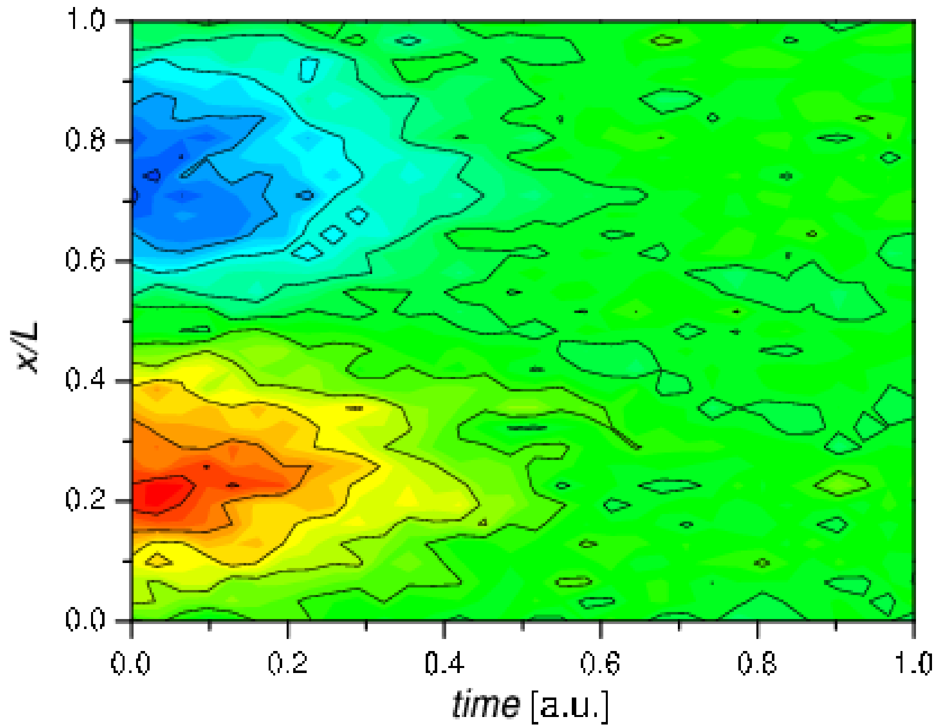
Periodic boundary condition.
(Separation into 8 bin.)

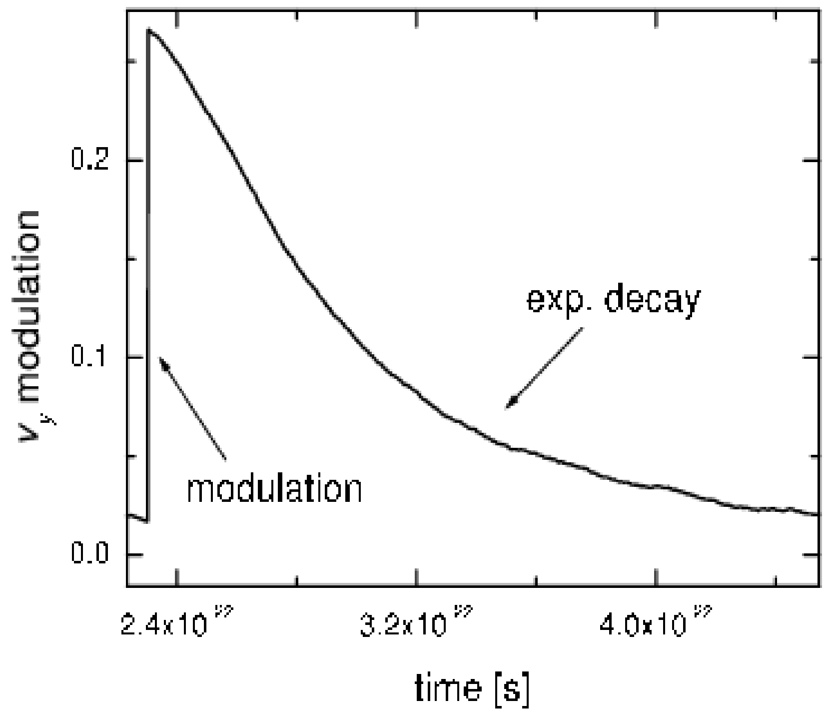


Sinusoid velocity perturbation
(artifical shear in the system):

$$\Delta v_y(x, t=t_0) = v_{m0} \sin(2\pi x/L)$$

MD measurement for viscosity – 2





The relaxation of this shear is exponential (see Navier-Stokes):

$$v_m(t) = v_{m0} \exp(-(t - t_0)/\tau)$$

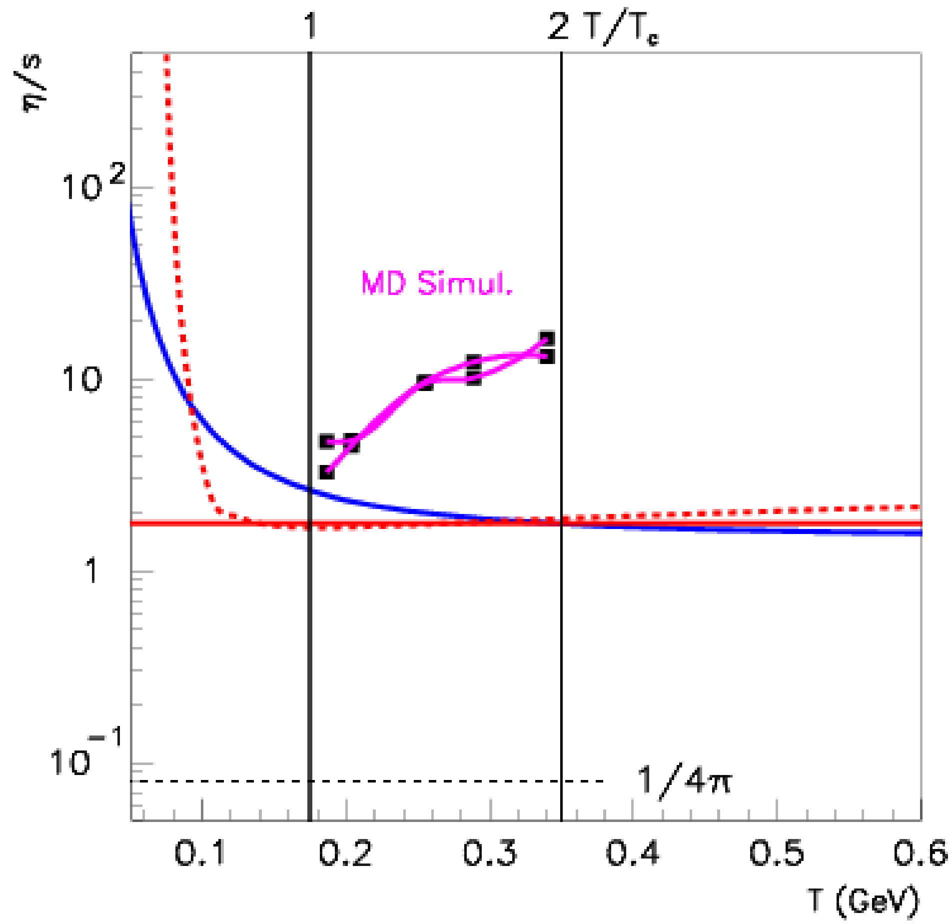
Here τ is related to the dynamical viscosity η_D :

$$\eta_D = \frac{\rho\, m_q}{\tau} (L/2\pi)^2$$

ρ : density [1/fm^3]

L : simulation box size [fm]

RESULTS from MD simulation for viscosity (100 000 part.):



MD simulation

for quark matter:

Minimum

$T = T_c \Rightarrow\Rightarrow \eta/s \approx 3$

Result is larger than AMY

$1 < T/T_c < 2 \Rightarrow \eta/s = 3 - 15$

Introduction

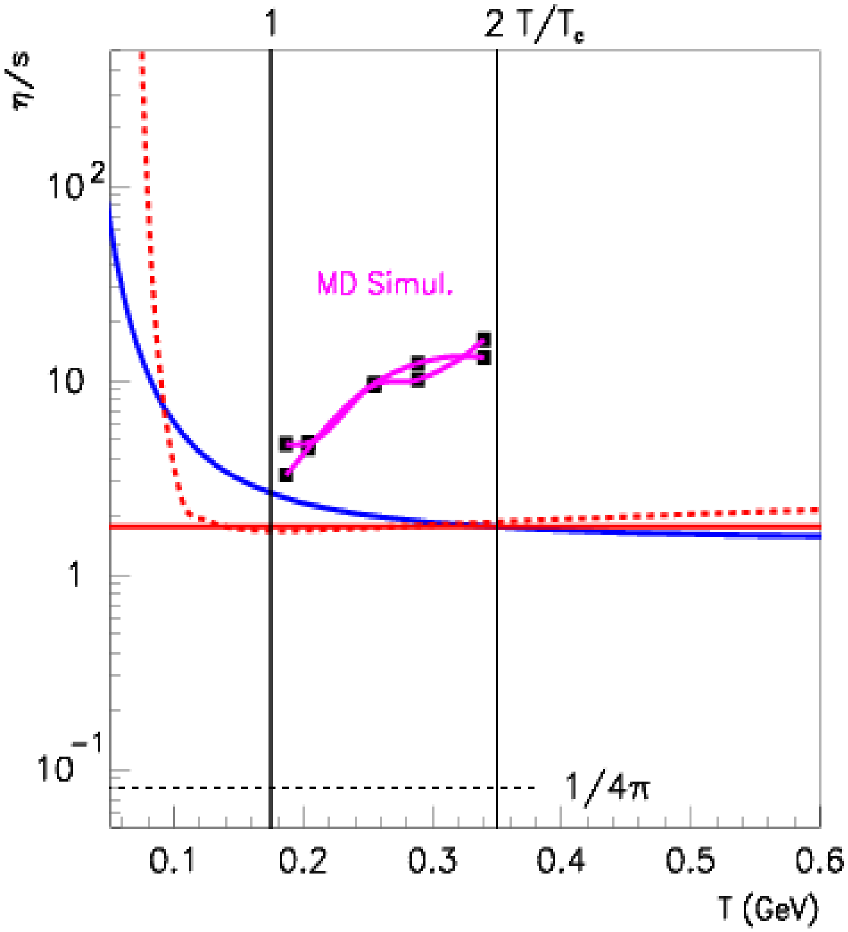
of antiquarks and gluons will

increases the entropy

descreases η/s

$\eta/s \approx 1\text{-}5$: even this is large

RESULTS from MD simulation for viscosity:



If Yukawa ↣ 0 at T/T_c ↣ ∞

then η/s ↣ ≈ 20

Massive quark plasma
will not approach
dense gluon field
[η/s =2]

Dense gluon field:
Anomalous viscosity (η_A)
in turbulent gluon fields,
$\eta_A \ll \eta$

$\eta_A/s \approx C\ (1/4\pi)$ C=?? (2-3)

[Asakawa, Bass, Müller, PRL96,2006]

What happen at T/Tc ↣ 1 ?

Cross-over phase transition in MD?

COMMENT after the MD simulation:

we obtain too large viscosity,
because we are using “particles” and
a reduced interaction between them

small viscosity: interaction energy is large
kinetic energy is small

'non-particle' picture of strongly interacting QGP ?
we loose hadronization successful models
we loose (particle) EOS and particle transport

Laminar -> turbulent flow is a good solution.
But what can we calculate in a turbulent state?

Summary:

1. Viscosity can be calculated in many ways:

   Classical description can give very small value for η/s seems to generate "perfect fluid" (?)

QM and QCD give	$\eta/s \approx 2$	at $T/T_c \geq 1$
Quasi-particle picture gives	$\eta/s \geq 0.9$	at $T/T_c \geq 1.8$
MD for quark matter gives	$\eta/s \geq 3$	at $T/T_c \geq 1.1$

   Further studies are needed, especially including antiquarks, g.

2. How large is the anomalous viscosity, η_A/s?

3. Viscosity and jets, direct experimental measurement ?

   Especially, if the viscosity is large: $\eta/s \geq 1$ at $T \approx 200$ MeV

   $\eta/s \geq 2$ at $T > 250$ MeV!

4. 'Non-particle' based descriptions?