Dynamical equilibration of strongly-interacting 'infinite' parton matter

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in collaboration with

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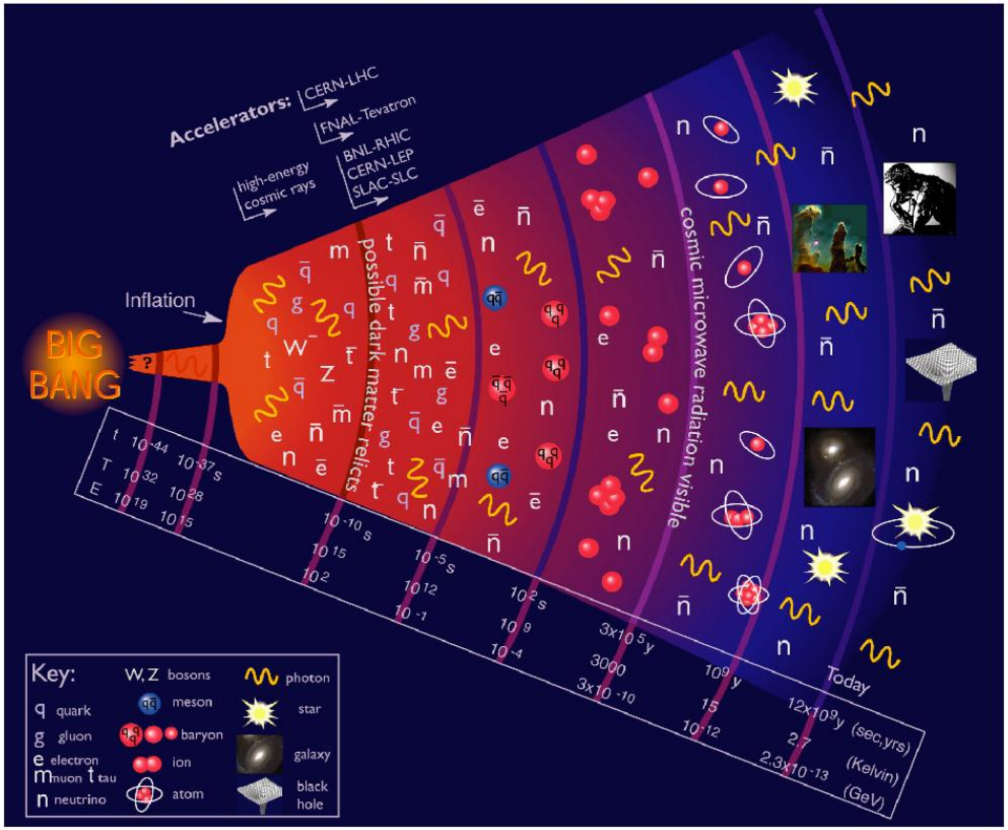
Motivation

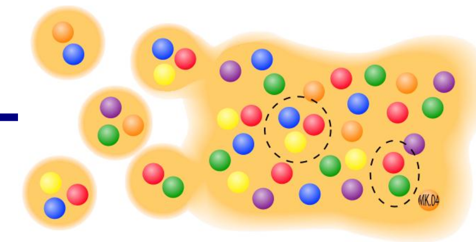


- ‘big-bang’ of the universe
  - steps with kinetic and chemical equilibrium
- laboratory ‘tiny bangs’
  - phase space configurations
  - far from an equilibrium
  - fast expansion
- local thermodynamic equilibrium

Crucial question

How and on what timescales a global thermodynamic equilibrium can be achieved in heavy-ion collisions?

From hadrons to partons



In order to study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma – we need a consistent non-equilibrium (transport) model with

- explicit parton-parton interactions (i.e. between quarks and gluons) beyond strings!
- explicit phase transition from hadronic to partonic degrees of freedom
- lQCD EoS for partonic phase

Transport theory: off-shell Kadanoff-Baym equations for the Green-functions $S^{<}_{h}(x,p)$ in phase-space representation for the partonic and hadronic phase

Parton-Hadron-String-Dynamics (PHSD)

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;
NPA831 (2009) 215;
W. Cassing, EPJ ST 168 (2009) 3

QGP phase described by

Dynamical QuasiParticle Model (DQPM)

A. Peshier, W. Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

The Dynamical QuasiParticle Model (DQPM)

Basic idea: Interacting quasiparticles

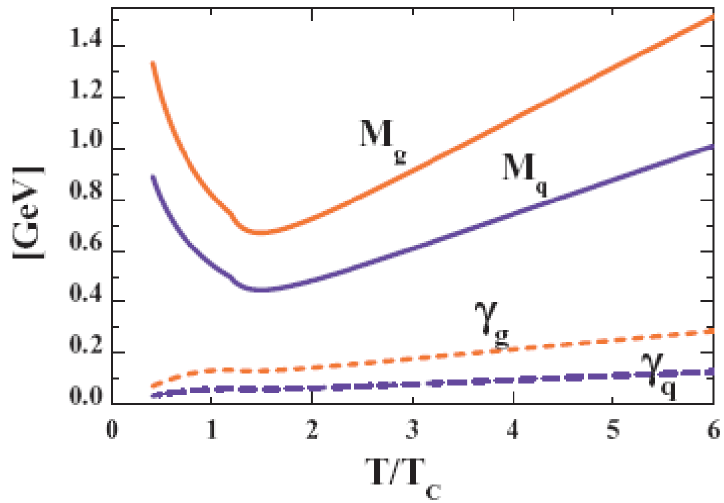
- massive quarks and gluons (g, q, q_{bar}) with spectral functions :

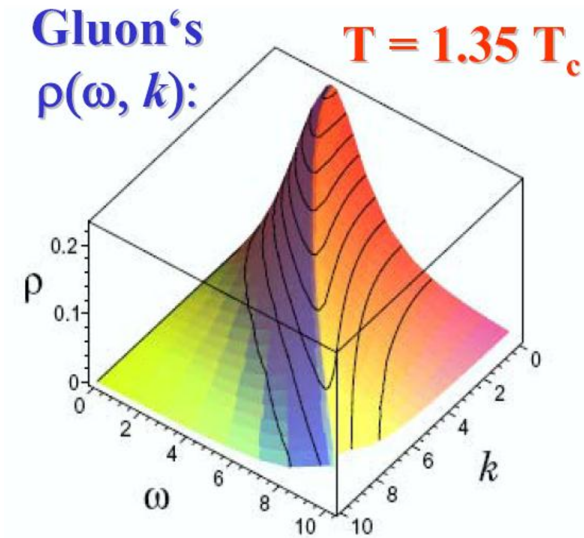
$$\rho(\omega) = \frac{\gamma}{\mathrm{E}} \left(\frac{1}{(\omega - \mathrm{E})^2 + \gamma^2} - \frac{1}{(\omega + \mathrm{E})^2 + \gamma^2} \right)$$

➢ fit to lattice (lQCD) results (e.g. entropy density)

➔ Quasiparticle properties:

large width and mass for gluons and quarks





- DQPM matches well lattice QCD
- DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)
- DQPM gives transition rates for the formation of hadrons → PHSD

Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

DQPM thermodynamics (N_f=3)

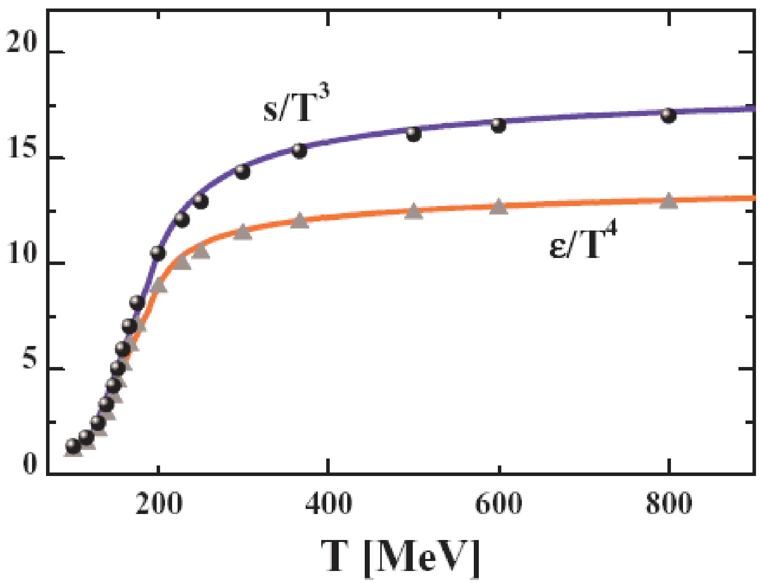
entropy $s = \frac{\partial P}{dT}$ → pressure P

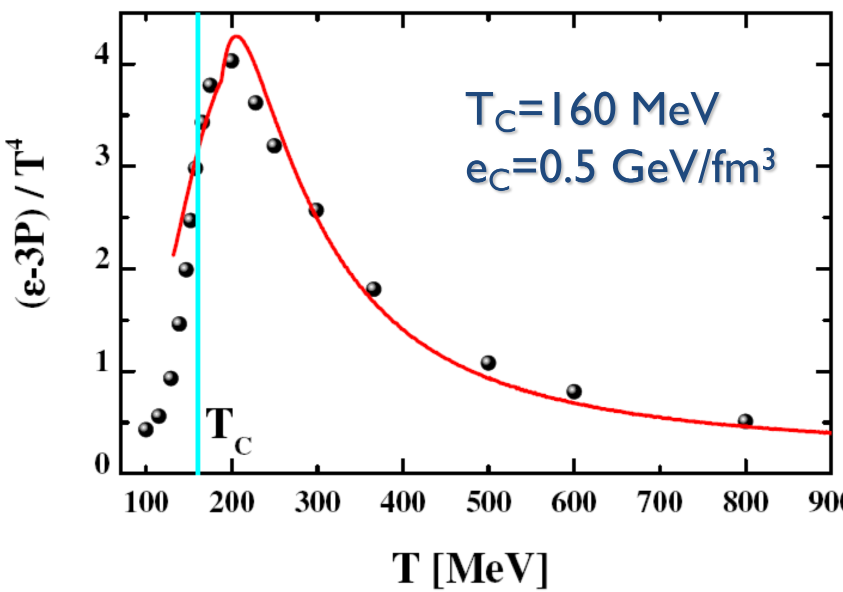
energy density: $\epsilon = Ts - P$

interaction measure:

$$W(T) := \epsilon(T) - 3P(T) = Ts - 4P$$

lQCD: Wuppertal-Budapest group
Y. Aoki et al., JHEP 0906 (2009) 088.

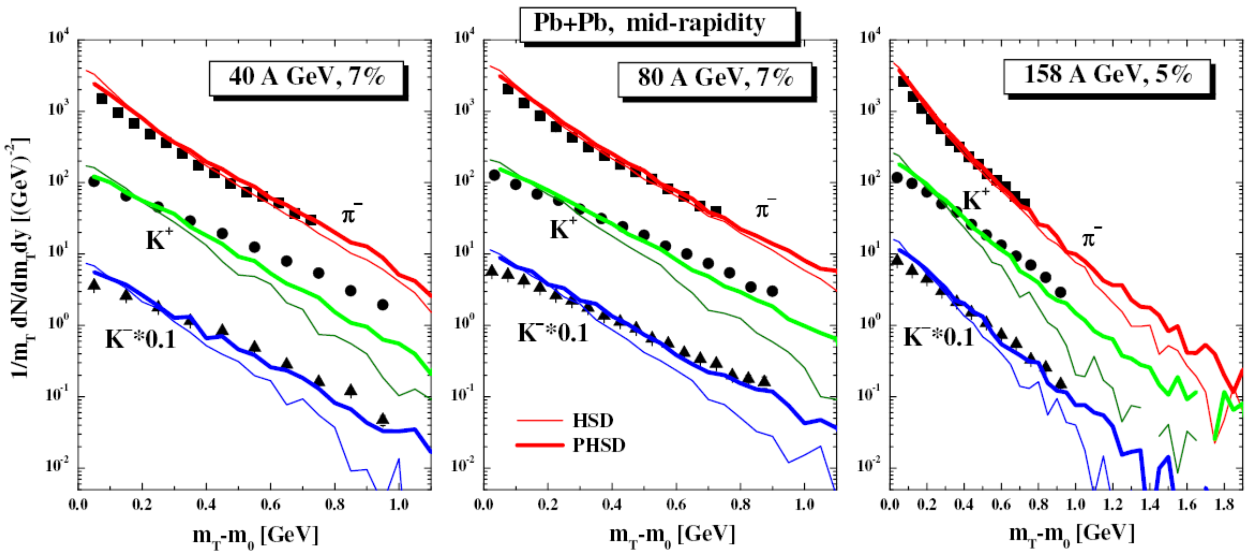




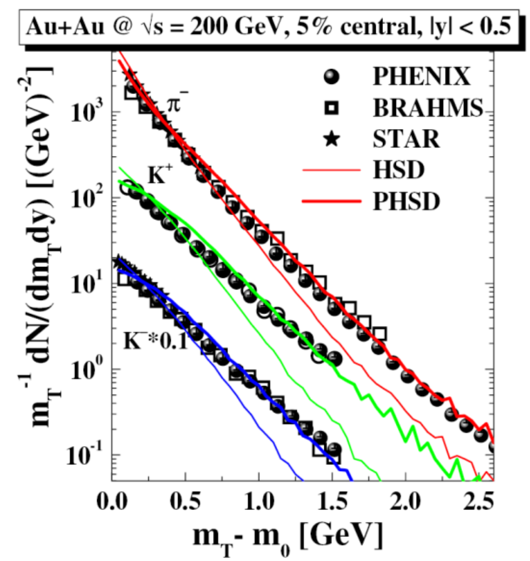
DQPM gives a good description of lQCD results !

PHSD: Transverse mass spectra

Central Pb + Pb at SPS energies



Central Au+Au at RHIC

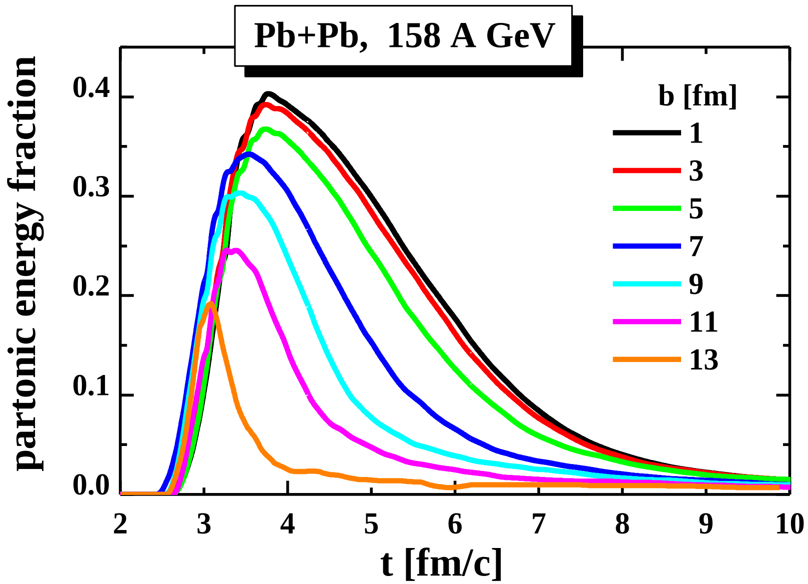


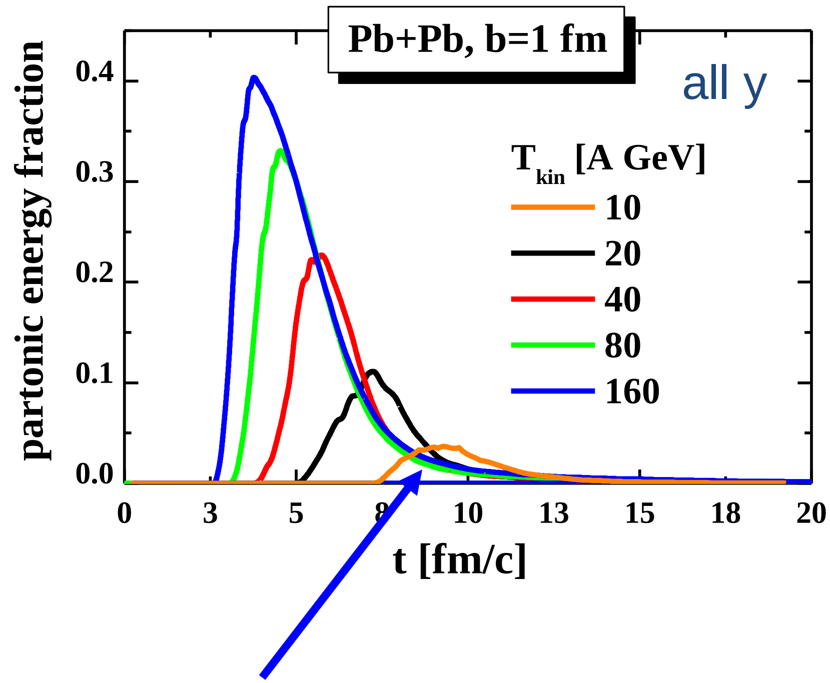
- PHSD gives harder m_T spectra and works better than HSD at high energies – RHIC, SPS (and top FAIR, NICA)
- however, at low SPS (and low FAIR, NICA) energies the effect of the partonic phase decreases due to the decrease of the partonic fraction

W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

Partonic phase at SPS/FAIR/NICA energies

partonic energy fraction vs centrality and energy

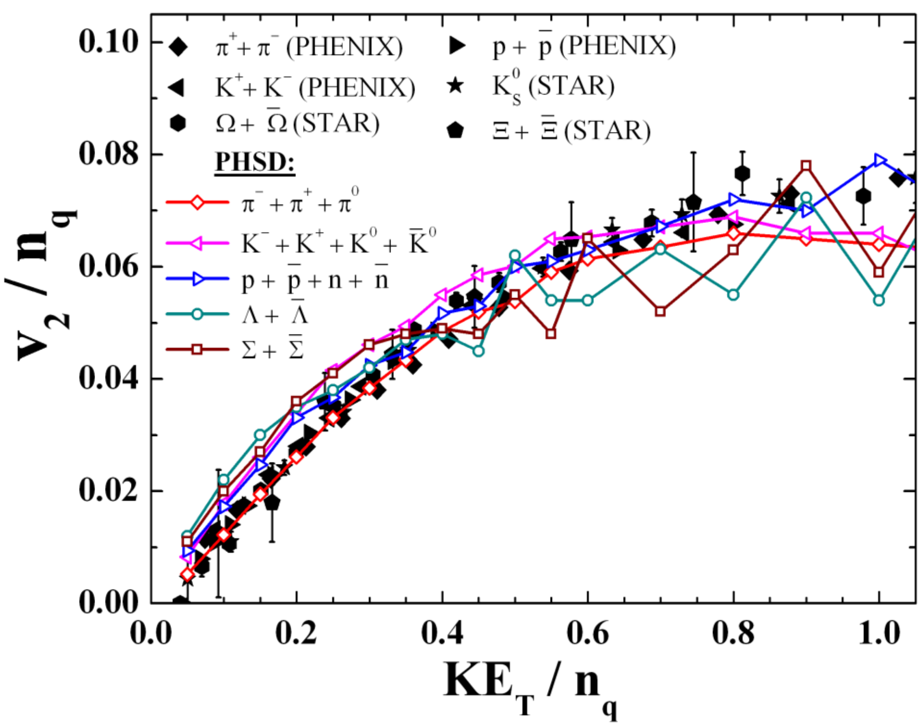




Dramatic decrease of partonic phase with decreasing energy and/or centrality !

Cassing & Bratkovskaya, NPA 831 (2009) 215

Elliptic flow scaling at RHIC



The scaling of v_2 with the number of constituent quarks n_q is roughly in line with the data

E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

PHSD in a box

Goal

- study of the dynamical equilibration of strongly interacting parton matter within the PHSD

PHSD in a box

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- study of the dynamical equilibration of strongly interacting parton matter within the PHSD

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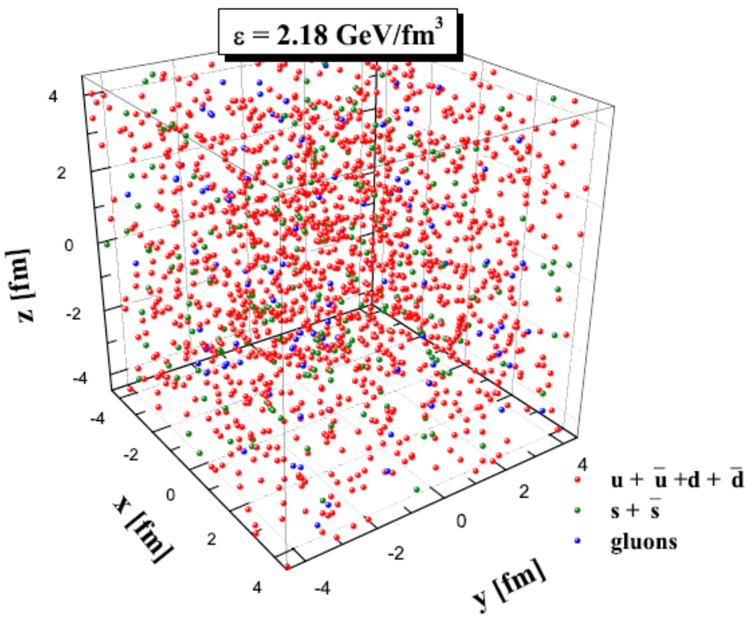
Realization

- a cubic box with periodic boundary conditions
- various values for chemical potential and energy density
- the size of the box is fixed to 9^3 fm^3

Initialization



- light and strange quarks, antiquarks and gluons with random space positions
- initial number of partons is given

$$N_{q(g)} = d_{q(g)} \int_0^\infty \frac{d\omega}{2\pi} \int \frac{d^3p}{(2\pi)^3} 2\omega \rho_{q(g)}(\omega, \mathbf{p}) n_{F(B)}$$

- ratios between the different quark flavors are

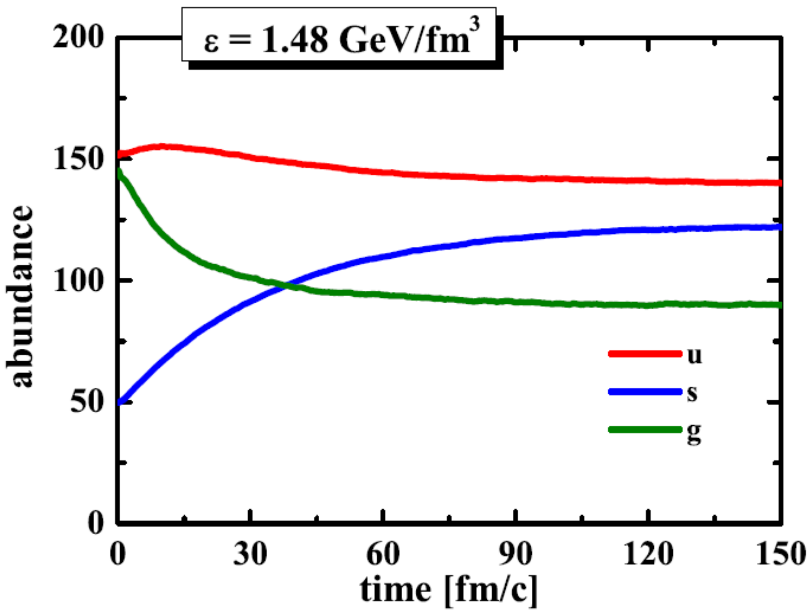
$$N_u \div N_d \div N_s = 3 \div 3 \div 1$$

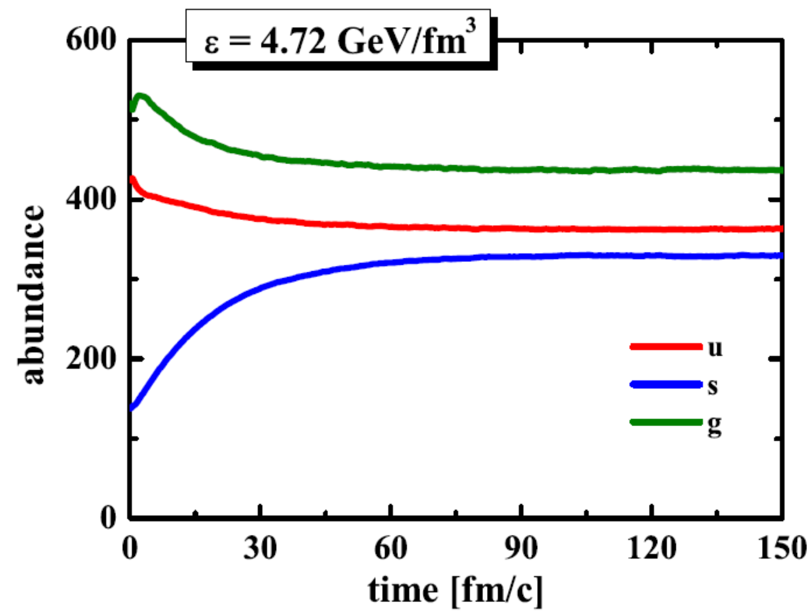
- Four-momenta are distributed according to the $F_1(\omega, \mathbf{p})$ distribution by Monte Carlo simulations

$$F_1(\omega, \mathbf{p}) = \frac{d_q(g)}{4\pi^3} p^2 \omega \rho_{q(g)}(\omega, \mathbf{p}) n_{F(B)}$$

Chemical equilibrium

- A sign of chemical equilibrium is the stabilization of the numbers of partons of the different species in time



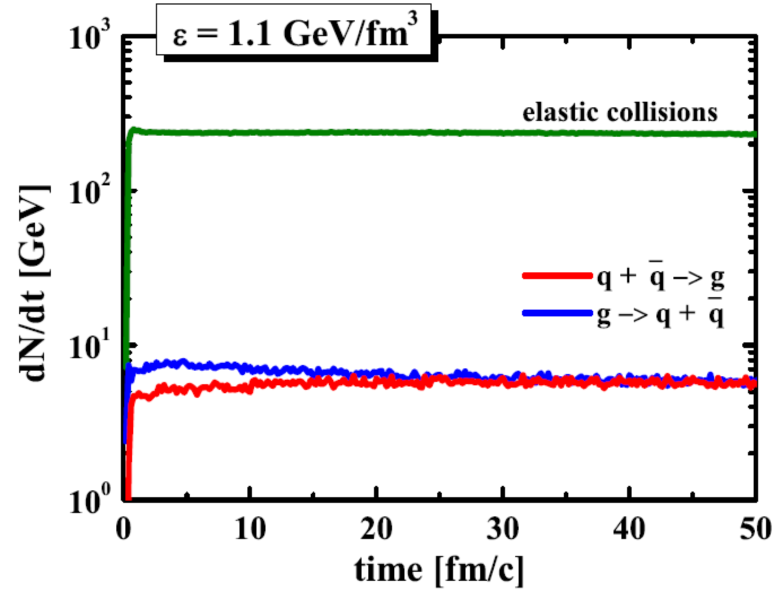


- The final abundancies vary with energy density

Detailed balance

- The reactions rates are practically constant and obey detailed balance for
  - gluon splitting
  - quark + antiquark fusion

- The elastic collisions lead to the eventual thermalization of all pacticle species (e.g. u, d, s quarks and antiquarks and gluons)



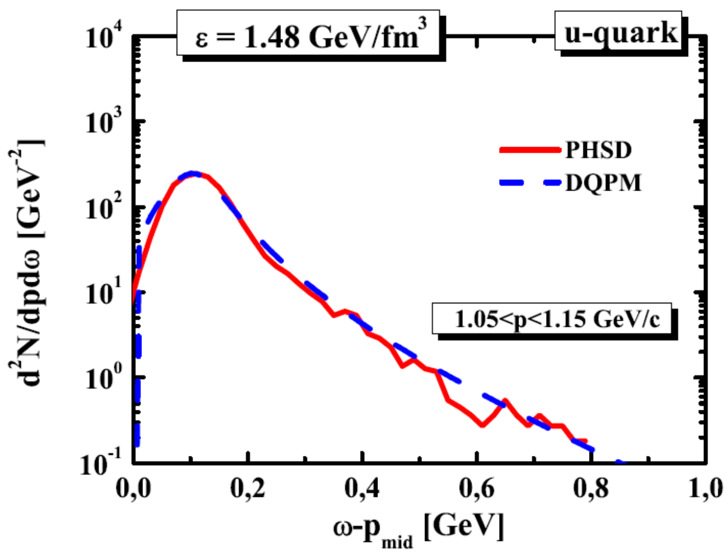
- The numbers of partons dynamically reach the equilibrium values through the inelastic collisions

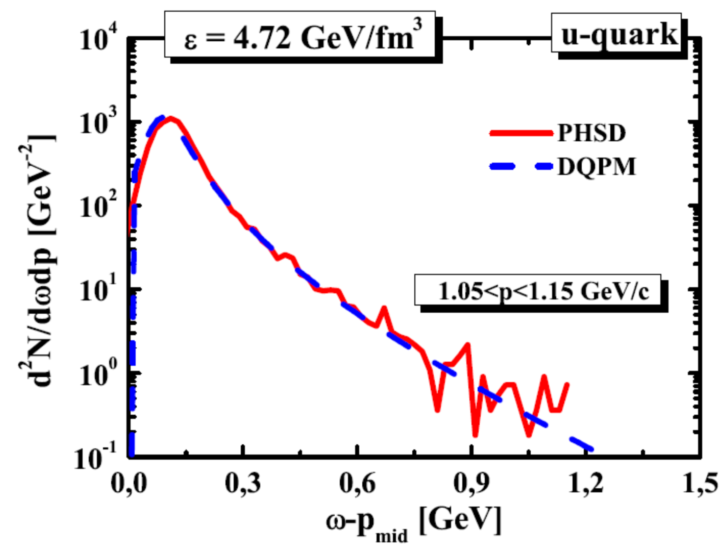
- $q + q \rightarrow q + q$
- $q + \bar{q} \rightarrow q + \bar{q}$
- $\bar{q} + \bar{q} \rightarrow \bar{q} + \bar{q}$
- $q + g \rightarrow q + g$
- $\bar{q} + g \rightarrow \bar{q} + g$

- $q + \bar{q} \rightarrow g$
- $g \rightarrow q + \bar{q}$

Thermal equilibration

- Comparison between PHSD simulation in the box and the DQPM model
- DQPM predictions can be evaluated: $$\frac{d^2N}{d\omega dp} = \frac{V d_u}{2\pi^3} p_{mid}^2 \, \omega \rho_u(\omega, p_{mid}) e^{-\omega/T}$$





- Dynamical calculations are in a good agreement with the DQPM model
- The system is in a dynamical equilibrium

Summary

- PHSD provides a consistent description of off-shell parton dynamics in line with a lattice QCD equation of state and incorporates dynamical hadronization in line with conservation laws

- PHSD gives harder m_T spectra and works better than HSD at RHIC and at high SPS energies

- The quark-number scaling of v_2 holds fairly well in PHSD at RHIC

- PHSD within a box allows to study the dynamical equilibration of strongly interacting parton matter

Back up

The Dynamical QuasiParticle Model (DQPM)

Basic idea: Interacting quasiparticles

- massive quarks and gluons (g, q, q_{bar}) with spectral functions :

$$\rho(\omega) = \frac{\gamma}{\mathbf{E}} \left(\frac{1}{(\omega - \mathbf{E})^2 + \gamma^2} - \frac{1}{(\omega + \mathbf{E})^2 + \gamma^2} \right)$$

$E^2 = p^2+M^2-\gamma^2$

quarks

mass: $m^2(T) = \frac{N_c^2 - 1}{8N_c} g^2 \left(T^2 + \frac{\mu_q^2}{\pi^2} \right)$

width: $\gamma_q(T) = \frac{N_c^2 - 1}{2N_c} \frac{g^2 T}{4\pi} \ln \frac{c}{g^2}$

gluons:

$M^2(T) = \frac{g^2}{6} \left((N_c + \frac{1}{2} N_f) T^2 + \frac{N_c}{2} \sum_q \frac{\mu_q^2}{\pi^2} \right)$

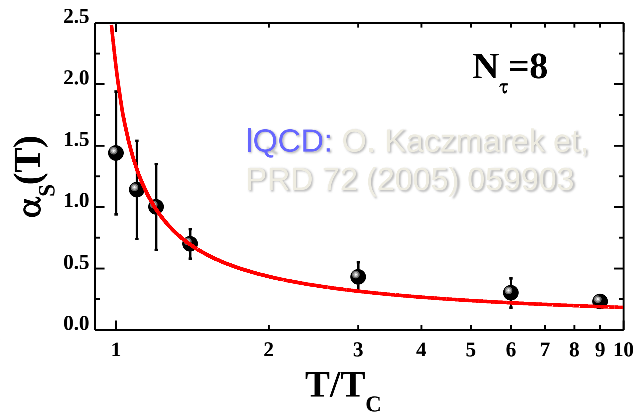
$\gamma_g(T) = N_c \frac{g^2 T}{4\pi} \ln \frac{c}{g^2}$

$N_c = 3$, $N_f=3$

running coupling: $\alpha_S(T) = g^2(T)/(4\pi)$

$$g^2(T/T_c) = \frac{48\pi^2}{(11N_c - 2N_f) \ln(\lambda^2 (T/T_c - T_s/T_c)^2}$$

➔ 3 parameters: $T_s/T_c=0.46$; $c=28.8$; $\lambda=2.42$



➢ fit to lattice (lQCD) results (e.g. entropy density)

➔ quasiparticle properties

DQPM: Peshier, Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

PHSD: Hadronization details

Local covariant off-shell transition rate for q+qbar fusion
=> meson formation

$$\frac{dN_m(x,p)}{d^4x d^4p} = Tr_q Tr_{\bar{q}} \; \delta^4(p - p_q - p_{\bar{q}}) \; \delta^4\left(\frac{x_q + x_{\bar{q}}}{2} - x\right)$$
$$\times \omega_q \; \rho_q(p_q) \; \omega_{\bar{q}} \; \rho_{\bar{q}}(p_{\bar{q}}) \; |v_{q\bar{q}}|^2 \; W_m(x_q - x_{\bar{q}}, p_q - p_{\bar{q}})$$
$$\times N_q(x_q, p_q) \; N_{\bar{q}}(x_{\bar{q}}, p_{\bar{q}}) \; \delta(\text{flavor, color}).$$

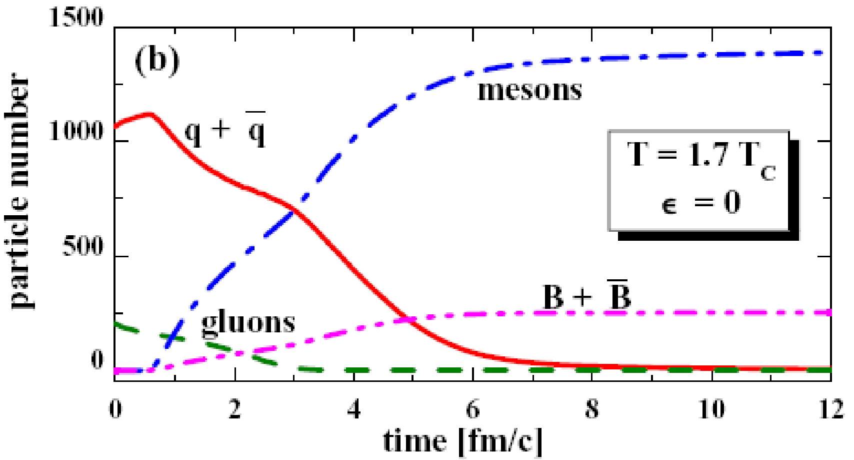
using $$Tr_j = \sum_j \int d^4x_j d^4p_j / (2\pi)^4$$

- $N_j(x,p)$ is the phase-space density of parton j at space-time position *x* and 4-momentum *p*
- W_m is the phase-space distribution of the formed ‚pre-hadrons': (Gaussian in phase space) $\sqrt{< r^2 >} = 0.66 \text{ fm}$
- $v_{q\bar{q}}$ is the effective quark-antiquark interaction from the DQPM

Cassing, Bratkovskaya, PRC 78 (2008) 034919; Cassing, EPJ ST 168 (2009) 3

PHSD: hadronization of a partonic fireball

E.g. time evolution of the partonic fireball at initial temperature 1.7 T_c at μ_q=0



Consequences:

➢Hadronization: $q+q_{bar}$ or 3q or $3q_{bar}$ fuse to color neutral hadrons (or strings) which subsequently decay into hadrons in a microcanonical fashion, i.e. obeying all conservation laws (i.e. 4-momentum conservation, flavor current conservation) in each event!

➢ Hadronization yields an increase in total entropy S (i.e. more hadrons in the final state than initial partons) and not a decrease as in the simple recombination models!

➢Off-shell parton transport roughly leads a hydrodynamic evolution of the partonic system

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;
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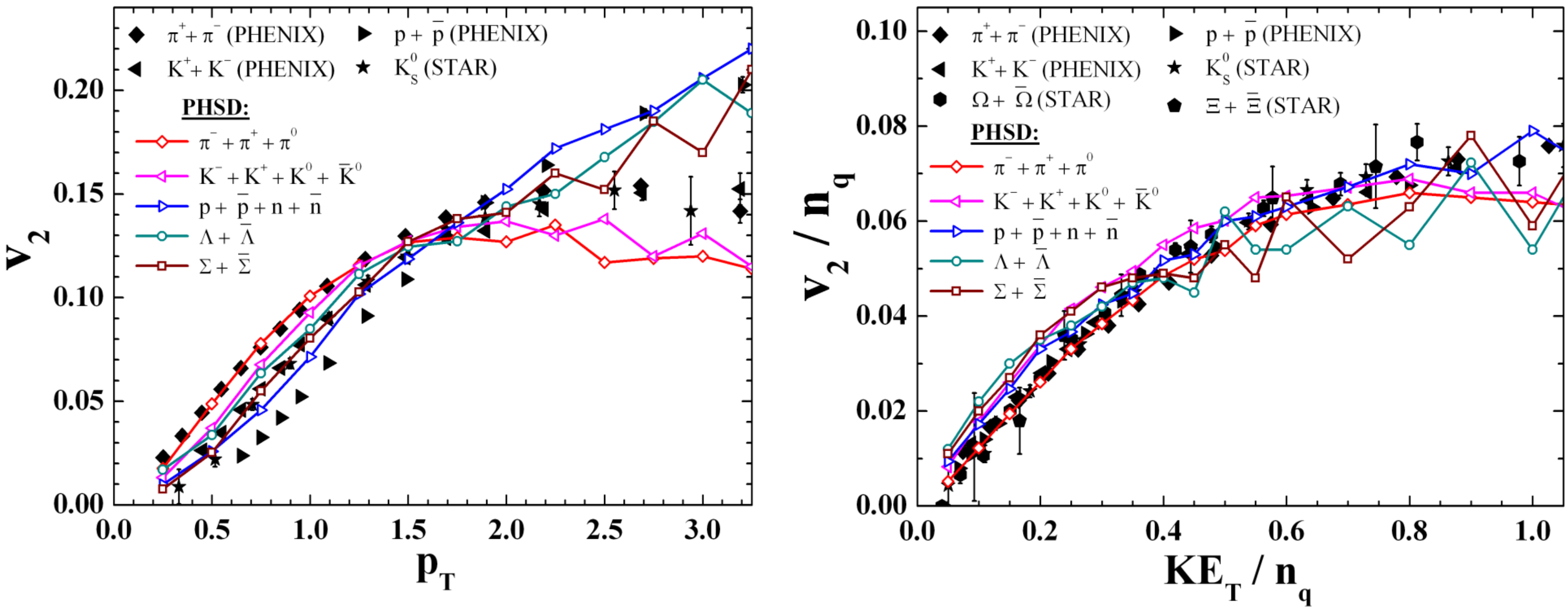
Elliptic flow scaling at RHIC



The mass splitting at low p_T is approximately reproduced as well as the meson-baryon splitting for p_T > 2 GeV/c !

The scaling of v_2 with the number of constituent quarks n_q is roughly in line with the data .

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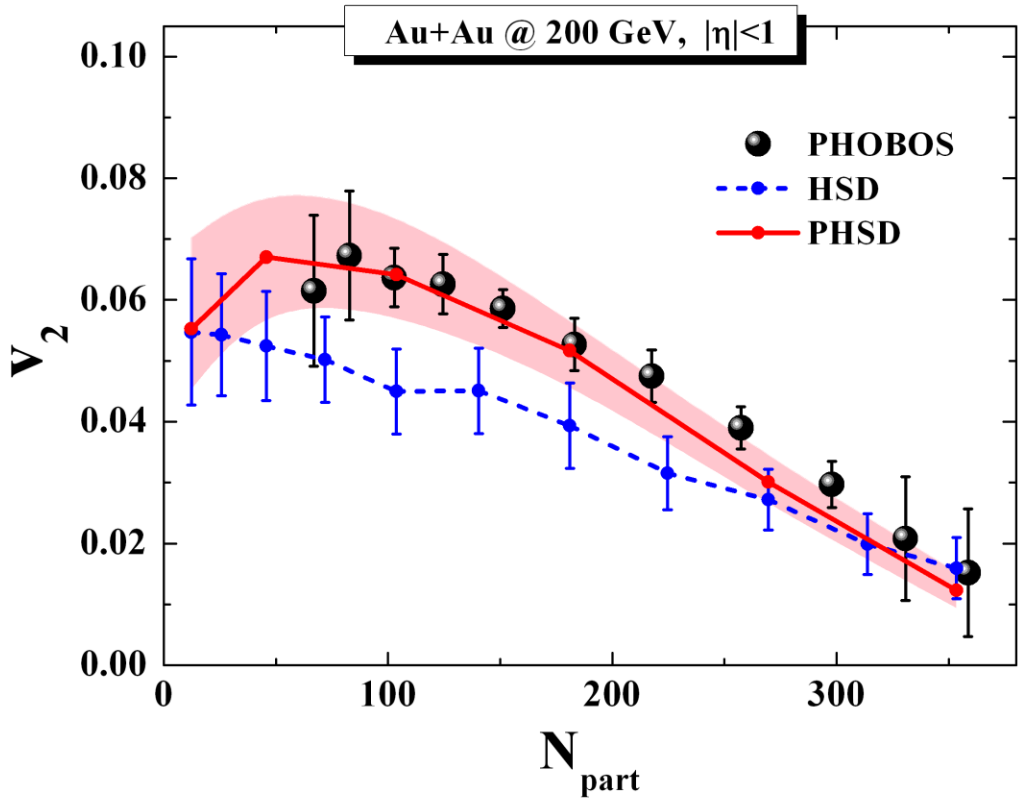
Elliptic flow versus centrality in PHSD

Au+Au at midrapidity $|\eta| < 1$



enhancement of v_2 due to the partonic interactions

v_2 from PHSD is larger relative to HSD (in line with the data from PHOBOS)

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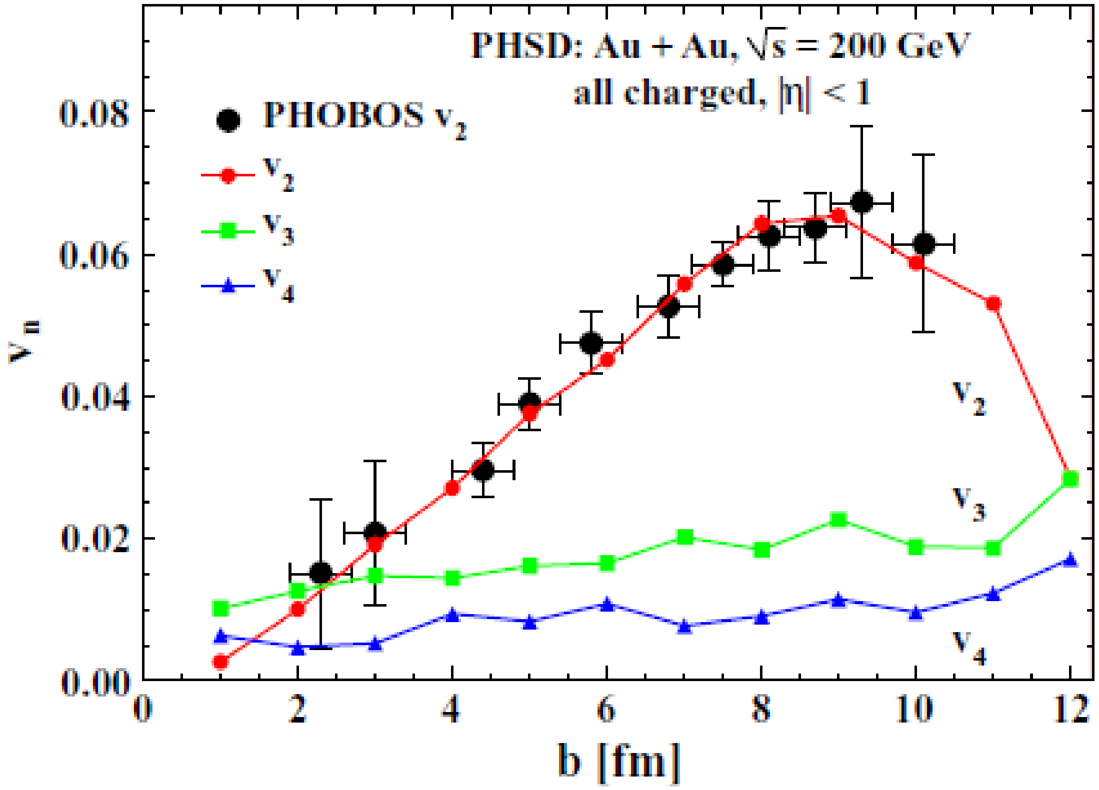
Anisotropic flows v_2, v_3, v_4 vs. centrality



v_3, v_4 are only weakly sensitive to centrality (the impact parameter b)

v_2 increases strongly with b up to peripheral collisions

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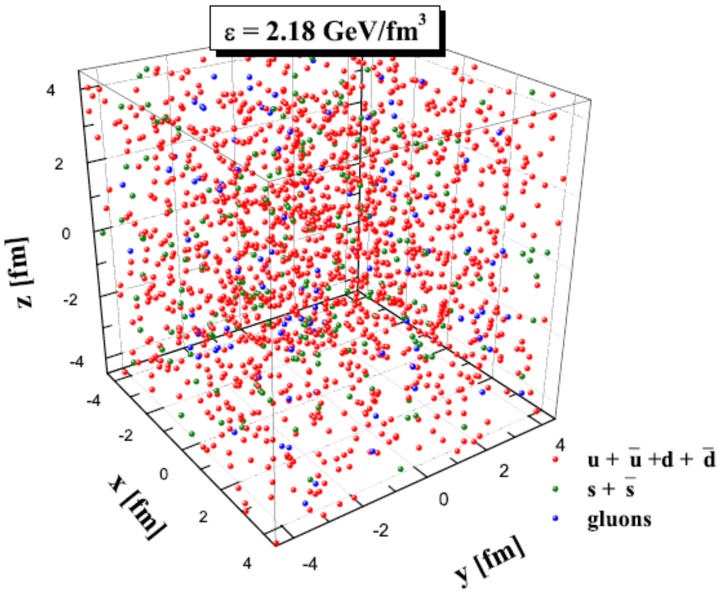
Initialization



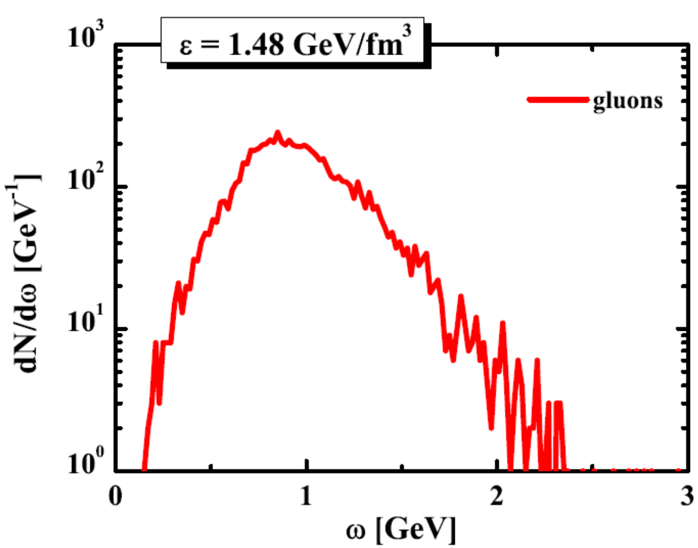
- light and strange quarks, antiquarks and gluons with random space positions
- initial number of partons is given

$$N_{q(g)} = d_{q(g)} \int_0^\infty \frac{d\omega}{2\pi} \int \frac{d^3p}{(2\pi)^3} 2\omega\rho_{q(g)}(\omega, \mathbf{p}) n_{F(B)}$$

- ratios between different quark flavors are

$$N_u \div N_d \div N_s = 3 \div 3 \div 1$$

initial energy distribution



initial invariant momentum distribution