Results from Regensburg and comments after 30 years

- The SQAGP-

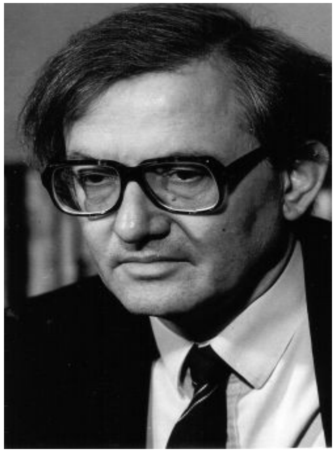
P. Lévai, Wigner RCP, Budapest

17 July 2016,
Uli Heinz - 60,
CERN

Regensburg:
Cathedral + Historische Wuerstkueche (1164)


photo by © Adam Świerzewski

Regensburg:



Uli Heinz + Leon van Hove J. Zimanyi

Content:

1. The idea of "quark-gluon plasma"

1973: Quantum Chromodynamics (QCD)

Strong interaction: quarks and gluons

SU(3) Yang – Mills field theory

asymptotic freedom

1975-1980: at high energy density

(high temperature and/or high density)

quarks and gluons are weakly coupled

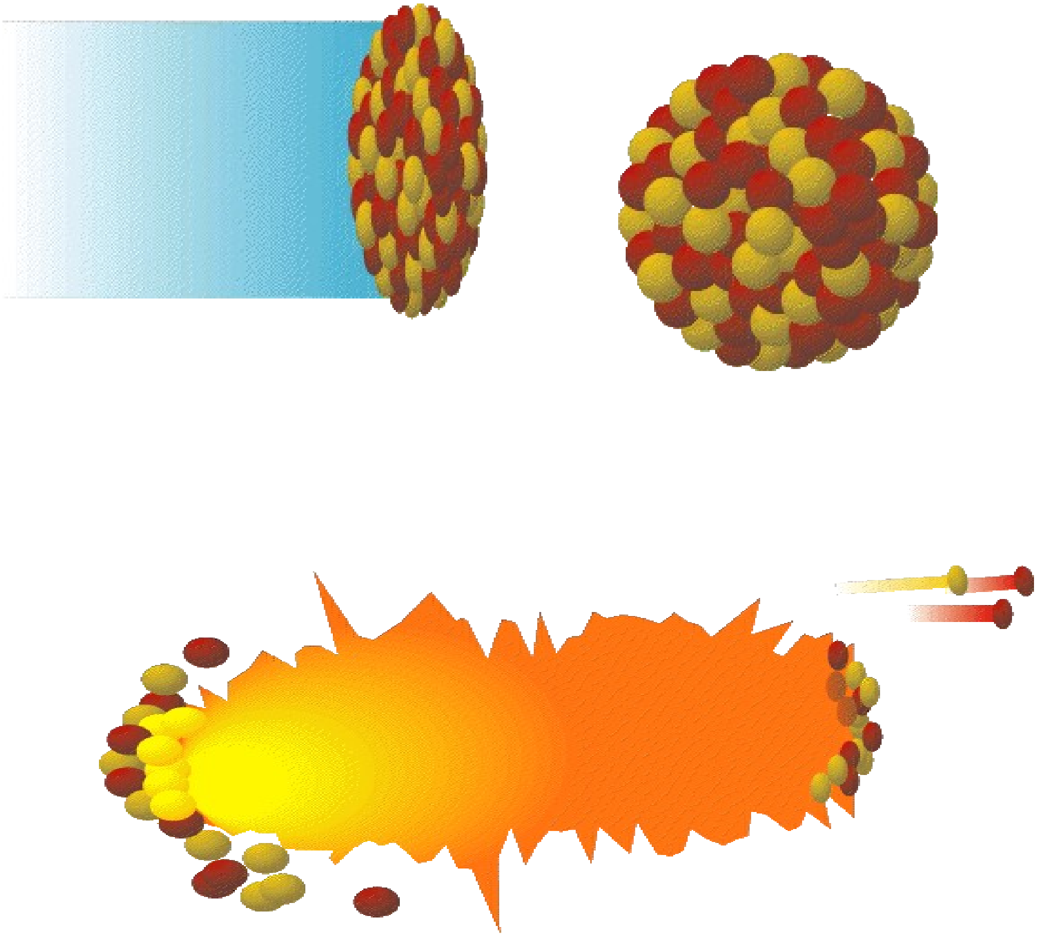
quark-gluon matter/plasma can exist

perturbative description of QGP

(Linde'80: problems appear beyond g^6 order)

(+ other challenges in theory)

➤➤➤ RELATIVISTIC HEAVY ION COLLISIONS



Relativistic heavy ion collisions:

$T = 100 - 500$ MeV

↣ $(1 – 5) \cdot 10^{11}$ K

$n = (1 – 5) \cdot n_0$

$n_0 = 0.15$ part/fm^3

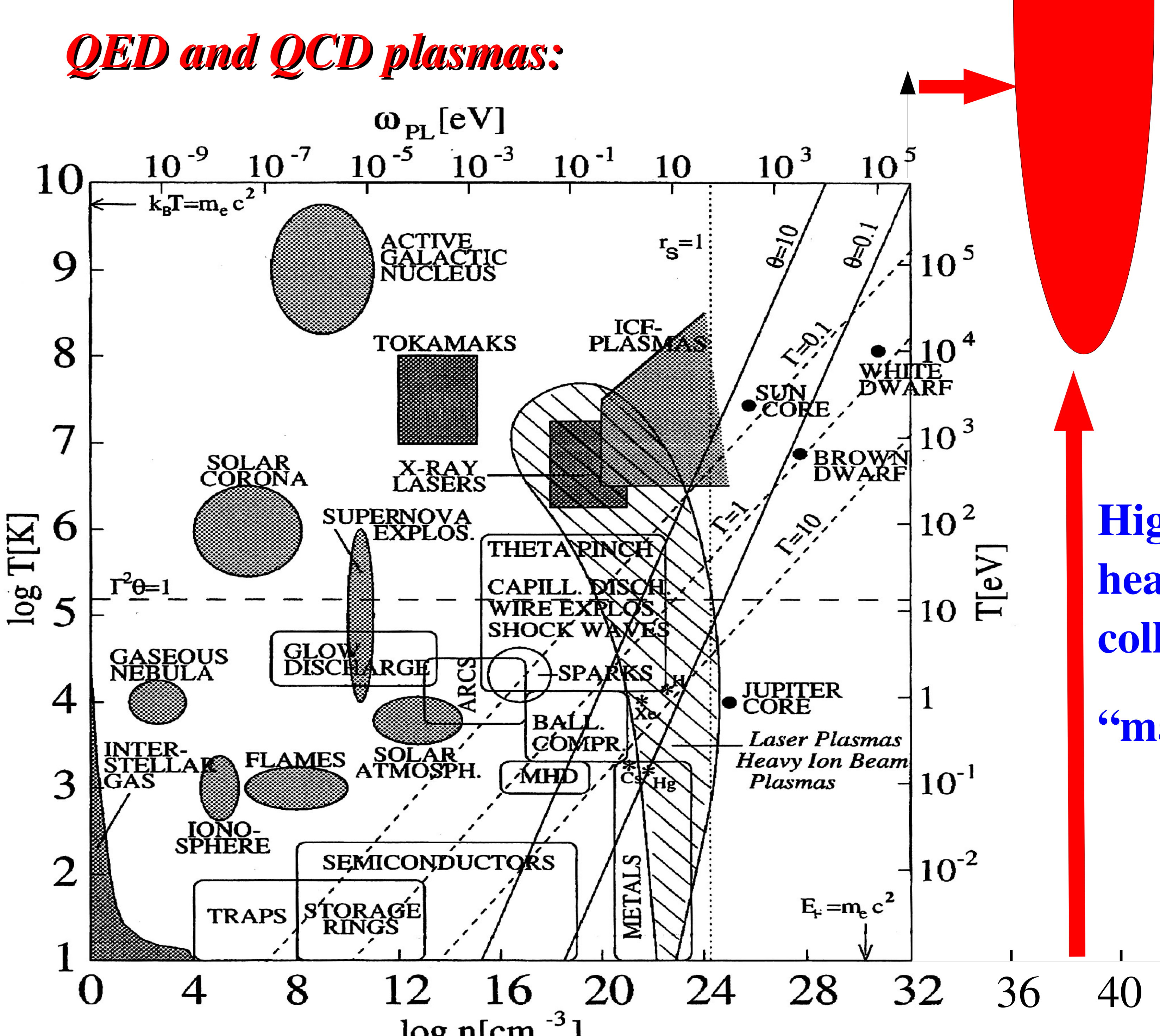
$= 1.5 \cdot 10^{38}$ part/cm^3

BEVALAC, SIS, AGS, CERN SPS,

RHIC: 2000 – ... **LHC: 2010 – ...**

NUCLOTRON: 201X – ... **FAIR: 201X – ...** **(?)**

QED and QCD plasmas:



QGP

QM (Hibrid stars)

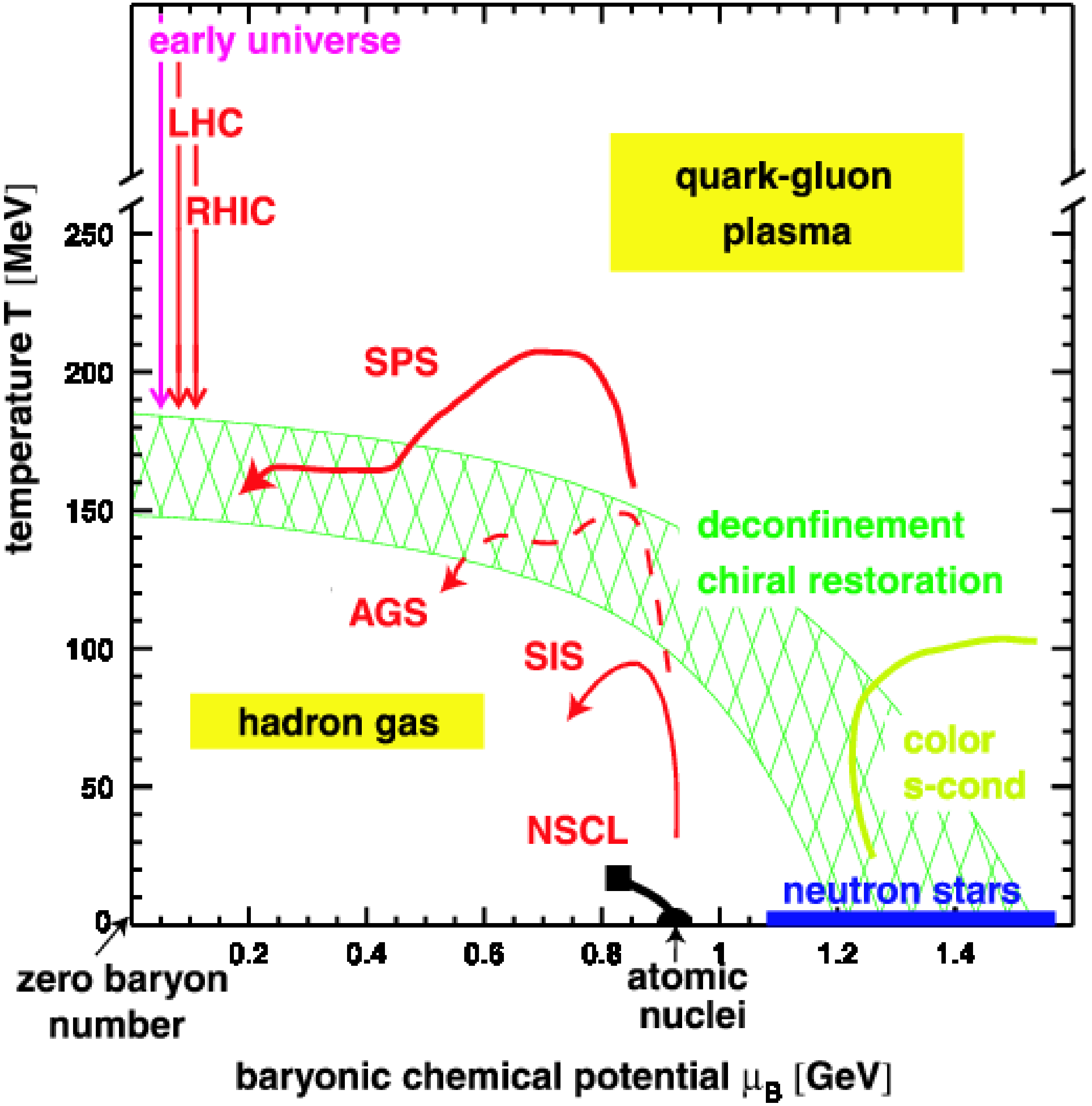
High energy heavy ion collisions:

“matter” of nucleons hadrons quarks

R. Redmer, *Phys. Reports* **282**, 35 (1997)

2. The production of "quark-gluon plasma" in heavy ion collisions

1980 – 2000

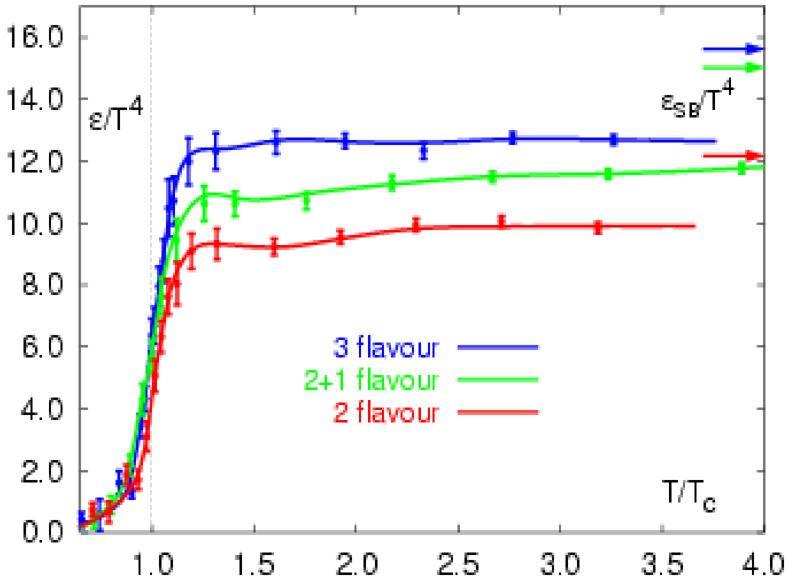


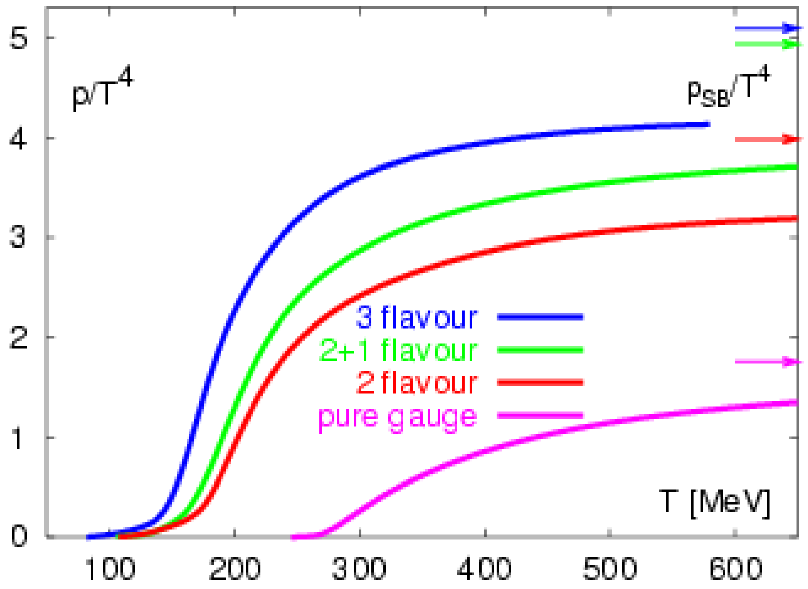
BASIS: EOS for strongly interacting matter from lattice-QCD

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

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

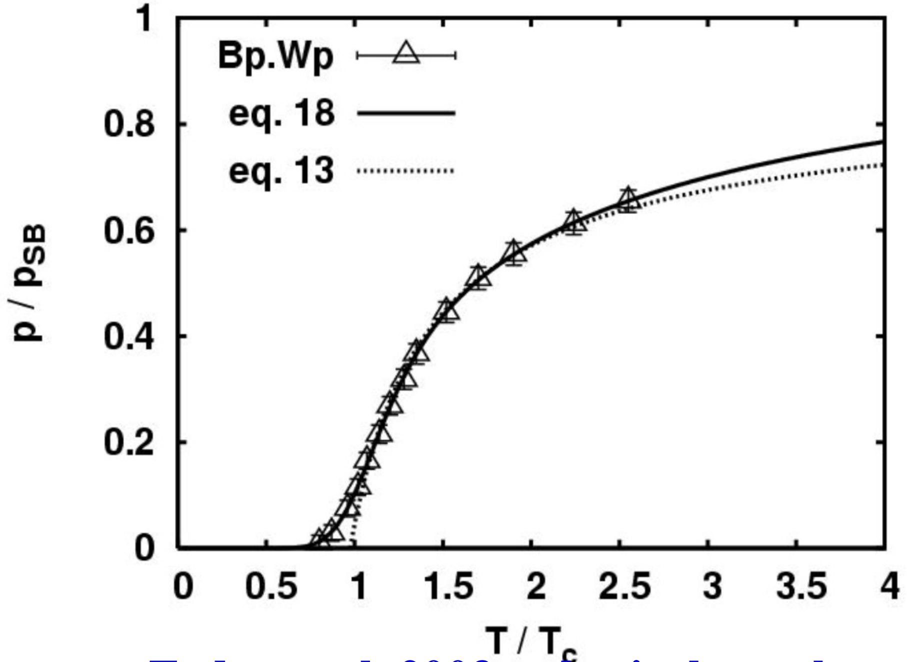
$T/T_c = 1.5\text{-}2.0 \rightarrowtail \varepsilon =$ 6-20 GeV/fm^3 (RHIC ?)

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

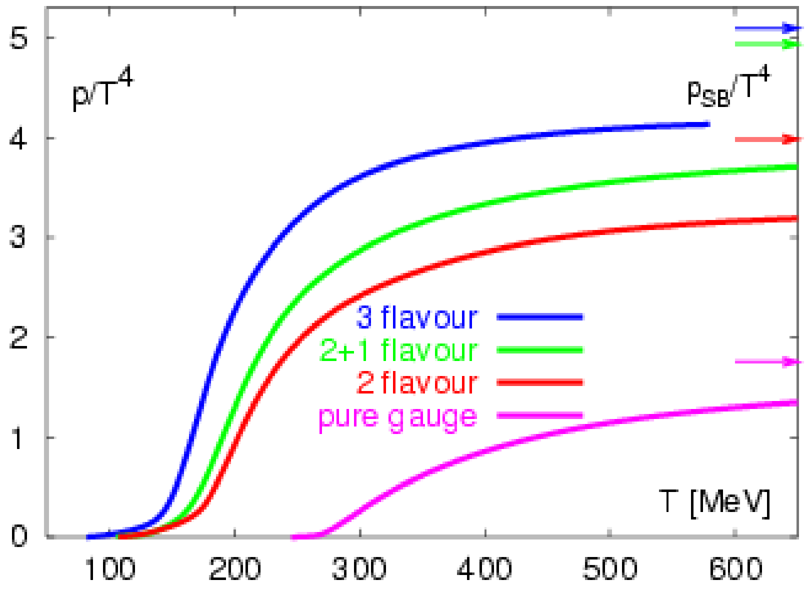
Lattice-QCD results: EOS for strongly interacting QGP

Lattice-QCD calculations ➔ $\varepsilon(T)$, $P(T)$ 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

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

What can we learn from the quasi-particle description ???

Introducing quasi-particle picture:

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

Fix degrees of freedom (d=16)

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

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

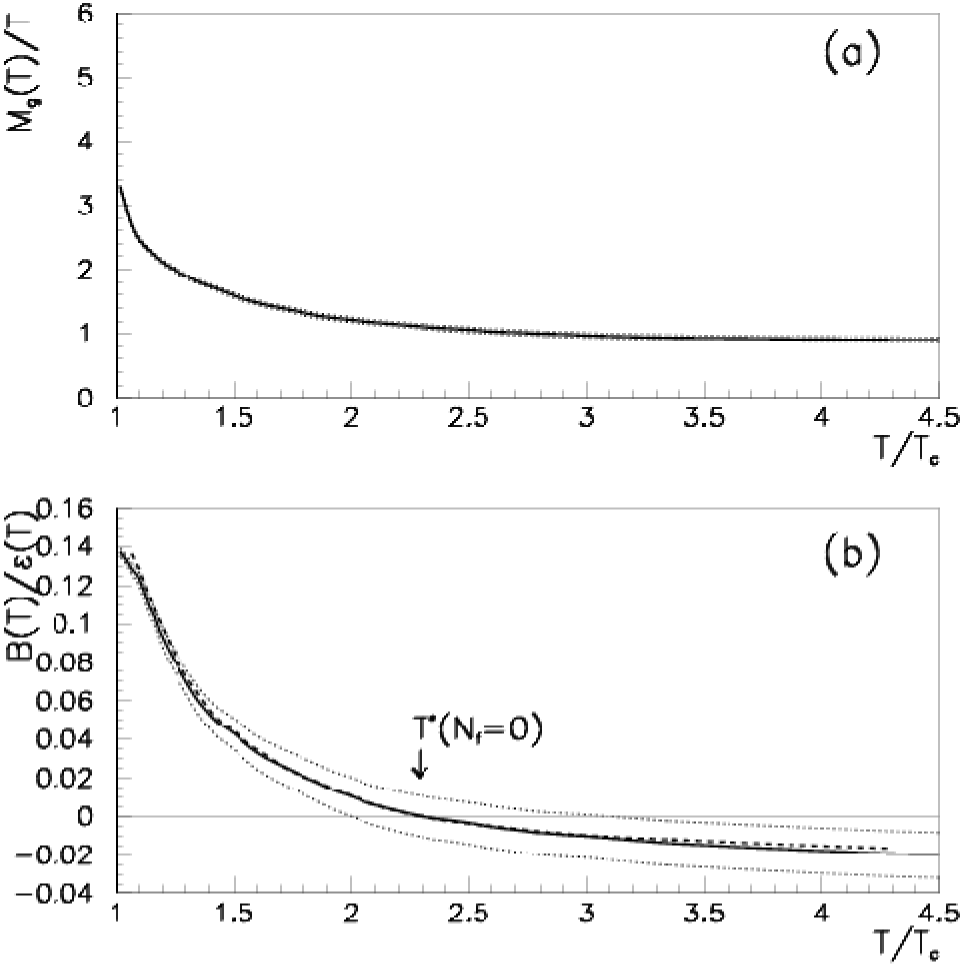
?(T), P(T) ↣ M(T), B(T)

Mass + Interaction

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

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

Fix degrees of freedom (d=16)



?(T), P(T) ↣ M(T), B(T)

M(T)/T = c * g(T)   [c=1/√2]

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

T → Tc, $\alpha_s = g^2/4\pi \rightarrow$ 1.5 !!!

$T > 2\ T_c$ B(T) is small (≈0)

Free quasi particles

$T < 2\ T_c$ B(T) / ε ≈ 0.15

Interacting quasi-particles

(+ new excitations ?)

"EQUILIBRIUM PHYSICS"

Quark matter formation in heavy ion collisions

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

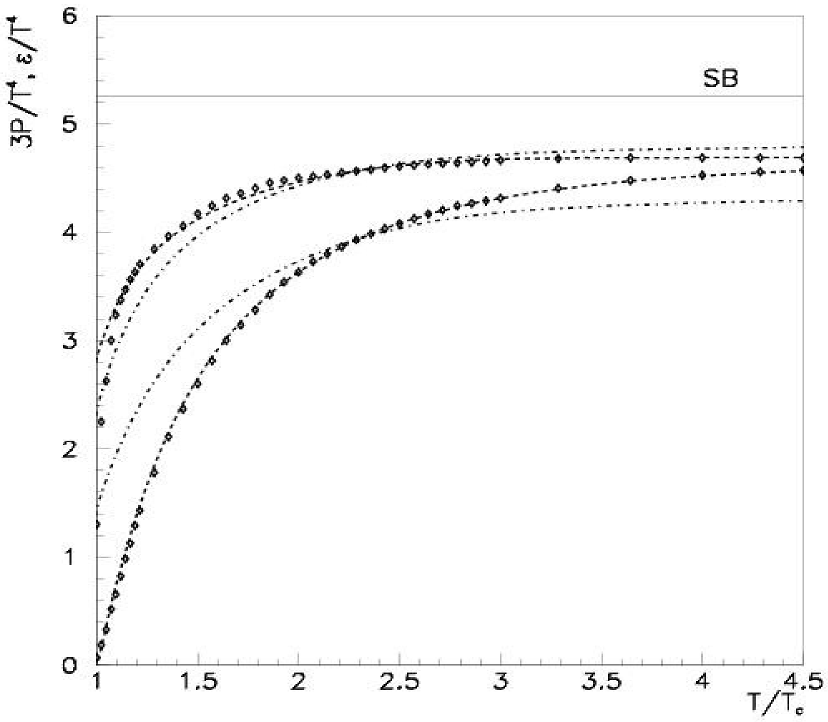


Fig.4. SU(3), N_f=0 --- EOS + Lattice QCD data

(Karsch et al. 1992)

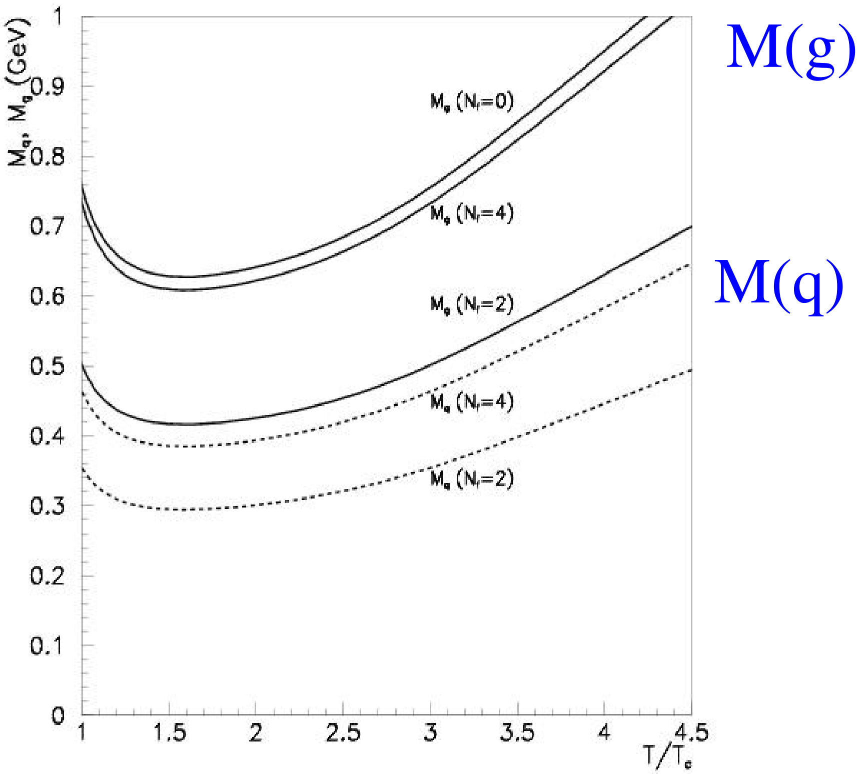


Fig.9. SU(3), N_f=0,2,4 --- $M_g(T)$, $M_q(T)$

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

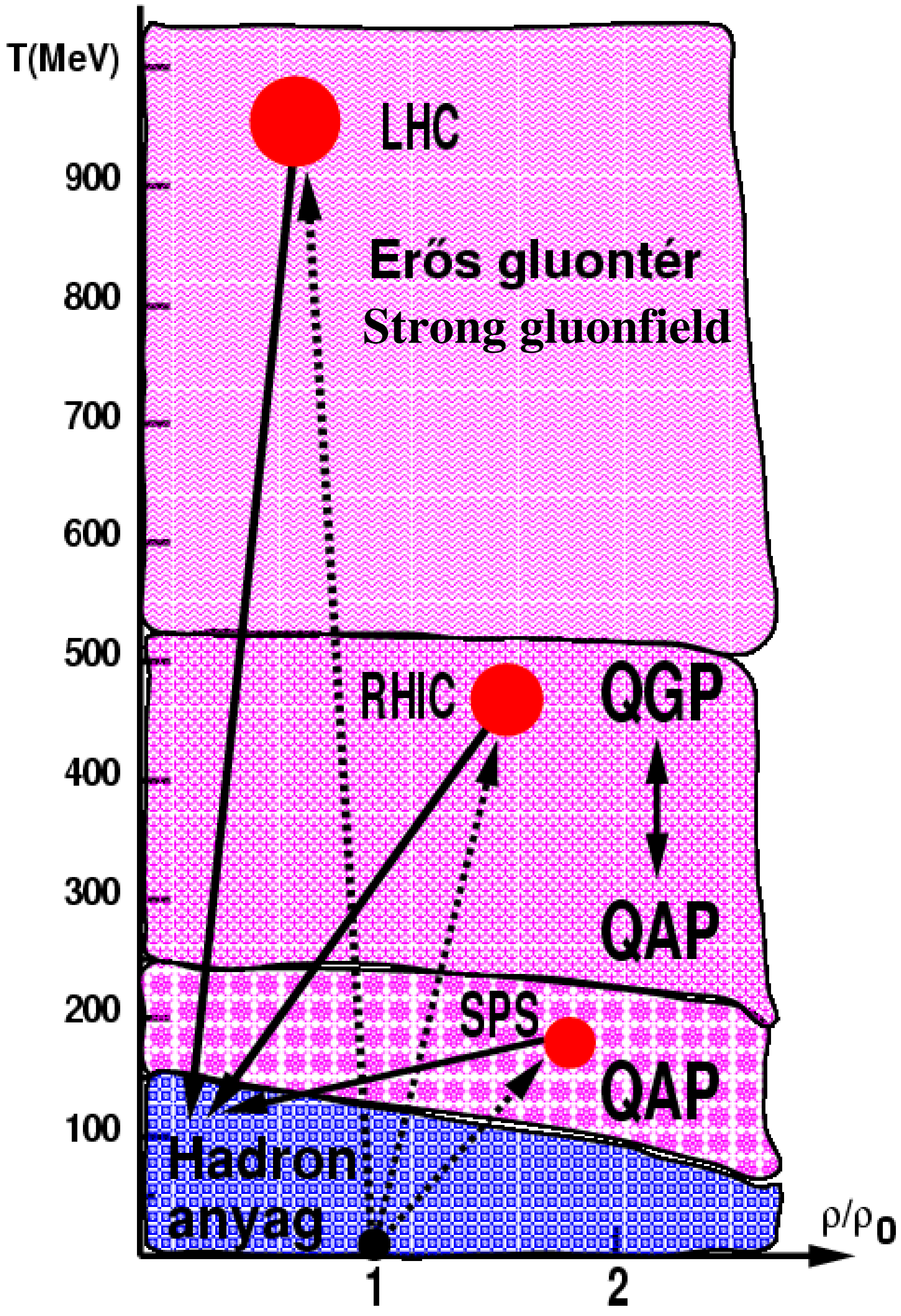
[L.P, Heinz U., 1996, PRC51,3326]

➔ Quark and antiquark dominated matter (QAP) [gluons are suppressed]

HADRONIZATION ⇔ QUARK COALESCENCE

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

[ALCOR: 1995-2005]



Final hadronic states at different energies are very similar:

T = 170 – 140 MeV,

μ_B = 0 – 200 MeV

v_T = 0.8 – 0.4 c

Soft spectra are thermal

We need to know the microscopical mechanisms existing/working inside the deconfined phases for <u>clear statements</u>

about QGP formation

High-p_T physics

Jets !

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

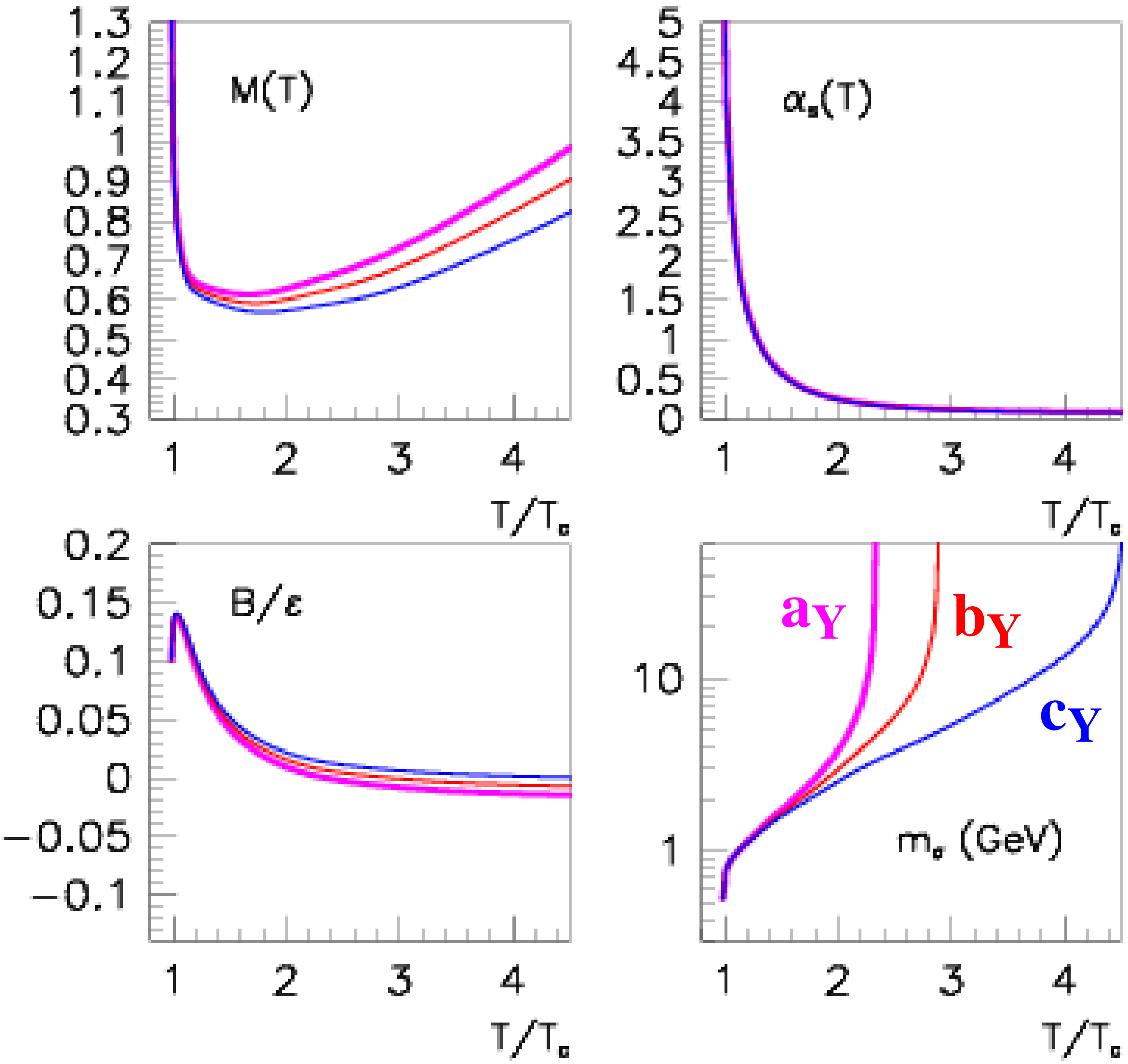
$$M(T) = M_0(T) - g\sigma = M_0(T) - \frac{g^2}{m_\sigma^2} n$$

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.

Hydrodynamical description in heavy ion collisions:

Fermi (1950): statistical models in high energy particle collisions
intensive interaction ↣ collectivity ↣ hydrodyn.

Landau (1955): strong stopping in high energy particle collisions
high energy density ↣ hydrodynamical evolution

Greiner et al., Heinz et al. , Zimanyi et al., Gyulassy et al., ...
Cleymans et al., Toneev et al., Bugaev et al, ...
(1970-80-90-2000-...-...)
BEVALAC – AGS – SPS – RHIC – LHC energies
hydrodynamical evolution in the early stages
fireball formation in heavy ion collisions

Hydrodynamics forever ? **Maybe YES !**
Collectivity + EOS ⇔ hydrodynamics

General questions: --- degrees of freedom ?
--- equation of state (EOS) ?

1975-1995: massless quarks, antiquarks and gluons will form
a plasma-like matter (QGP) with high energy density
with $T > 170$ MeV and $\varepsilon > 2$ GeV/fm^{3,} ;
first order phase transition between quarks and hadrons;
asymptotic freedom in QCD ↣↣ weakly coupled QGP;

1995-2000: lattice QCD results ↣↣ deviation from Boltzmann limit;
interaction is important ↣↣ sQGP !!!!!
massive quasiparticles? heavy gluons ? QAP around T_c?

2000-2005: new lattice QCD results at finite densities;
cross-over phase transition at T_c
we can discuss new properties, e.g. viscosity;

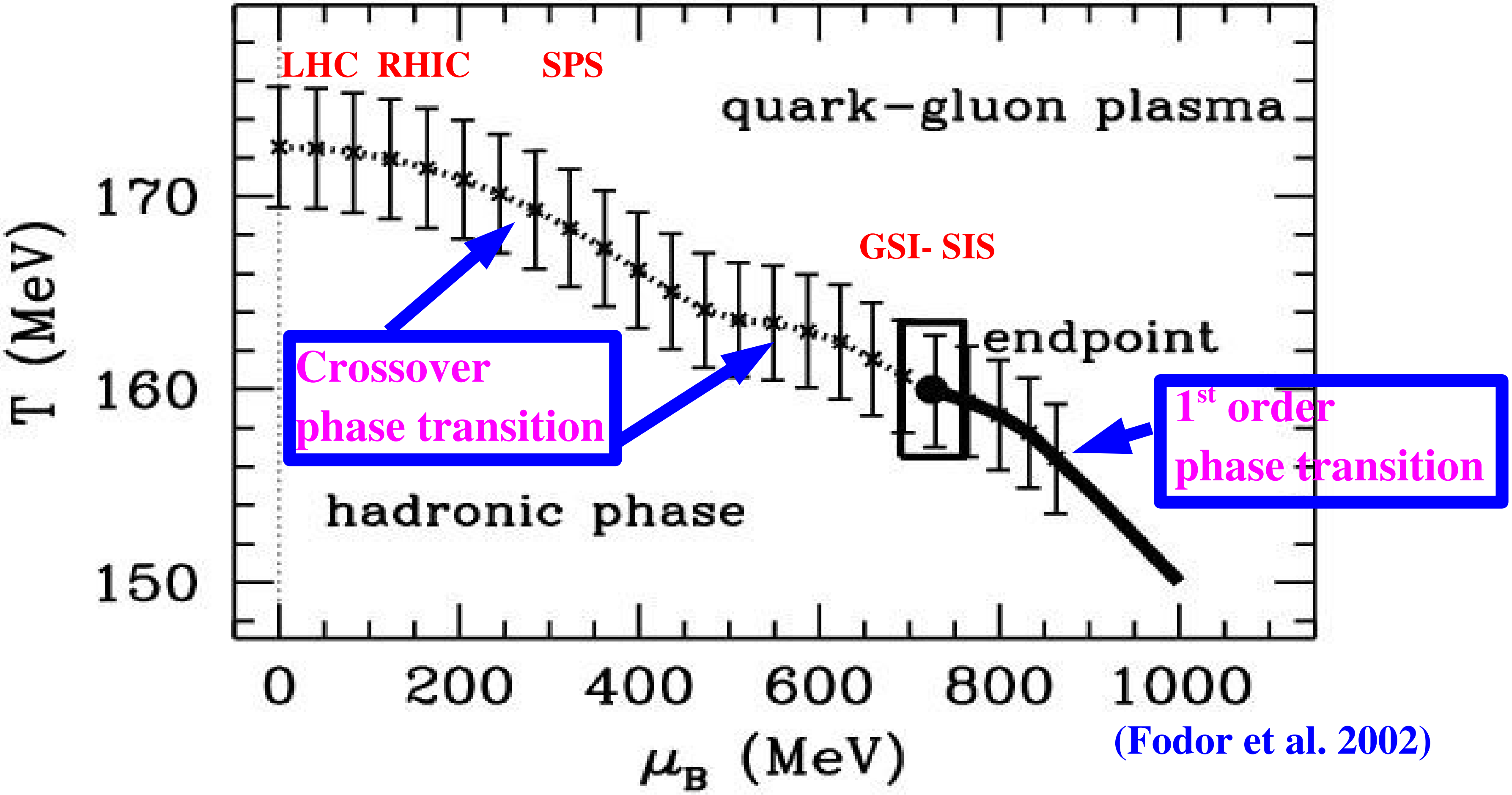
2005- ... : AdS/CFT, string theory ↣↣ ssQGP !!
black holes, ...,

Our recent understanding of different xQGP paradigms :

Matter	Degrees of freedom	Hadron production	Model descr.
QGP	free q,q,g (+B)	Thermal equilibrium fast thermalization (“miracles”) or parton-hadron duality	QCDphenom. thermodyn.
wQGP	on-shell massive quasi-q,g $\Gamma_i \sim g^2 T \ln 1/g < m_i \sim g T$	Thermal equilibrium Quark-coalescence Resonance-production + decay	pQCD QAP, MD
sQGP	quasiparticles with mass distribution strong inter ↣ spectral func. $\Gamma_i \approx m_i \sim g T$	Quark-coalescence qq, qq – correlators	Lattice QCD QCD phenom
ssQGP	no quasipartic. (geometry) [except high energy jets]	Compactification in higher (effective) dimens.	AdS/CFT
	or		
	interaction ↣ LFWF form.	Coalescence	QAP, Schröd.
	or		
	strong field dominance	Black hole phenomenology	Gen. relativity

Quark matter formation in heavy ion collisions

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



(Fodor et al. 2002)

Crossover phase transition at small and intermediate baryon densities:

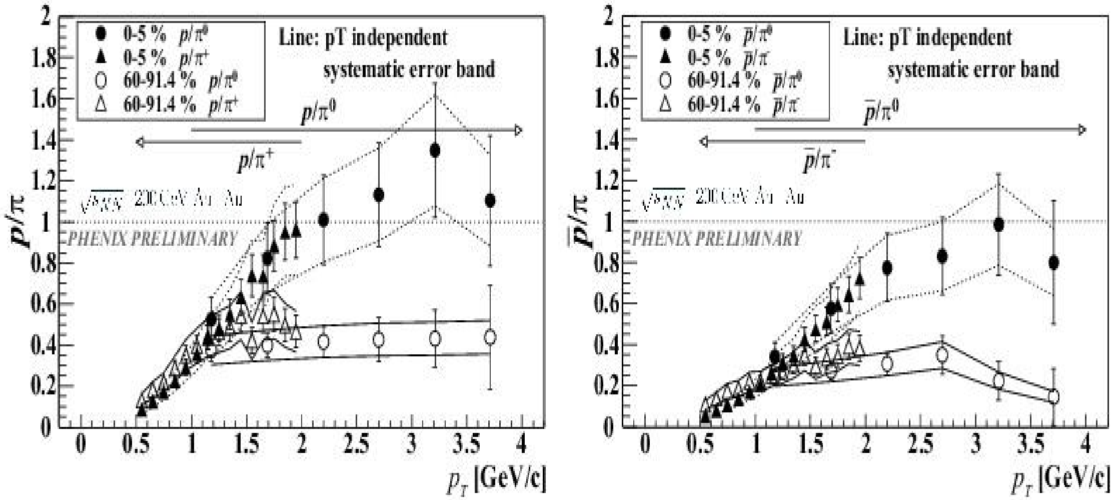
What is the microscopical mechanism of the hadronization ????

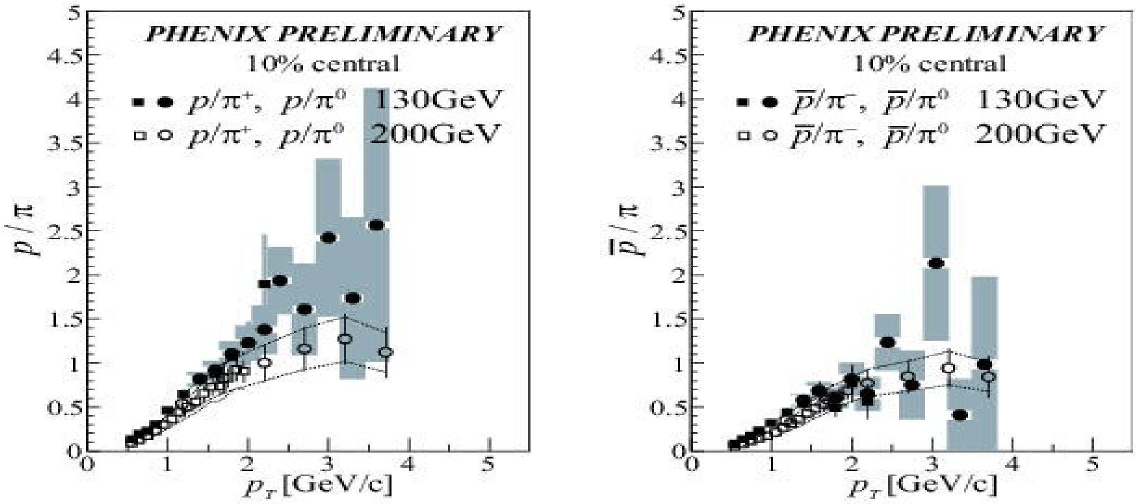
⇒ **QUARK COALESCENCE is one possibility**

Interacting massive quarks around T_c !!

QM02: First results from RHIC at √s = 130 and 200 A GeV -- $p/\pi^+, \bar{p}/\pi^-$

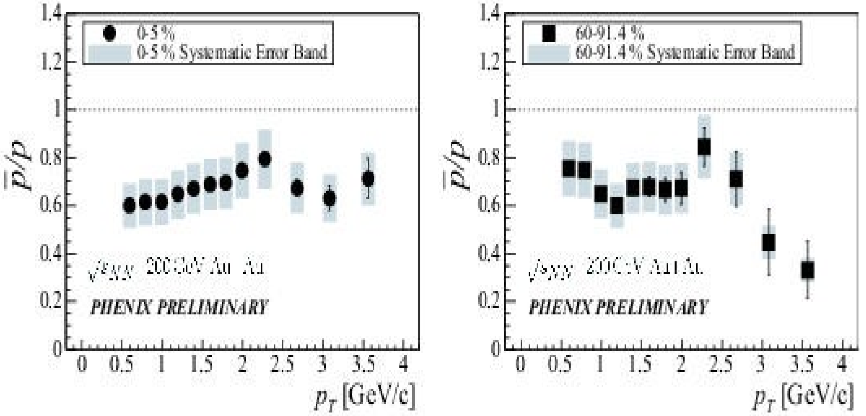
PHENIX Coll., T. Sakaguchi, NPA715(2003)757.





$$N(\bar{p}) > N(\pi^-)!!!$$

Anomalous antiproton (proton) production ??



The birth of "intermediate p_T-region"

Quark coalescence/recombination: 2003

Hwa & Yang;

Greco. Levai & Ko;

Friese et al.

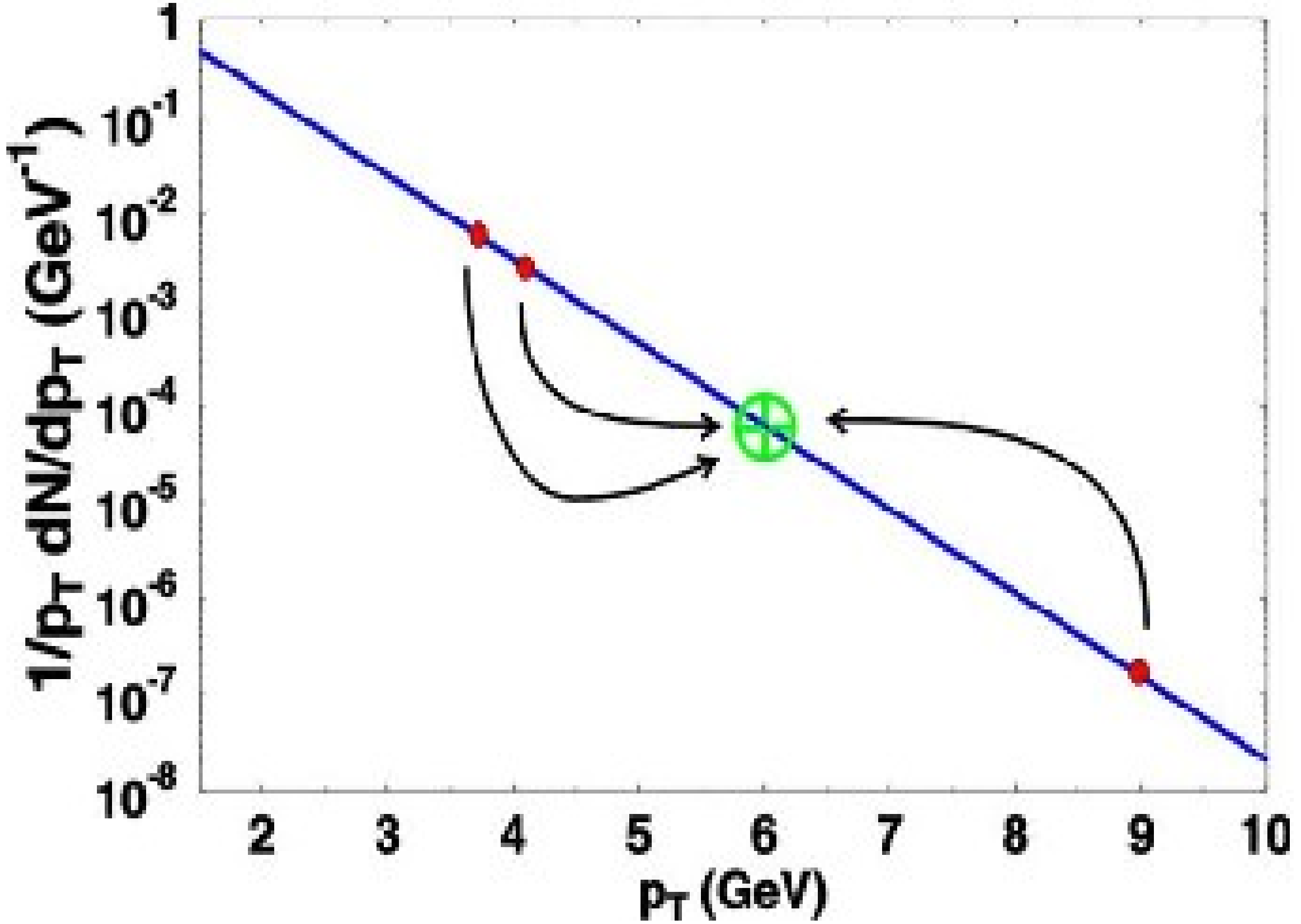
Jet quenching + quark coal. overlap

5 years of activity

The success of quark coalescence/recombination models:

it explains the measured anomalous baryon/meson ratios !!!

it assumes the presence of bulk quark matter !!!



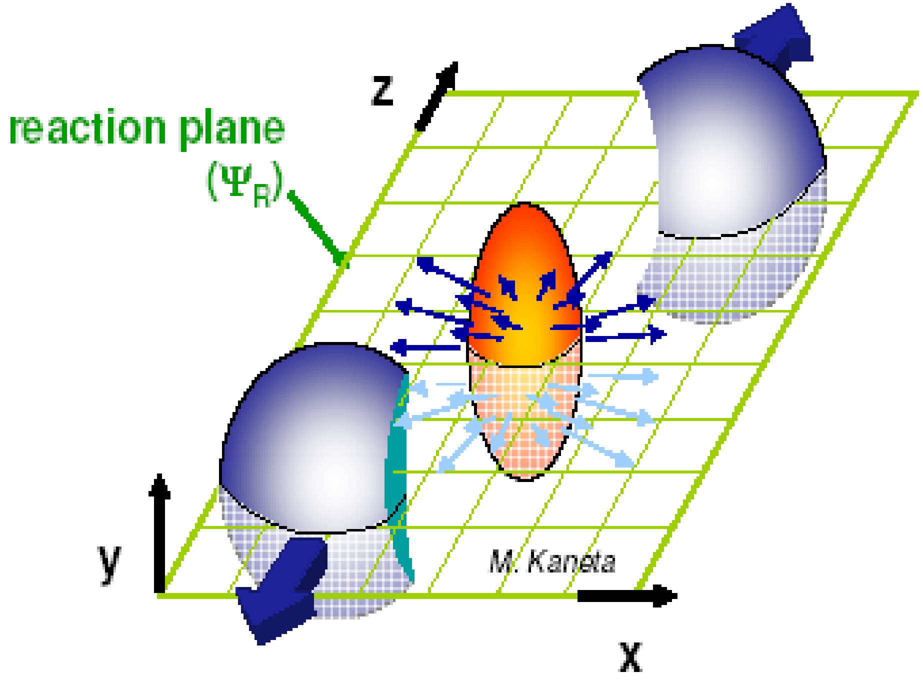
Coal/Recom models: the properties of ***bulk quark matter***

is transformed from small/intermediate-p_T to high-p_T regions.

PQCD (indep. jet-fragmentation): high-p_T region ↣ low-p_T

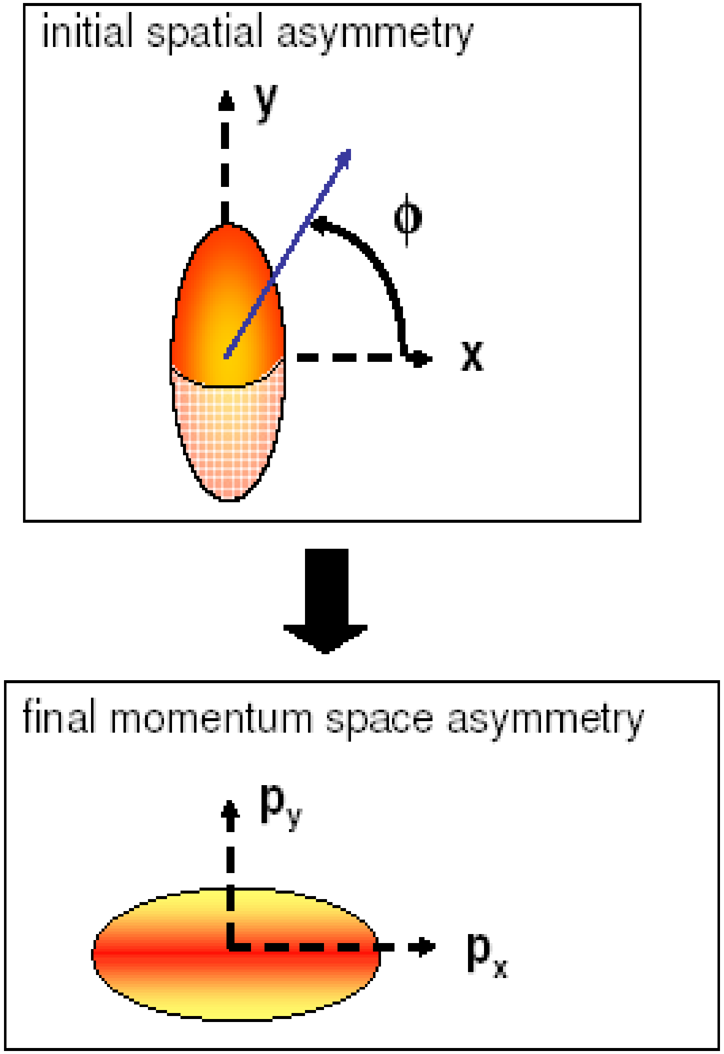
Collective motion in non-central AA collisions at RHIC energies:

the produced matter has a hydrodynamical evolution (expansion, etc.)



$$dN/d(\phi-\Psi_R) = N_0(1 + 2v_1\cos(\phi-\Psi_R) + 2v_2\cos(2(\phi-\Psi_R)) + \dots)$$

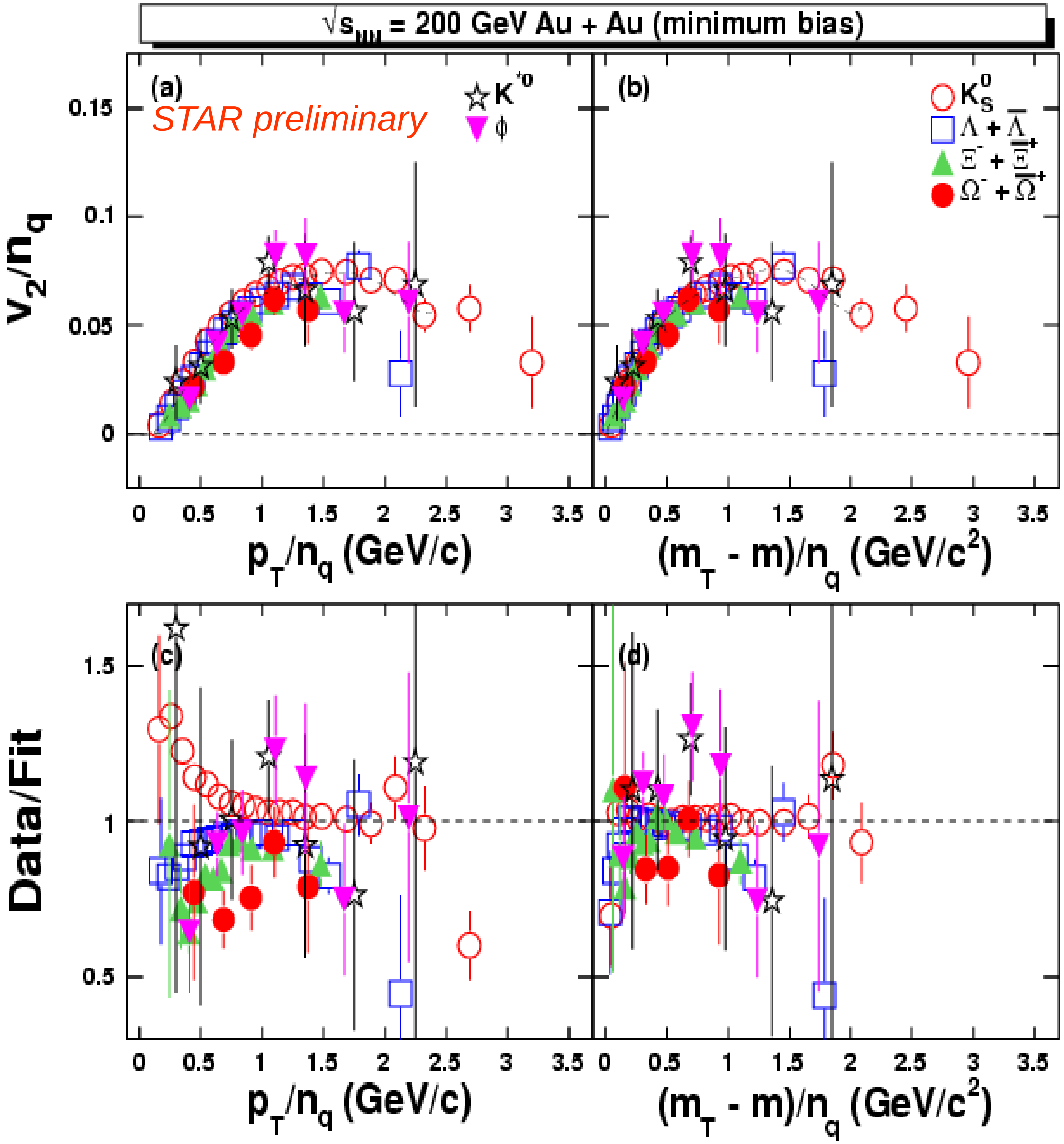
Elliptic flow quantified by: v_2



initial spatial asymmetry

final momentum space asymmetry

Collective motion in non-central AA collisions at RHIC energies:



Constituent quark scaling can be clearly seen in v_2 !

Quark-antiquark matter ?

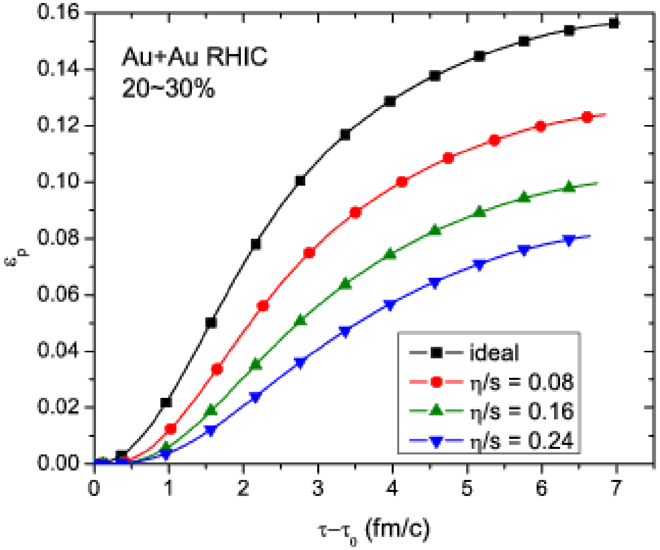
A quark dominated deconfined matter with collective behaviour is produced at RHIC !!

Is this sQGP ?

➣ transport properties, viscosity, etc.

Prologue: How to measure $(\eta/s)_{\mathrm{QGP}}$

Hydrodynamics converts
spatial deformation of initial state $\Longrightarrow$
momentum anisotropy of final state,
through anisotropic pressure gradients



Shear viscosity degrades conversion efficiency

$\varepsilon_x = \frac{\langle\langle y^2 - x^2\rangle\rangle}{\langle\langle y^2 + x^2\rangle\rangle} \Longrightarrow \varepsilon_p = \frac{\langle T^{xx} - T^{yy}\rangle}{\langle T^{xx} + T^{yy}\rangle}$

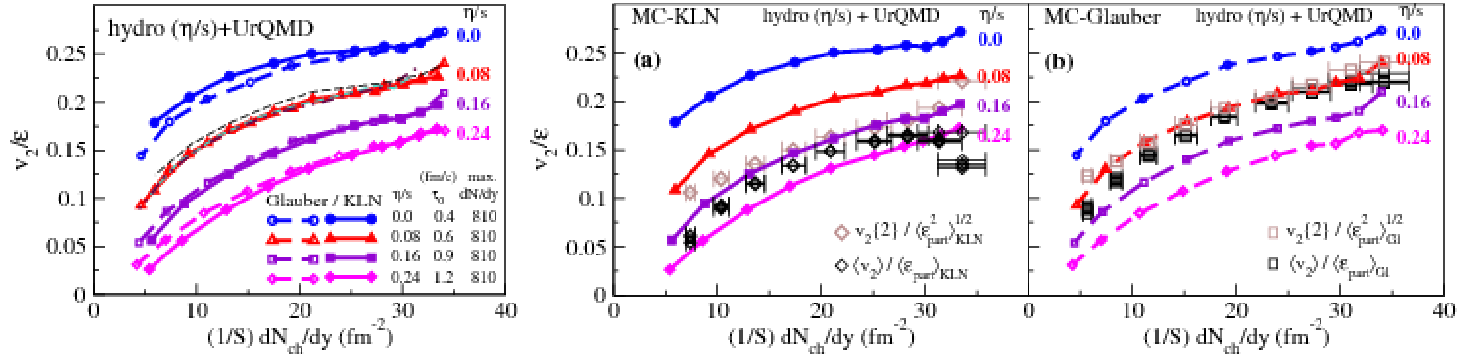
of the fluid; the suppression of ε_p is monotonically related to η/s.

The observable that is most directly related to the total hydrodynamic momentum anisotropy ε_p is the **total (p_T-integrated) charged hadron elliptic flow v_2^{ch}**:

$$\varepsilon_p = \frac{\langle T^{xx} - T^{yy}\rangle}{\langle T^{xx} + T^{yy}\rangle} \Longleftrightarrow \frac{\sum_i \int p_T dp_T \int d\phi_p\, p_T^2\, \cos(2\phi_p)\, \frac{dN_i}{dy p_T dp_T d\phi_p}}{\sum_i \int p_T dp_T \int d\phi_p\, p_T^2\, \frac{dN_i}{dy p_T dp_T d\phi_p}} \Longleftrightarrow v_2^{\mathrm{ch}}$$

Extraction of $(\eta/s)_{\rm QGP}$ from AuAu@RHIC

H. Song, S.A. Bass, U. Heinz, T. Hirano, C. Shen, PRL106 (2011) 192301

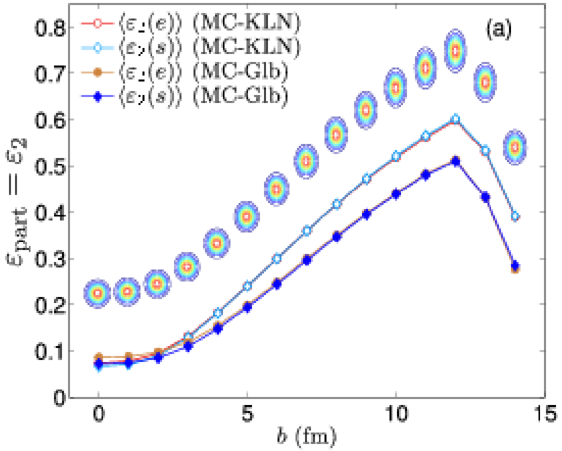


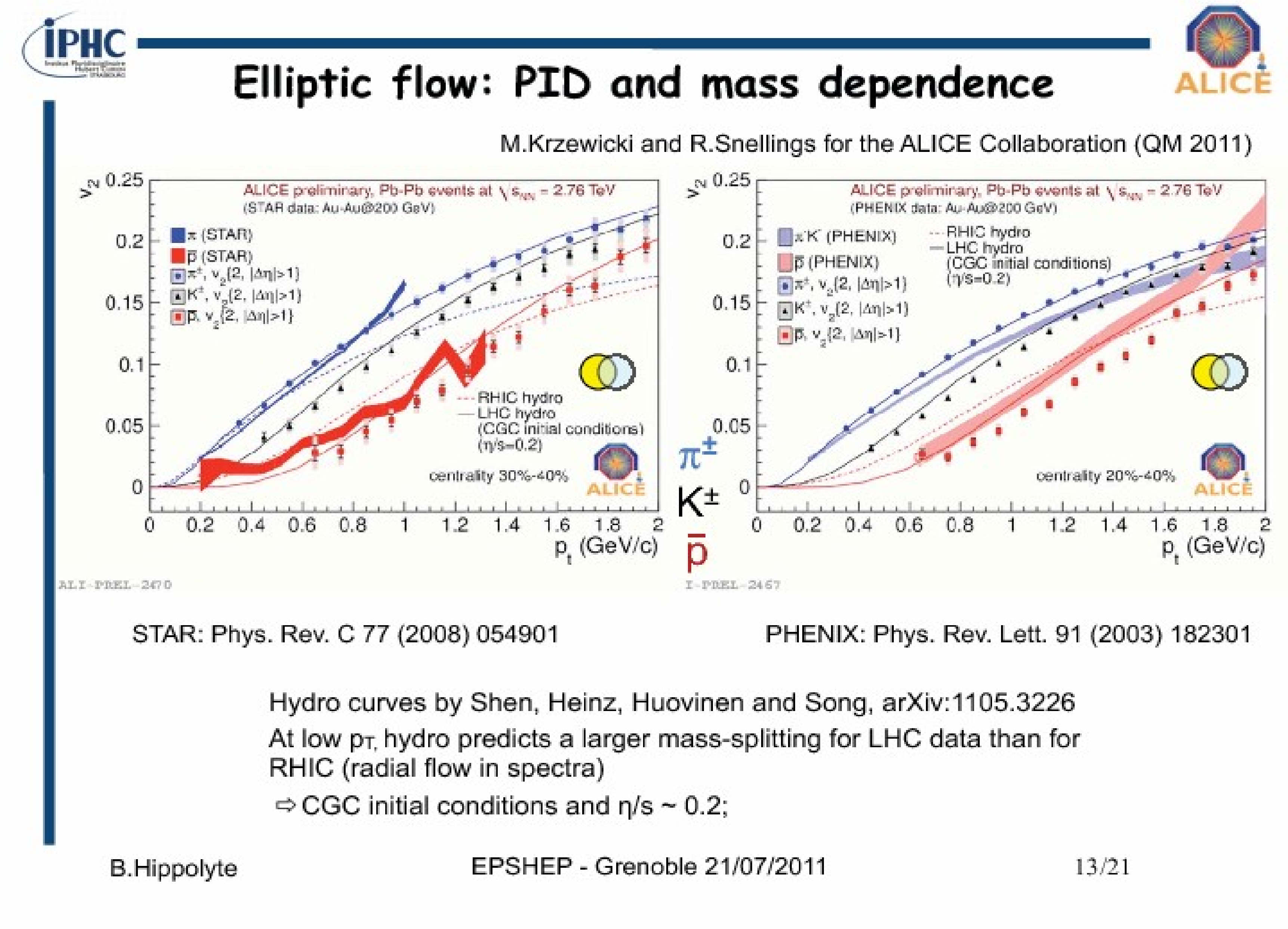
$1 < 4\pi(\eta/s)_{\rm QGP} < 2.5$

- All shown theoretical curves correspond to parameter sets that correctly describe centrality dependence of charged hadron production as well as p_T-spectra of charged hadrons, pions and protons at all centralities
- $v_2^{\rm ch}/\varepsilon_x$ vs. $(1/S)(dN_{\rm ch}/dy)$ is "universal", i.e. depends **only on** $\boldsymbol{\eta/s}$ but (in good approximation) not on initial-state model (Glauber vs. KLN, optical vs. MC, RP vs. PP average, etc.)
- dominant source of uncertainty: $\varepsilon_x^{\rm Gl}$ vs. $\varepsilon_x^{\rm KLN}$ ⟶
- smaller effects: *early flow* ⟶ increases $\frac{v_2}{\varepsilon}$ by ∼ few% ⟶ larger η/s

  bulk viscosity ⟶ affects $v_2^{\rm ch}(p_T)$, but ≈ not $v_2^{\rm ch}$

Zhi Qiu, U. Heinz, arXiv:1104.0650





Elliptic flow: PID and mass dependence

M.Krzewicki and R.Snellings for the ALICE Collaboration (QM 2011)

STAR: Phys. Rev. C 77 (2008) 054901

PHENIX: Phys. Rev. Lett. 91 (2003) 182301

Hydro curves by Shen, Heinz, Huovinen and Song, arXiv:1105.3226

At low p_T, hydro predicts a larger mass-splitting for LHC data than for RHIC (radial flow in spectra)

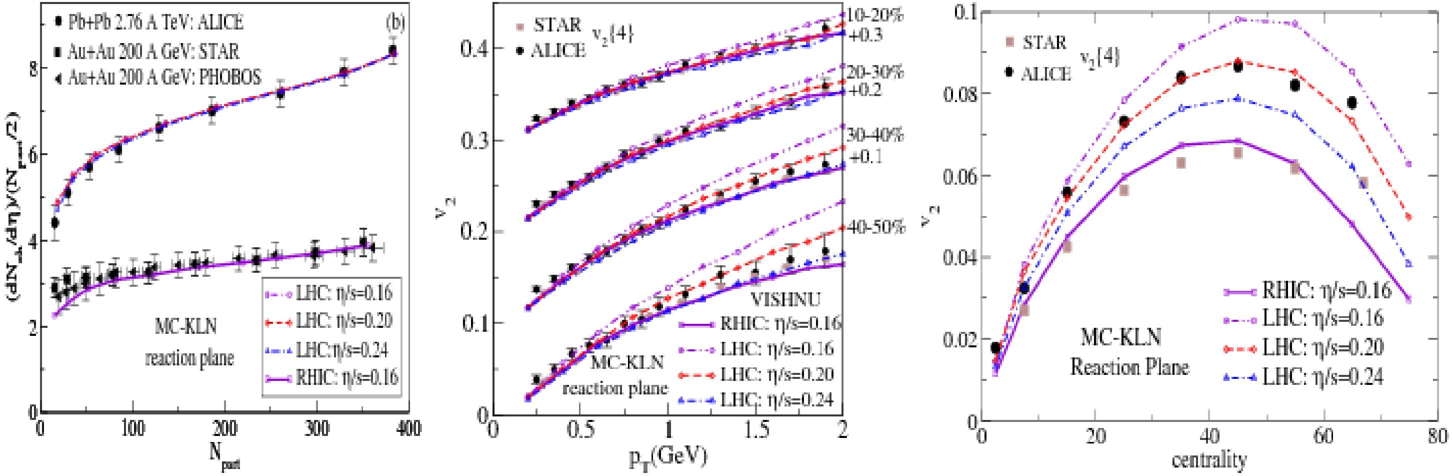
⇨ CGC initial conditions and η/s ~ 0.2;

B.Hippolyte EPSHEP - Grenoble 21/07/2011 13/21

Specific viscosity: $\eta / s \approx 0.2 \approx 2 \times (1 / 4\pi)$

Pre- and postdictions for PbPb@LHC

VISHNU with MC-KLN (H. Song, S.A. Bass, U. Heinz, PRC, arXiv:1103.2380)



- After normalization in 0-5% centrality collisions, MC-KLN + VISHNU (w/o running coupling, but including viscous entropy production!) reproduces centrality dependence of $dN_{\rm ch}/d\eta$ well in both AuAu@RHIC and PbPb@LHC
- $(\eta/s)_{\rm QGP} = 0.16$ for MC-KLN works well for charged hadron $v_2(p_T)$ and integrated v_2 in AuAu@RHIC, but overpredicts both by about 10-15% in PbPb@LHC
- Similar results from predictions based on pure viscous hydro $\Longrightarrow$ poster #4 (Shen) and arXiv:1105.3226
- **but:** At LHC, we see significant sensitivity of v_2 to initialization of viscous pressure tensor $\pi^{\mu\nu}$ (Navier-Stokes or zero), and it is not excluded that it may be possible to bring down v_2 at LHC to the ALICE data without increasing η/s at higher T (requires more study)

  $\Longrightarrow$ **QGP at LHC perhaps a bit, but not dramatically more viscous than at RHIC!**

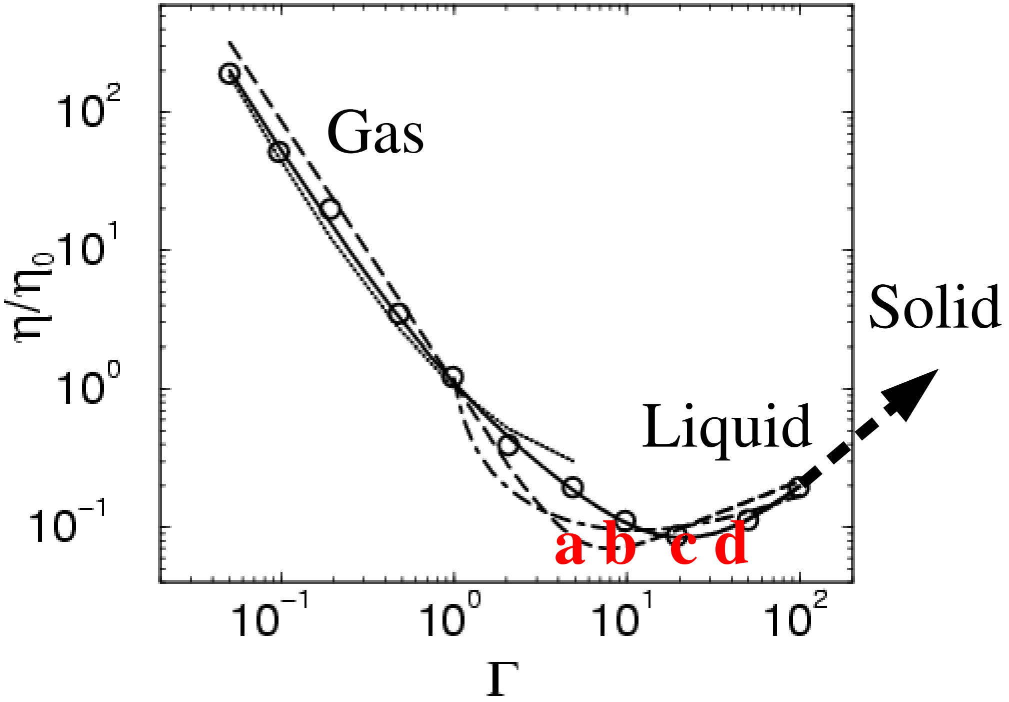
Motivations: - how large is the viscosity in QGP (around T_c) ?

- how can we determine it ?

Z. Donkó, P. Hartmann, G. Kálmán, P.L., M. Pocsai

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 $\eta/s(T)$???

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

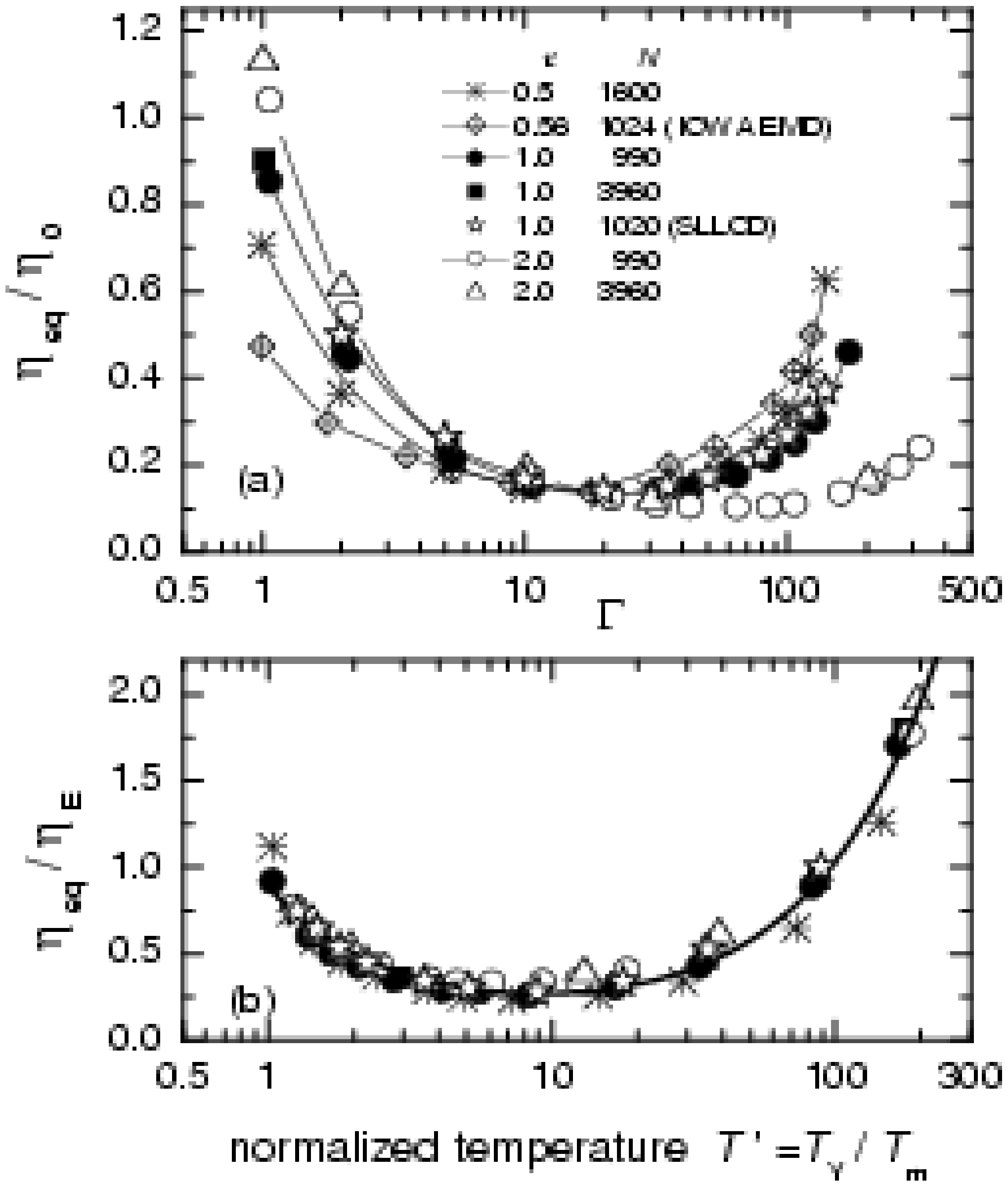
a, $\alpha_s = 0.17$ ↣ $\Gamma = 5.1$

b, $\alpha_s = 0.25$ ↣ $\Gamma = 7.3$

c, $\alpha_s = 1.0$ ↣ $\Gamma = 24$

d, $\alpha_s = 2.0$ ↣ $\Gamma = 40$

Answer in dense plasma physics: $\eta(T)$ 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)

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

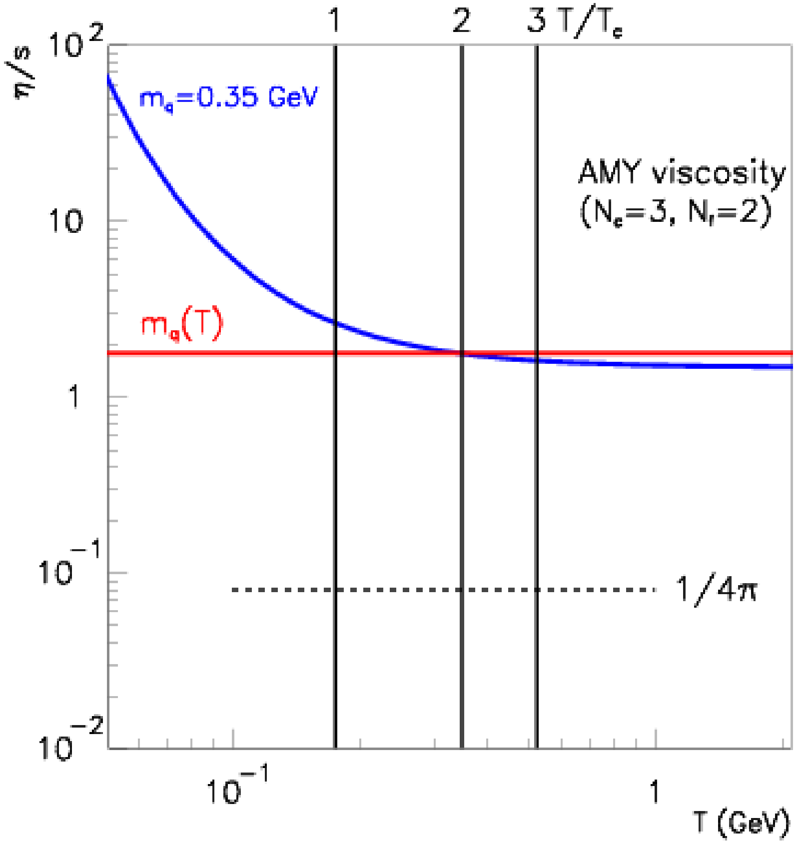
A, constant mass, $m_q = 0.35$ GeV, $m_g = \sqrt{2}\, m_q$

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

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

(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 $T \rightarrowtail \infty$ then

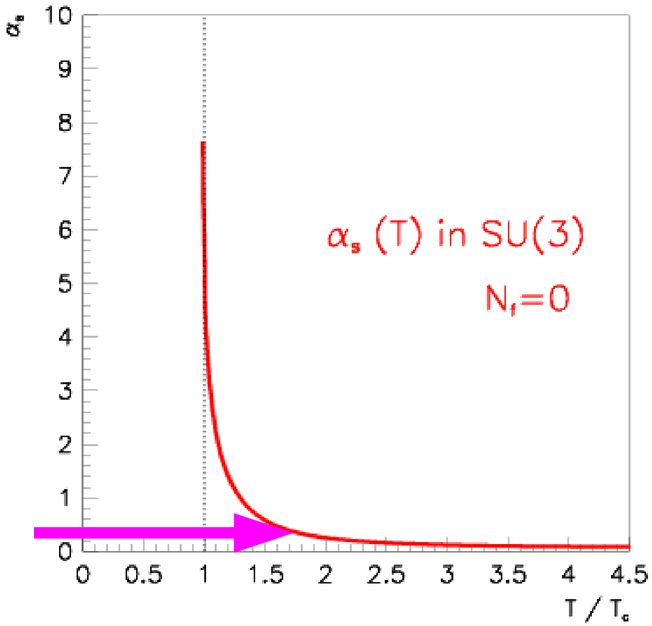
$\eta/s \rightarrowtail 20(1/4\pi)$

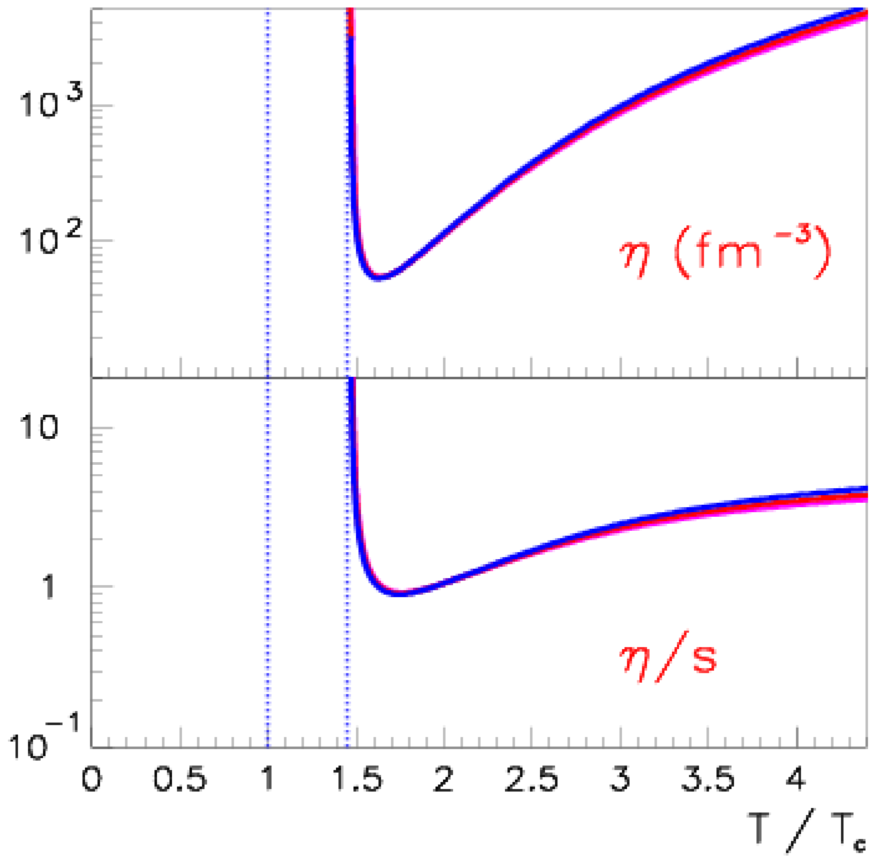
At $1 < T/T_c < 2$

$\eta/s = 2 - 3$

This matter is not a "perfect fluid" !

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





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

η/s = 0.9 at T=1.75 T_c

T ↣ T_c ➤➤➤➤➤ α_s(T) becomes extremely large

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

AMY: formula is good for α_s(T) < 0.3 !!! T/T_c ≥ 1.8 , η/s ≥ 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, M. Pocsai [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 [Interaction in

hep-ph/0606076 the $F(m_q)$.]

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

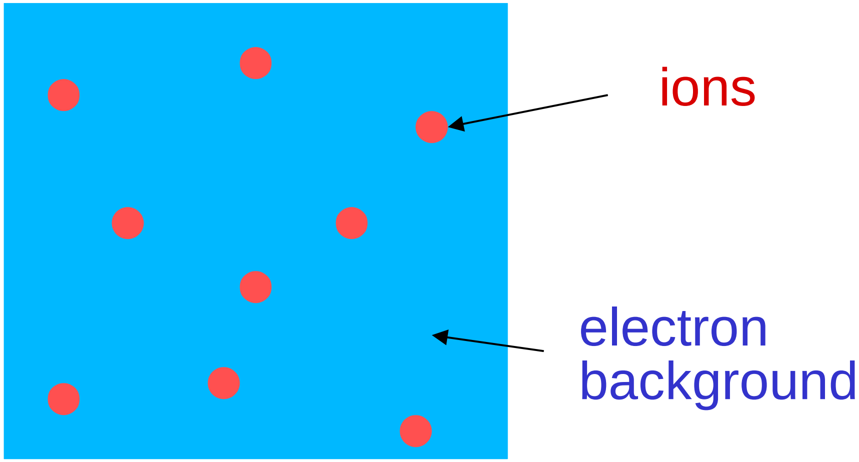
P. Hartmann, Z. Donkó, G. Kalman, P. Lévai

Nucl. Phys. A774, 2006, 881

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: $V(r)=\dfrac{Q^2}{r}$

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	→	*quarks (massive)*
electron background (neutralizing)	→	*gluon background* interacting !!!
$V(r_{ij})=\frac{Q^2}{r_{ij}}$	→	$V(r_{ij})=\frac{\langle\lambda_i\lambda_j\rangle\alpha_S}{r_{ij}}$
$\Gamma=\frac{Q^2}{a_{WS}k_BT}$	→	$\Gamma=\frac{C\alpha_S}{a_{WS}k_BT}$

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):

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

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 ($\bar{3}$)

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:

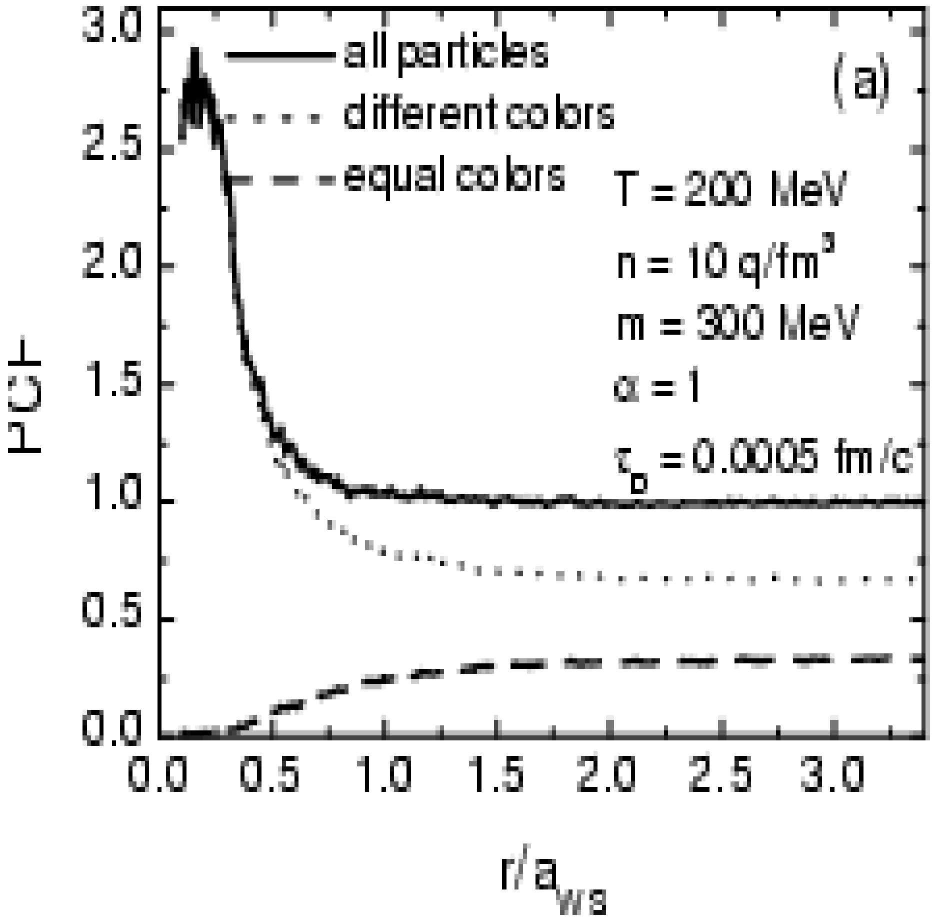
- kinetic temperature, $T(t)$
- pair correlation function, $g(r)$
- viscosity, η

Correlations

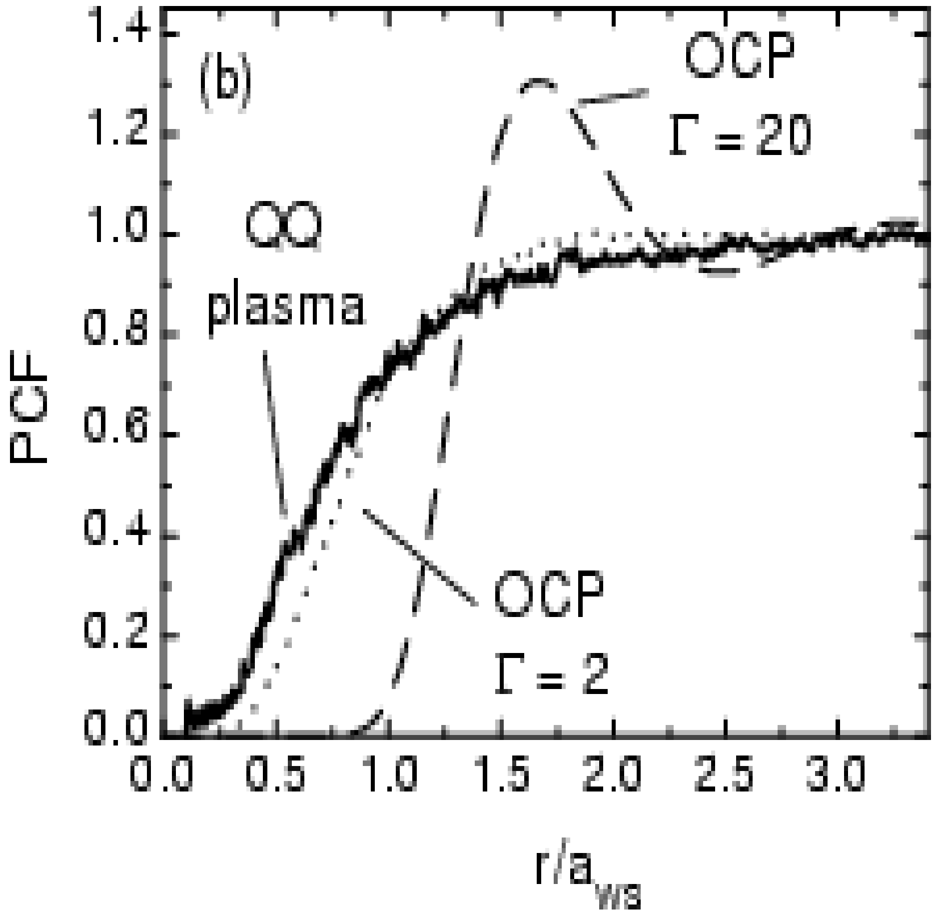
g(r) pair-correlation function: liquid or gas ? ⇒⇒⇒ “gas” !

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

QQ plasma

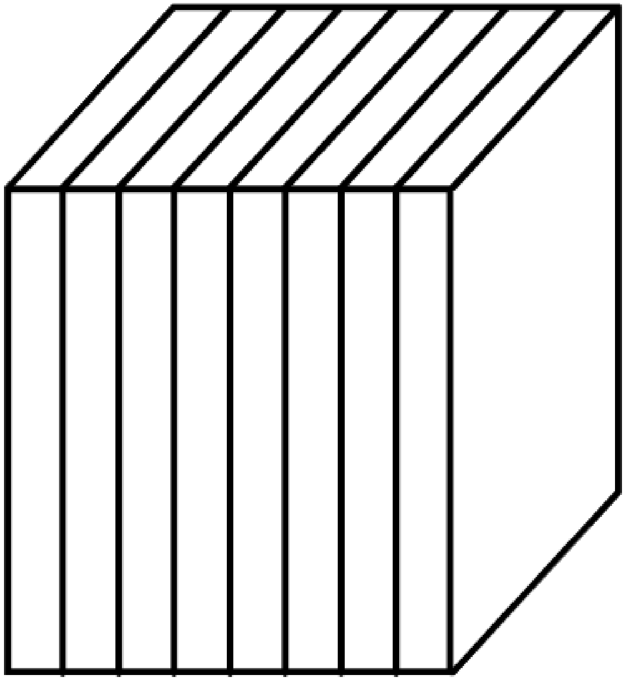


QQ and ee plasma

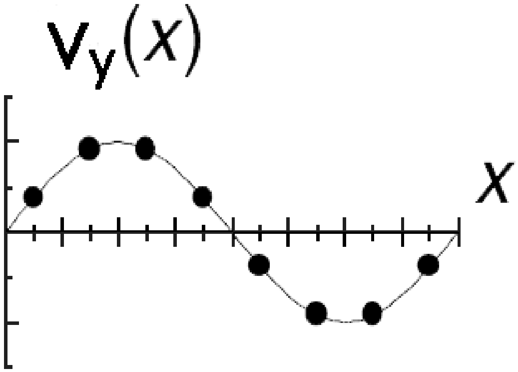


MD measurement for viscosity – 1

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



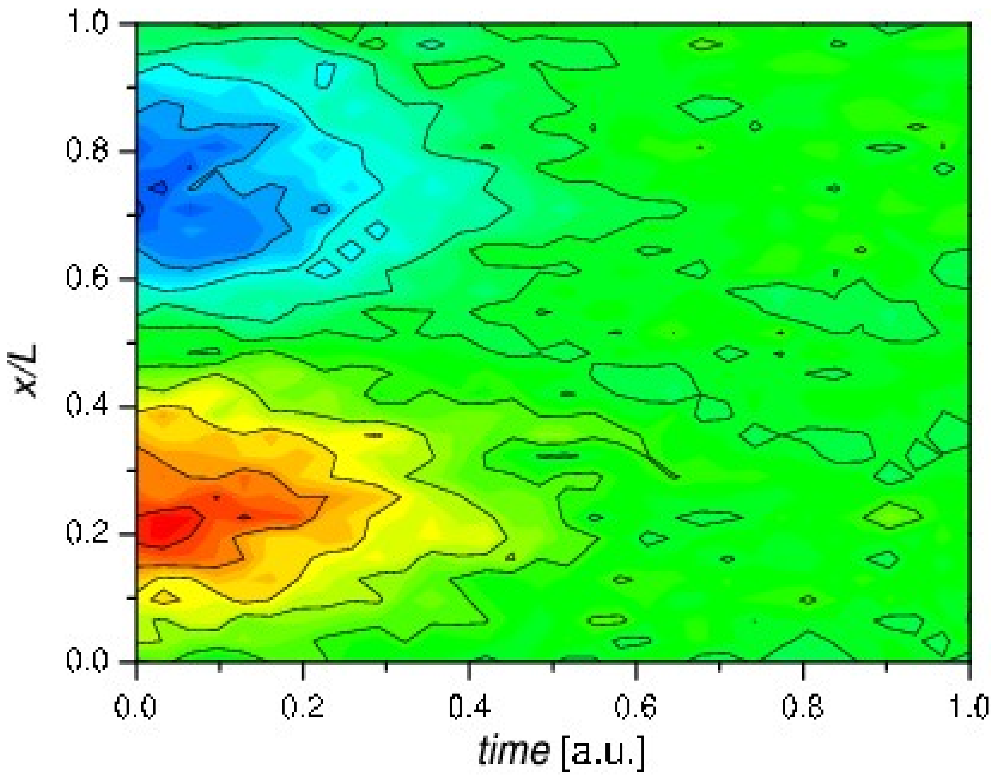
Periodic boundary condition.
(Separation into 8 bin.)

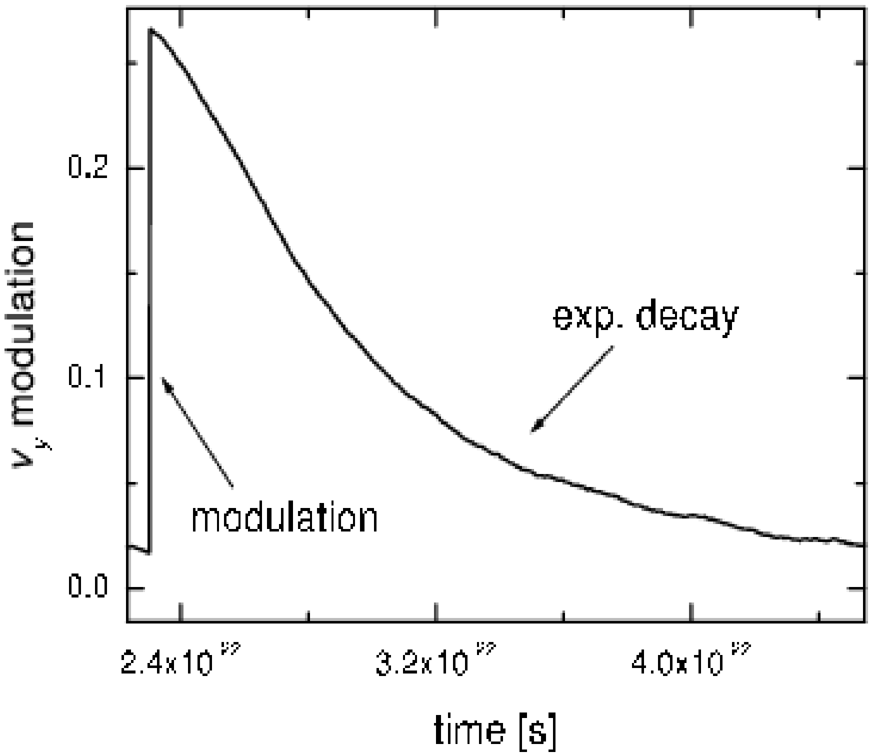


Sinusoid velocity perturbation
(artifical shear in the system):

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

MD measurement for viscosity – 2





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

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

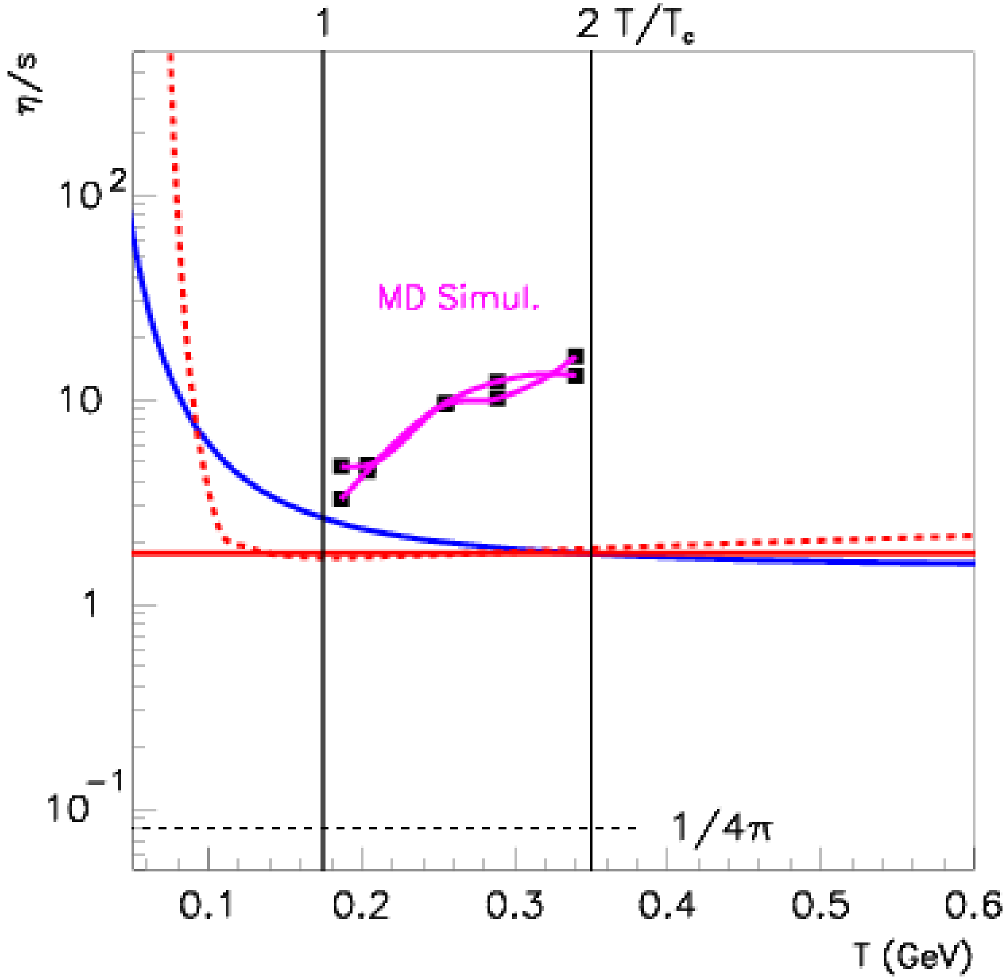
Here τ is related to the dynamical viscosity η_D :

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

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

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 ?
how can we invent such a description?

Summary on viscosity:

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. 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!

3. 'Non-particle' based descriptions?