High-density QCD

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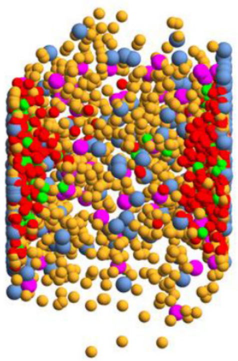
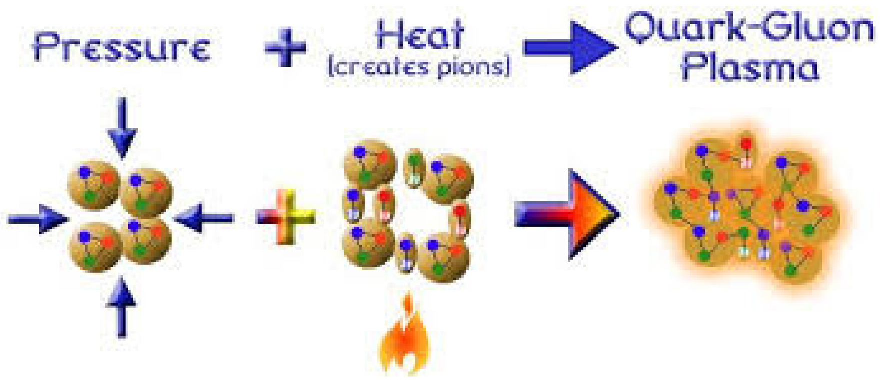


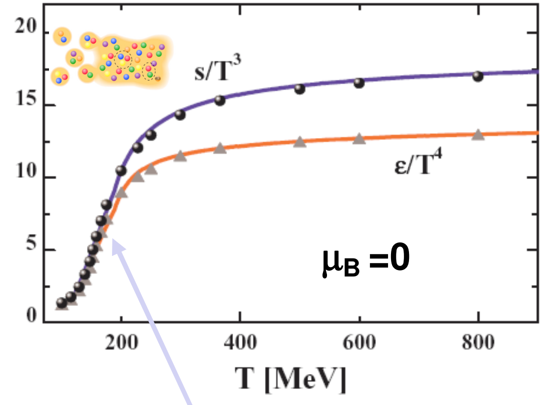
Heavy-ion collisions

❑ Heavy-ion collision experiment

➔ ‚re-creation‘ of the Big Bang conditions in laboratory:
matter at high pressure and temperature



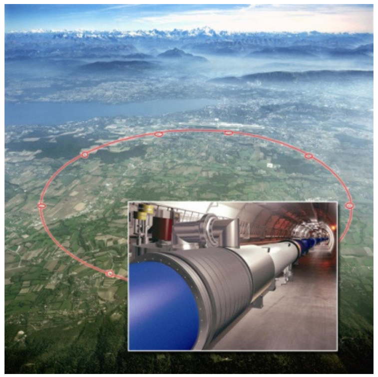
lQCD



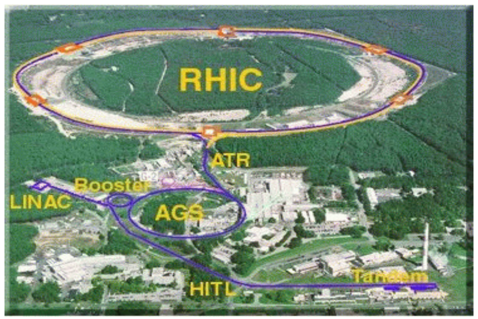
➔ phase transition from hadronic to partonic matter (quarks, gluons) at critical energy density ε_C ~0.5 GeV/fm^3

❑ Heavy-ion accelerators:

Large Hadron Collider -
LHC (CERN):
Pb+Pb up to 574 A TeV

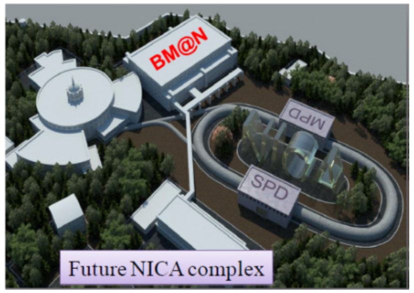


Relativistic-Heavy-Ion-Collider -
RHIC (Brookhaven):
Au+Au up to 21.3 A TeV

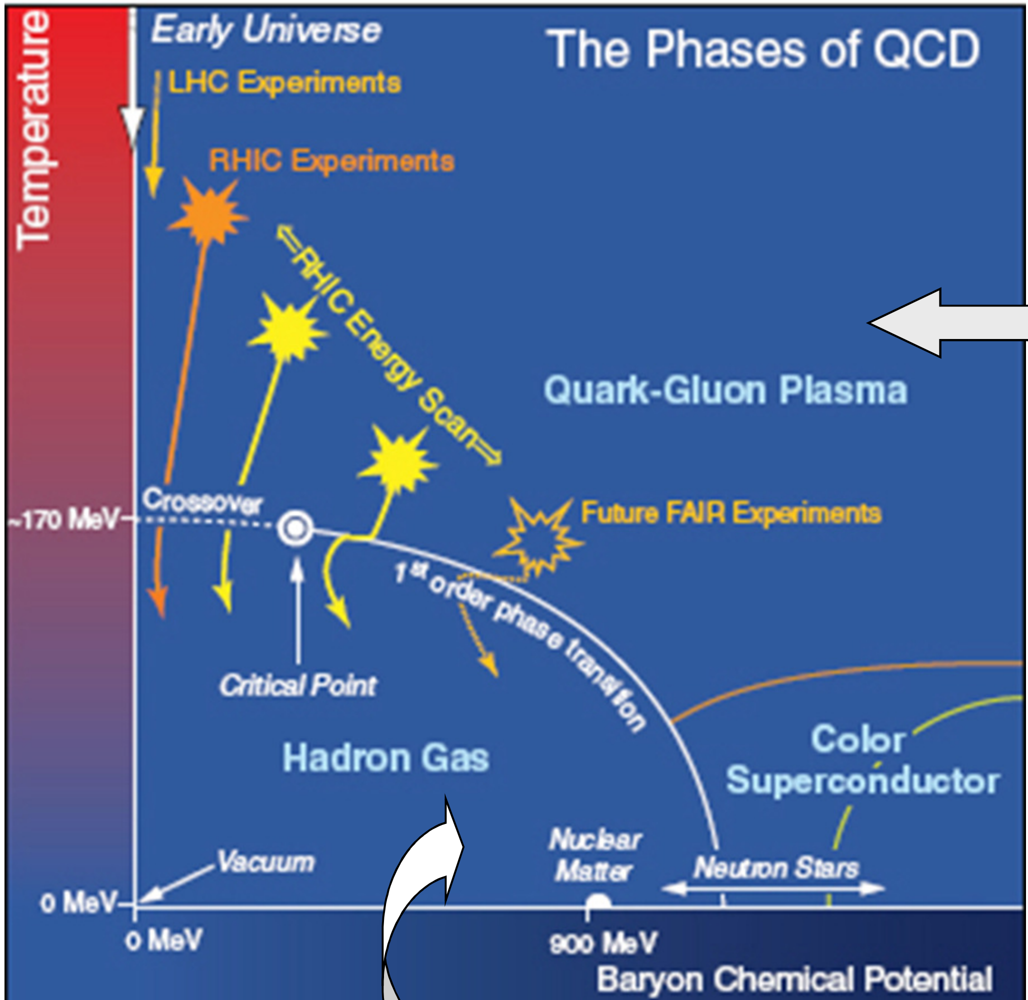


Facility for Antiproton and Ion
Research – FAIR (Darmstadt)
(Under construction)
Au+Au up to 10 (30) A GeV

Nuclotron-based Ion Collider
fAcility – NICA (Dubna)
(Under construction)
Au+Au up to 60 A GeV



The ‚holy grail‘ of heavy-ion physics:



The phase diagram of QCD

- Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma

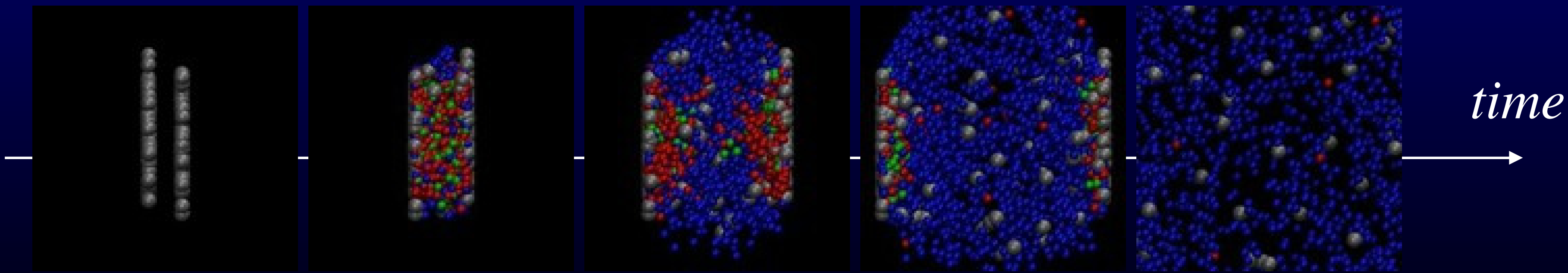
- Search for the critical point

- Study of the in-medium properties of hadrons at high baryon density and temperature

‚Little Bangs‘ in the Laboratory

Initial State

Hadronization



Au+Au

Quark-Gluon-Plasma ?

hadron degrees of freedom → quarks and gluons → hadron degrees of freedom

How can we proove that an equilibrium QGP has been created in central heavy-ion collisions ?!

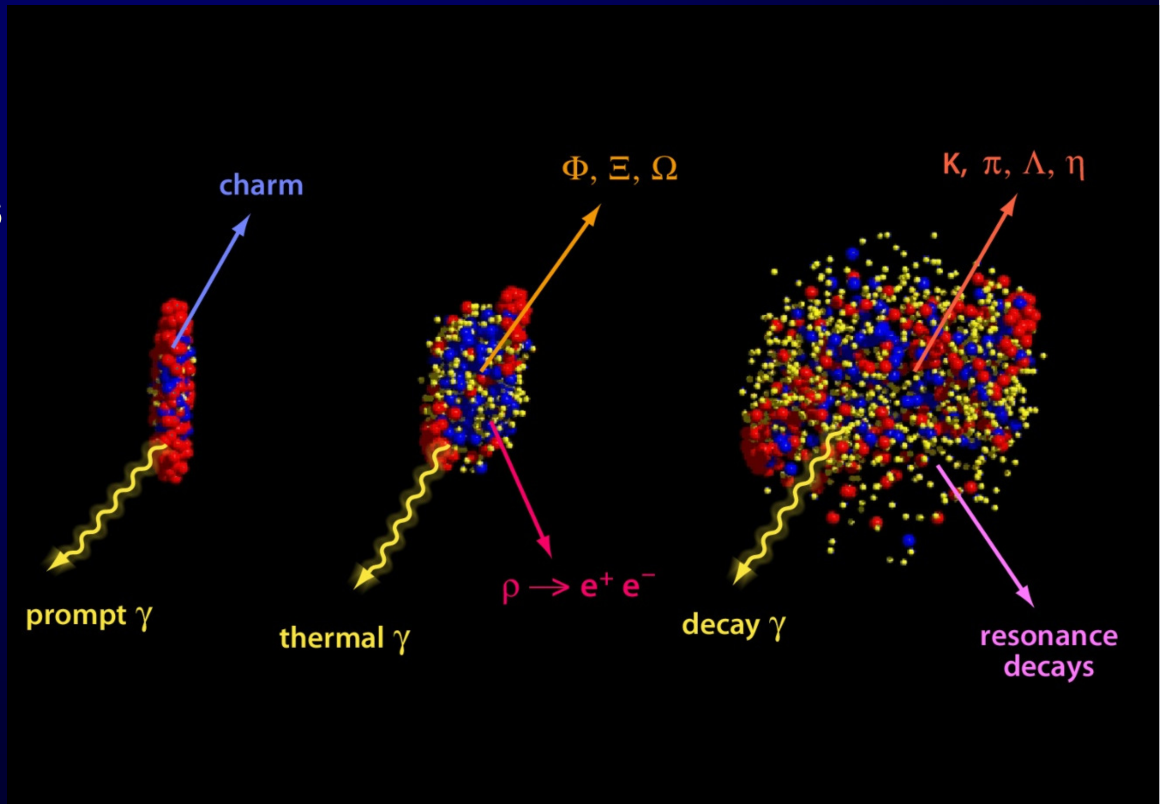
Signals of the phase transition:

- Multi-strange particle enhancement in A+A
- Charm suppression
- Collective flow (v_1, v_2)
- Thermal dileptons
- Jet quenching and angular correlations
- High p_T suppression of hadrons
- Nonstatistical event by event fluctuations and correlations
- ...

Experiment: measures final hadrons and leptons

How to learn about physics from data?

Compare with theory!



Basic models for heavy-ion collisions

- **Statistical models:**

basic assumption: system is described by a (grand) canonical ensemble of non-interacting fermions and bosons in thermal and chemical equilibrium

[- : no dynamics]

- **(Ideal) hydrodynamical models:**

basic assumption: conservation laws + equation of state; assumption of local thermal and chemical equilibrium

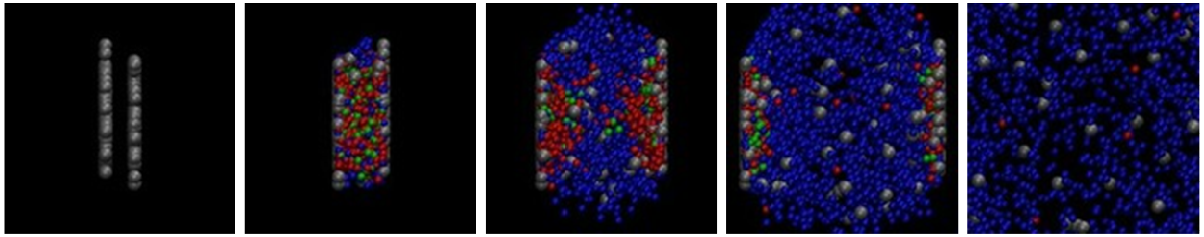
[- : simplified dynamics]

- **Transport models:**

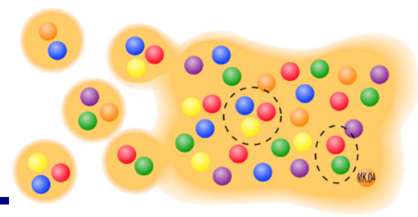
based on transport theory of relativistic quantum many-body systems -
Actual solutions: Monte Carlo simulations

[+ : full dynamics | - : very complicated]

➔ Microscopic transport models provide a unique dynamical description of nonequilibrium effects in heavy-ion collisions



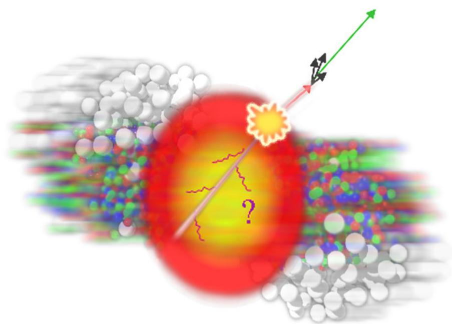
Models of HIC

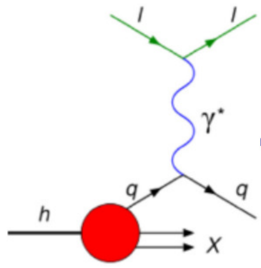


Goal: microscopic transport description of the partonic and hadronic phase

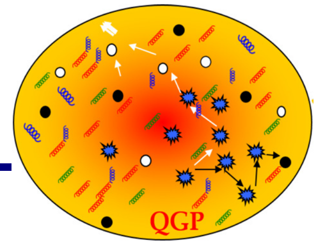
Problems:

- **What are the properties of the QGP degrees of freedom?**
- **How to model a QGP phase in line with lQCD data?**
- **How to solve the hadronization problem?**



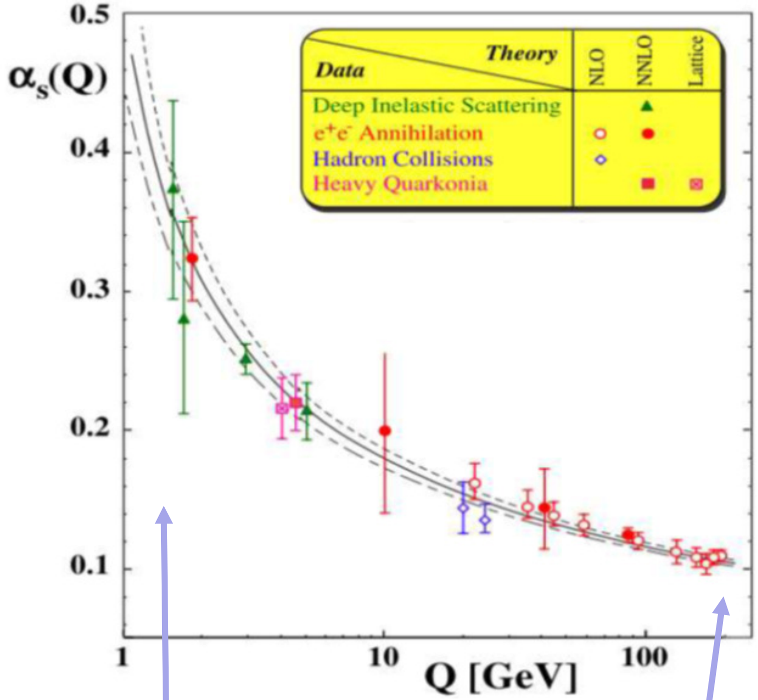


Thermal properties of QGP: α_S

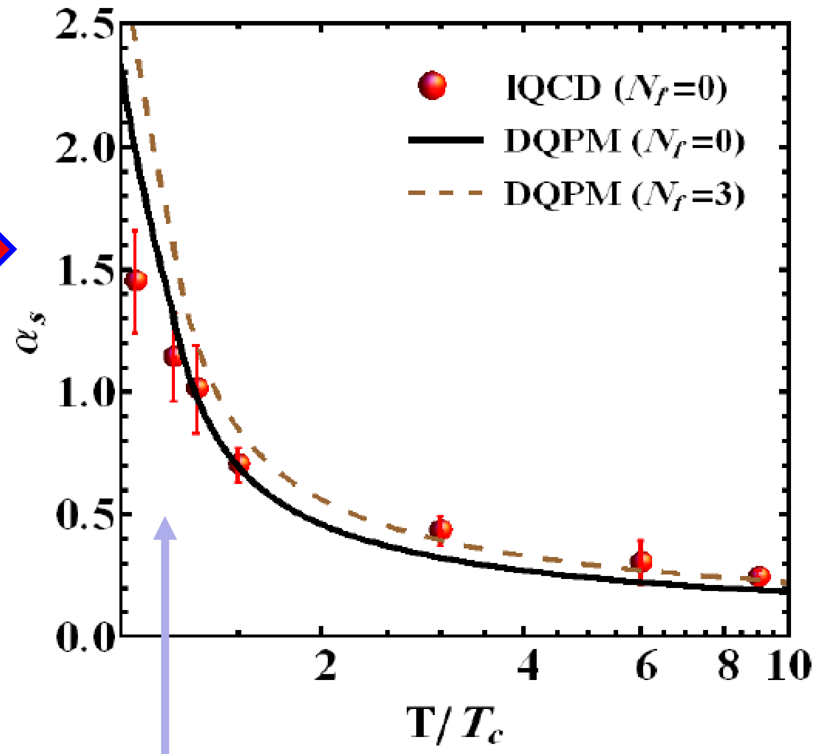


Running coupling

α_S (Q)



α_S (T)



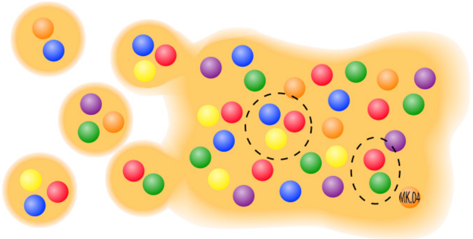
low energy
long distance

high energy
short distance

Non-perturbative QCD

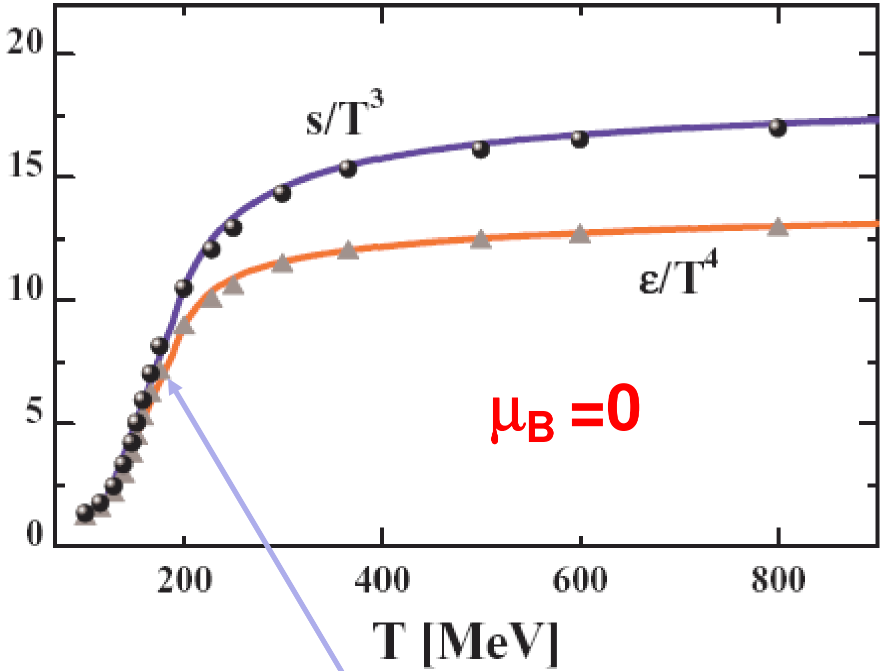
pQCD

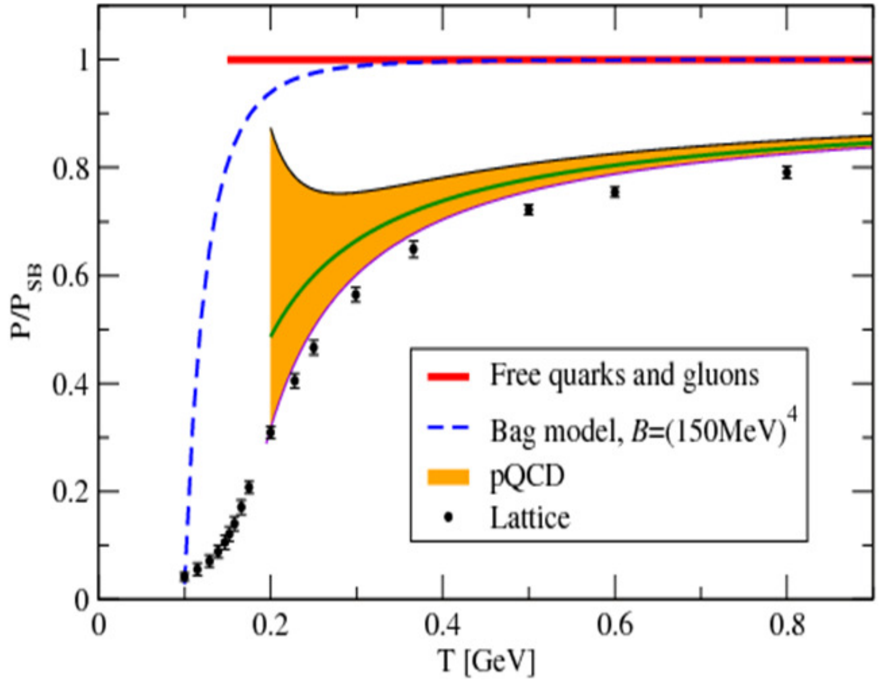
- Confinement
- Asymptotic freedom
- deconfined QGP



Thermal properties of QGP

Equation-of-state (EoS) from lQCD





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

Non-perturbative QCD ← pQCD

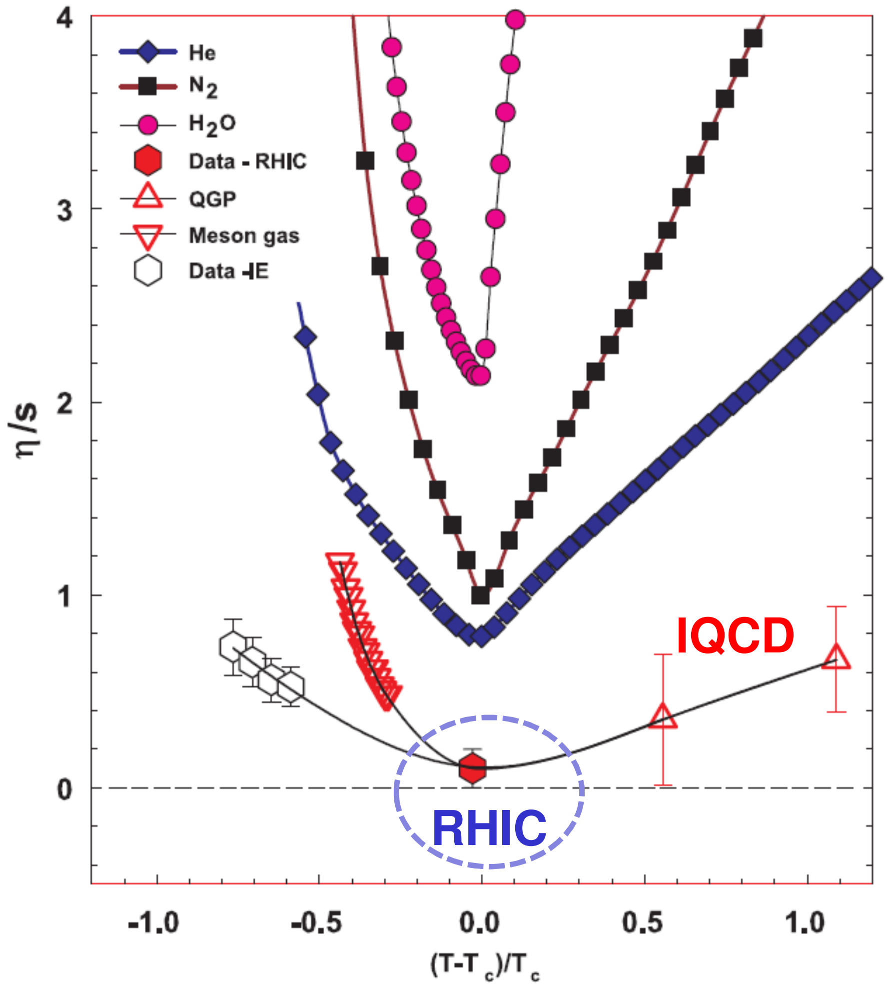
➔ Crossover transition from hadronic matter to QGP

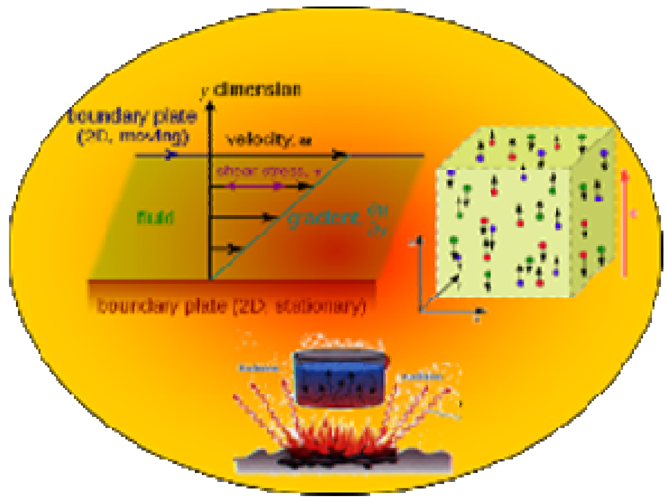
Critical conditions: ε_C ~0.5 GeV/fm^3 , T_C ~160 MeV

- can be reached in heavy-ion experiments at bombarding energies > 5 GeV/A

The properties of QGP from HIC

Compilation of the ratio of shear viscosity to entropy density for various substances





Exp. data + lQCD:

η/s near T_C is very small !

➔ QGP : close to an ideal liquid, not a gas of weakly interacting quarks and gluons

➔ QGP: strongly-interacting matter

Degrees-of-freedom of QGP

❖ lQCD gives QGP EoS ➔

need to be interpreted in terms of degrees-of-freedom

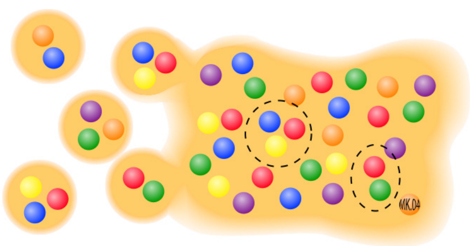
pQCD:

- ❑ weakly interacting system
- ❑ massless quarks and gluons

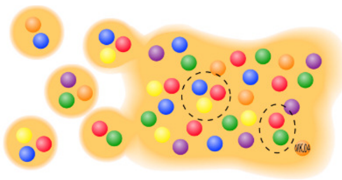
Thermal QCD
= QCD at high parton densities:

- ❑ strongly interacting system
- ❑ massive quarks and gluons

❖ Effective degrees-of-freedom



From SIS to LHC: from hadrons to partons



The goal: to **study of the phase transition** from hadronic to partonic matter and properties of the Quark-Gluon-Plasma from **microscopic origin**

➔ need a **consistent non-equilibrium transport model**

- ❑ with explicit **parton-parton interactions** (i.e. between quarks and gluons)
- ❑ explicit **phase transition** from hadronic to partonic degrees of freedom
- ❑ **lQCD EoS** for partonic phase (‚crossover' at μ_q=0)

❑ **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** (applicable for strongly interacting system!)

⇨ **Parton-Hadron-String-Dynamics (PHSD)**

QGP phase described by

Dynamical QuasiParticle Model (DQPM)

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

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

Dynamical QuasiParticle Model (DQPM) - Basic ideas:

DQPM describes QCD properties in terms of ‚resummed' single-particle Green's functions (propagators) – in the sense of a two-particle irreducible (2PI) approach:

gluon propagator: $\Delta^{-1} = P^2 - \Pi$ &	quark propagator $S_q^{-1} = P^2 - \Sigma_q$
gluon self-energy: $\Pi = M_g^2 - i2\Gamma_g\omega$ &	quark self-energy: $\Sigma_q = M_q^2 - i2\Gamma_q\omega$

(scalar approximation)

- the resummed properties are specified by complex (retarded) self-energies which depend on temperature (or the scalar parton density out-of equilibrium):
  - the real part of self-energies (Σ_q, Π) describes a dynamically generated mass (M_q,M_g);
  - the imaginary part describes the interaction width of partons (Γ_q, Γ_g)

- space-like part of energy-momentum tensor $T_{\mu\nu}$ defines the potential energy density and the mean-field potential (1PI) for quarks and gluons (U_q, U_g)

- 2PI framework guaranties a consistent description of the system in- and out-of equilibrium on the basis of Kadanoff-Baym equations with proper states in equilibrium

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

The Dynamical QuasiParticle Model (DQPM)

Properties of interacting quasi-particles:
massive quarks and gluons (g, q, q_{bar})
with Lorentzian spectral functions:

$$A_i(\omega, T) = \frac{4\omega \Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2 \Gamma_i^2(T)}$$

$$(i = q, \bar{q}, g)$$

- **Modeling of the quark/gluon masses and widths → HTL limit at high T**
  - **quarks:**

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

    width: $\Gamma_{q(\bar{q})}(T) = \frac{1}{3} \frac{N_c^2 - 1}{2N_c} \frac{g^2 T}{8\pi} \ln\left(\frac{2c}{g^2} + 1\right)$

  - **gluons:**

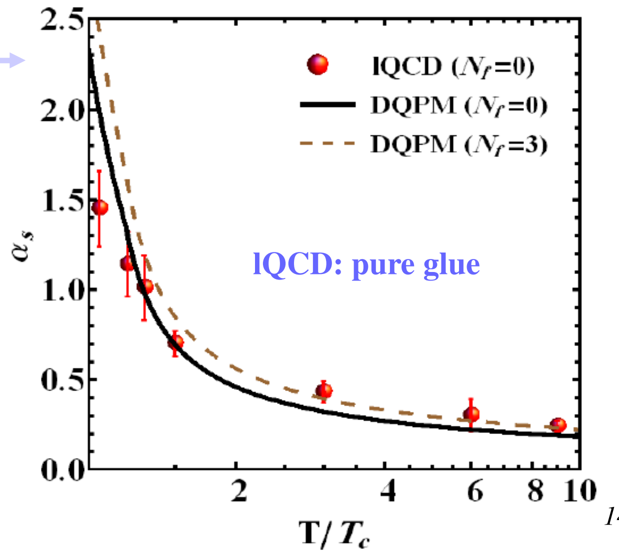
    $M_g^2(T) = \frac{g^2}{6}\left(\left(N_c + \frac{N_f}{2}\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$

    $\Gamma_g(T) = \frac{1}{3} N_c \frac{g^2 T}{8\pi} \ln\left(\frac{2c}{g^2} + 1\right)$

    $N_c = 3$, $N_f = 3$

  - **running coupling: T-dependent $\alpha_S(T)$**

$$\alpha_s(T) = \frac{g^2(T)}{4\pi} = \frac{12\pi}{(11N_c - 2N_f)\ln[\lambda^2(T/T_c - T_s/T_c)^2]}$$



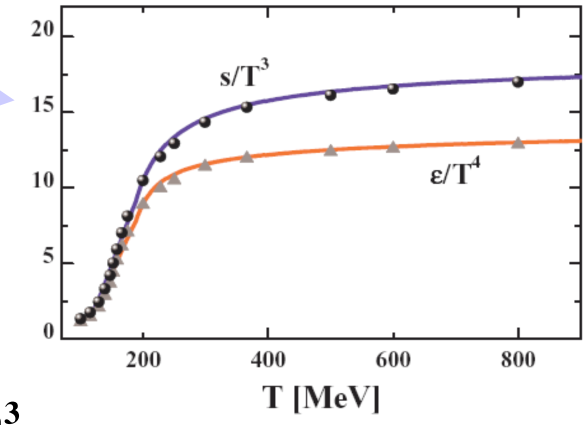
❑ **fit to lattice (lQCD) results (e.g. entropy density)**

with 3 parameters: T_s/T_c=0.46; c=28.8; λ=2.42
(for pure glue N_f=0)

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

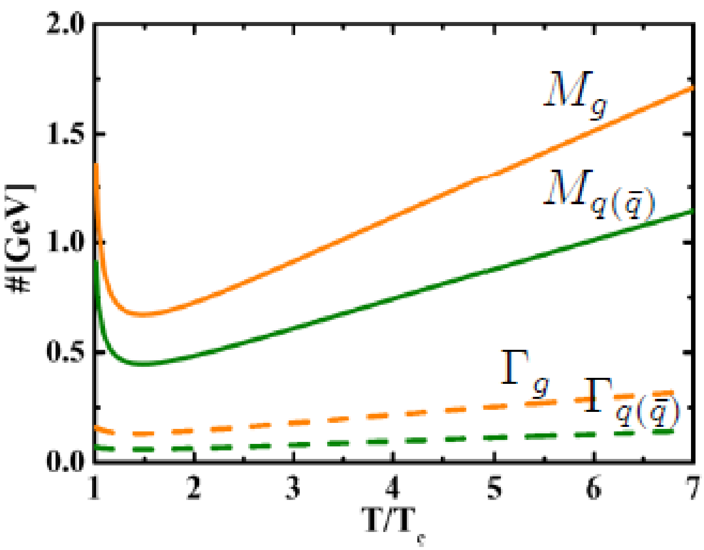
The Dynamical QuasiParticle Model (DQPM)

- **fit to lattice (lQCD) results (e.g. entropy density)**
  - * **BMW lQCD data S. Borsanyi et al., JHEP 1009 (2010) 073**

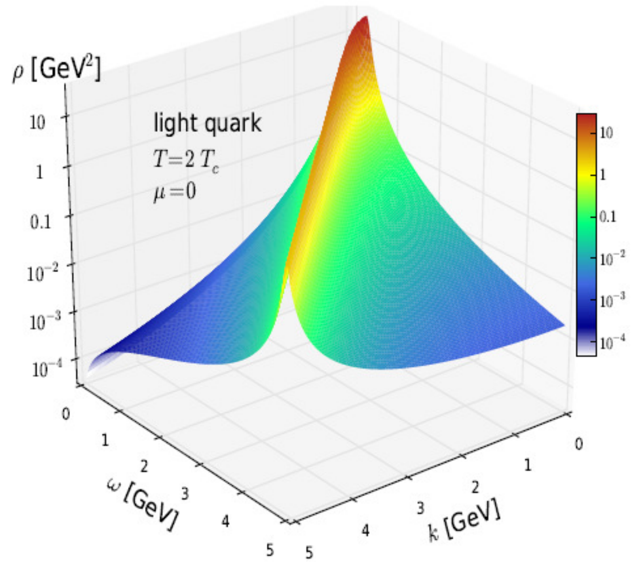


➔ **Quasiparticle properties:**

- **large width and mass for gluons and quarks**

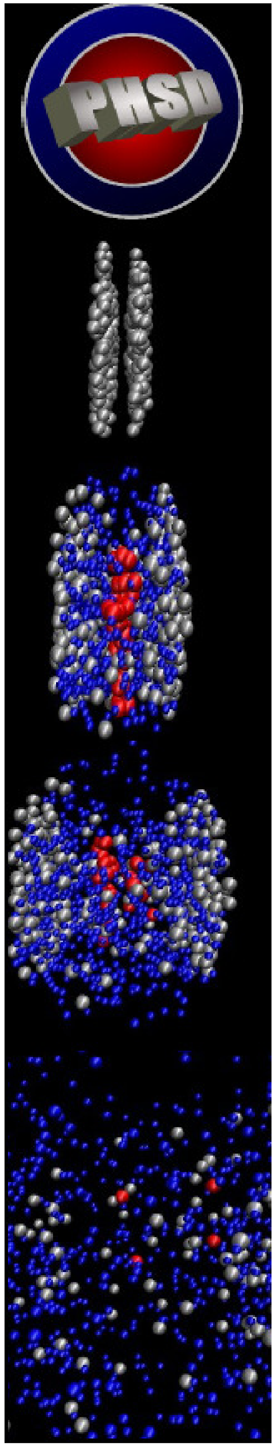


T_C=158 MeV
ε_C=0.5 GeV/fm^3

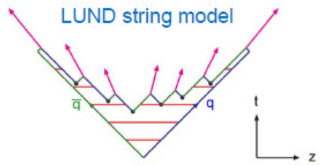


- **DQPM matches well lattice QCD**
- **DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)**
- **DQPM gives transition rates for the formation of hadrons → PHSD**

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

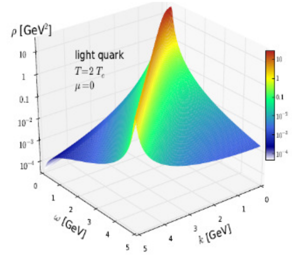


Parton-Hadron-String-Dynamics (PHSD)



- **Initial A+A collisions – HSD:**
  N+N → string formation → decay to pre-hadrons

- **Formation of QGP stage if ε > ε$_{critical}$:**
  dissolution of pre-hadrons → (DQPM) →
  → massive quarks/gluons + mean-field potential U_q



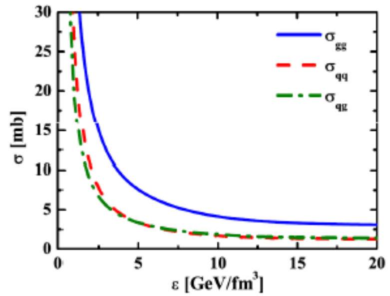
- **Partonic stage – QGP :**
  based on the Dynamical Quasi-Particle Model (DQPM)

  - (quasi-) elastic collisions:

$$q+q \to q+q \qquad g+q \to g+q$$
$$q+\bar{q} \to q+\bar{q} \qquad g+\bar{q} \to g+\bar{q}$$
$$\bar{q}+\bar{q} \to \bar{q}+\bar{q} \qquad g+g \to g+g$$

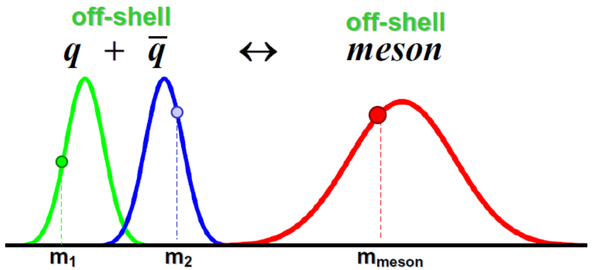
  - inelastic collisions:

$$q+\bar{q} \to g \qquad q+\bar{q} \to g+g$$
$$g \to q+\bar{q} \qquad g \to g+g$$



- **Hadronization (based on DQPM):**

$$g \to q+\bar{q}, \qquad q+\bar{q} \leftrightarrow meson \ \ (or\ 'string\ ')$$
$$q+q+q \leftrightarrow baryon \ \ (or\ 'string\ ')$$

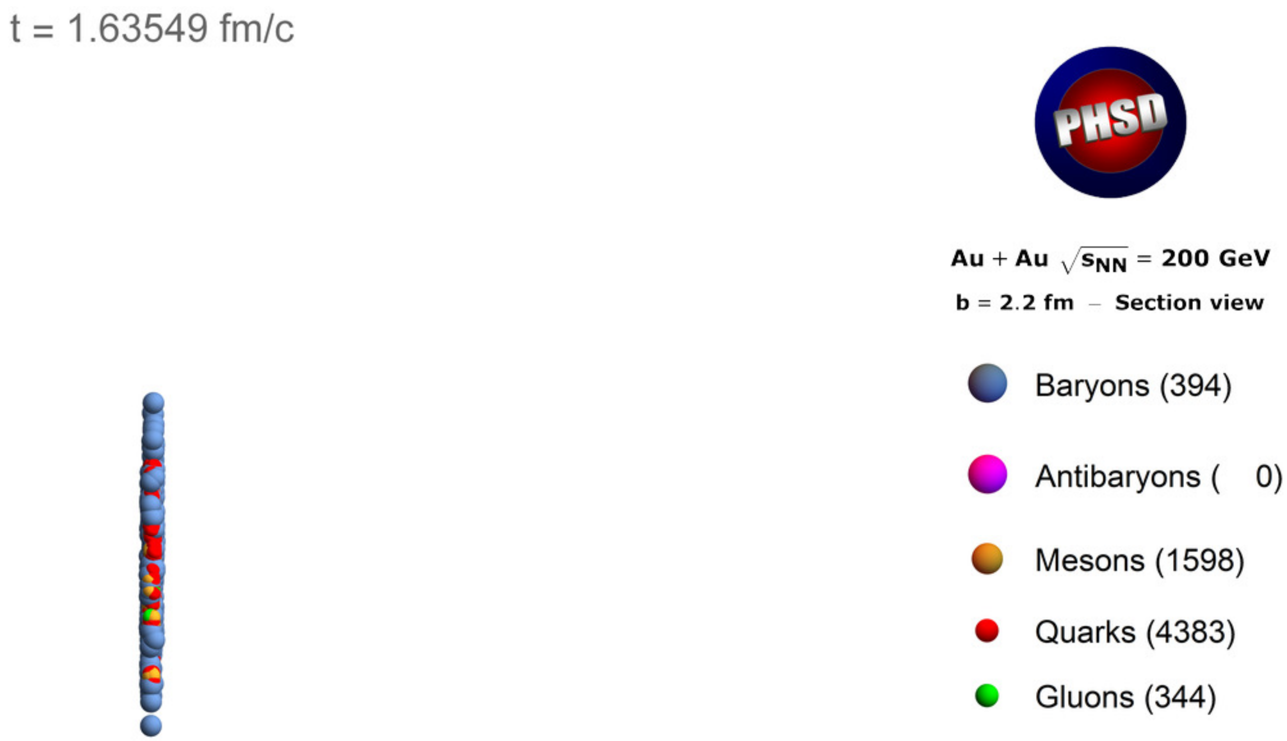


- **Hadronic phase: hadron-hadron interactions – off-shell HSD**

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

Au+Au at 200 A GeV, b=2.2 fm

Au+Au at 200 A GeV, b=2.2 fm



P.Moreau

Au+Au at 200 A GeV, b=2.2 fm

t = 2.06543 fm/c

Au + Au $\sqrt{s_{NN}}$ = 200 GeV

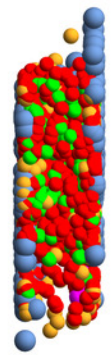
b = 2.2 fm – Section view

- Baryons (396)
- Antibaryons (2)
- Mesons (1136)
- Quarks (5066)
- Gluons (516)

P.Moreau

Au+Au at 200 A GeV, b=2.2 fm

t = 3.20258 fm/c



Au + Au $\sqrt{s_{NN}}$ = 200 GeV

b = 2.2 fm – Section view

Baryons (413)

Antibaryons (13)

Mesons (1080)

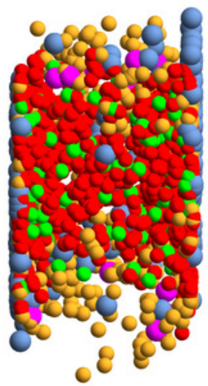
Quarks (4708)

Gluons (761)

P.Moreau

Au+Au at 200 A GeV, b=2.2 fm

t = 5.56921 fm/c



Au + Au $\sqrt{s_{NN}}$ = 200 GeV

b = 2.2 fm – Section view

Baryons (472)

Antibaryons (70)

Mesons (1724)

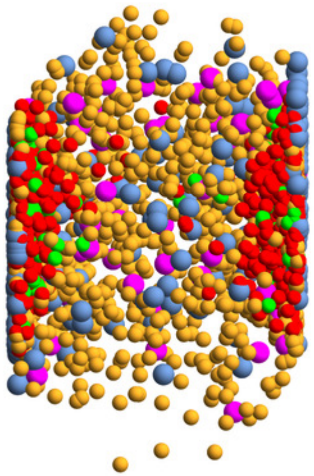
Quarks (3843)

Gluons (652)

P.Moreau

Au+Au at 200 A GeV, b=2.2 fm

t = 8.06922 fm/c



Au + Au $\sqrt{s_{NN}}$ = 200 GeV

b = 2.2 fm – Section view

Baryons (559)

Antibaryons (139)

Mesons (2686)

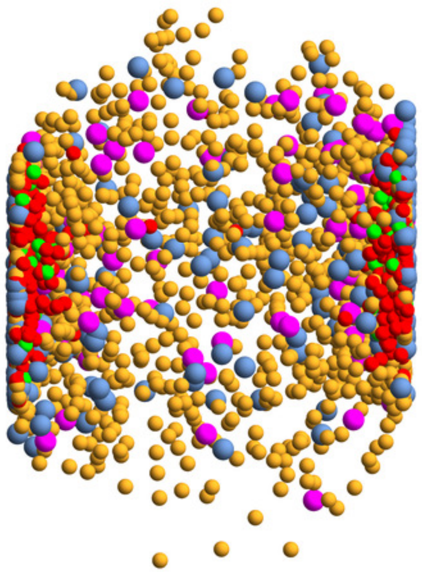
Quarks (2628)

Gluons (442)

P.Moreau

Au+Au at 200 A GeV, b=2.2 fm

t = 10.5692 fm/c



Au + Au $\sqrt{s_{NN}}$ = 200 GeV

b = 2.2 fm – Section view

Baryons (604)

Antibaryons (187)

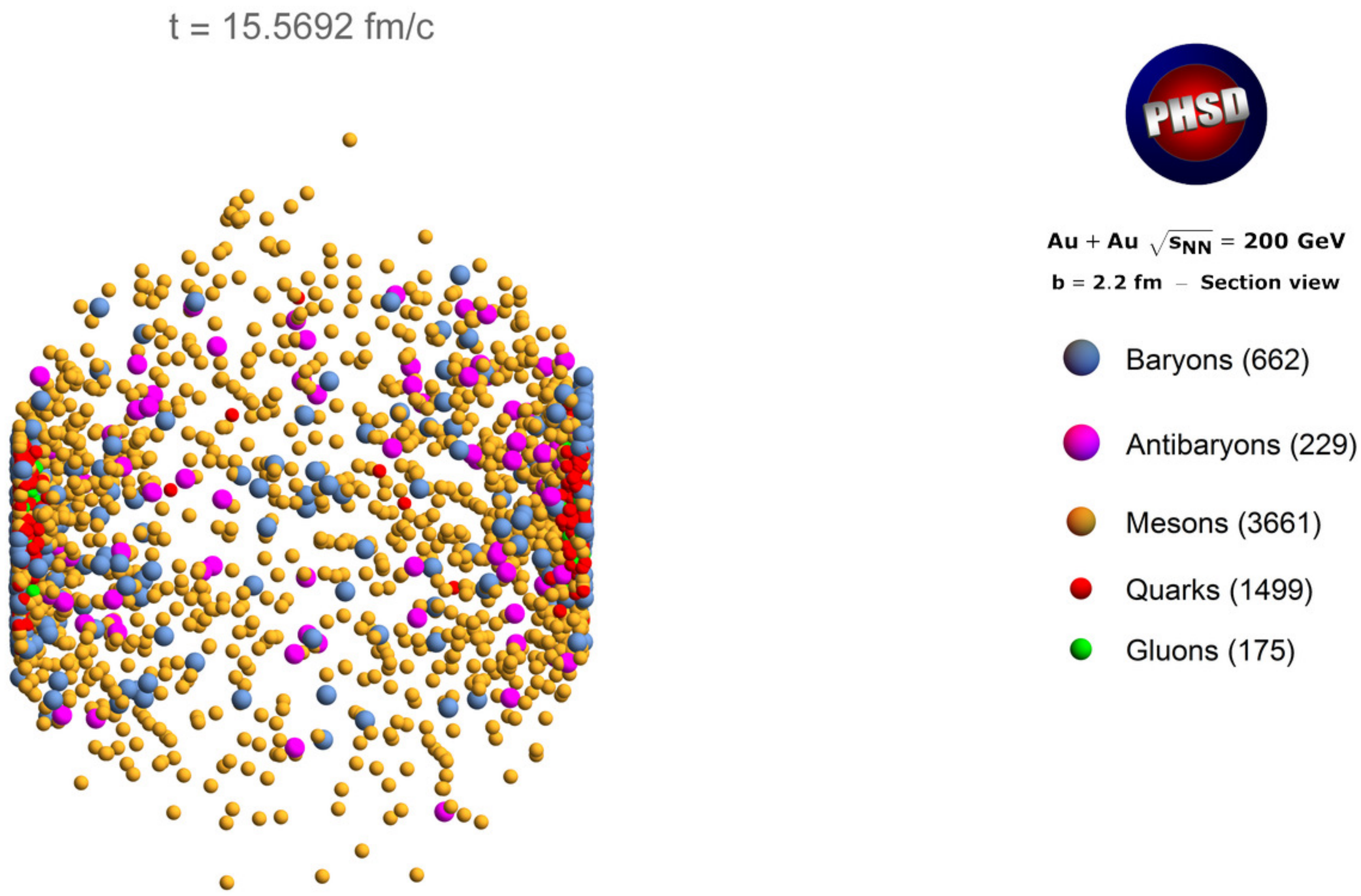
Mesons (3169)

Quarks (2076)

Gluons (319)

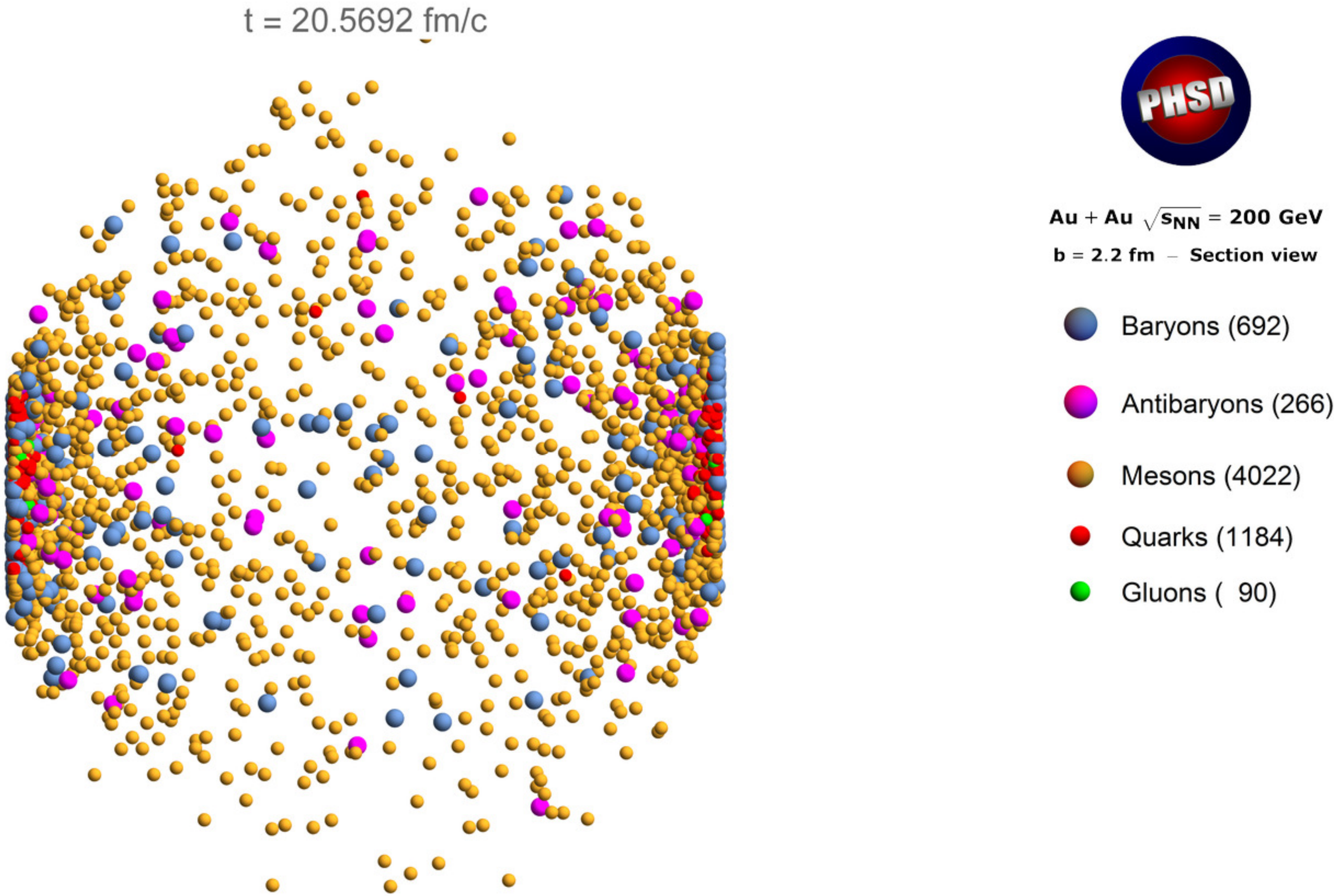
P.Moreau

Au+Au at 200 A GeV, b=2.2 fm



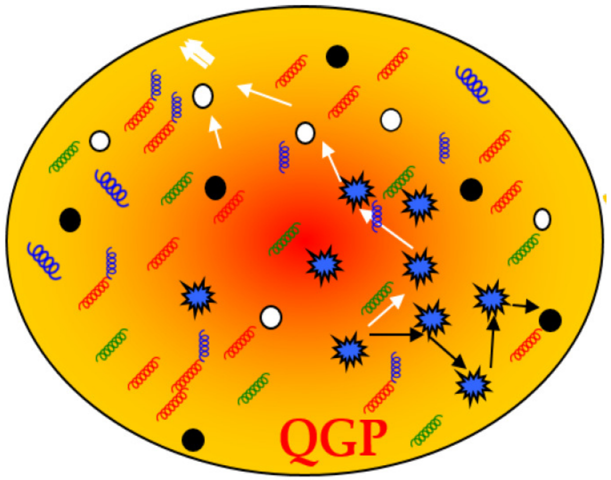
P.Moreau

Au+Au at 200 A GeV, b=2.2 fm



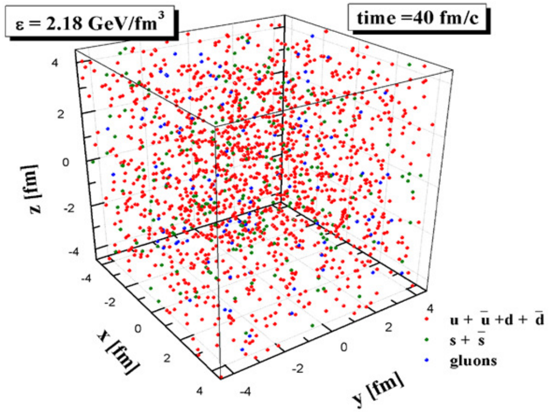
P.Moreau

Thermodynamic and transport properties of sQGP in equilibrium at finite temperature and chemical potential



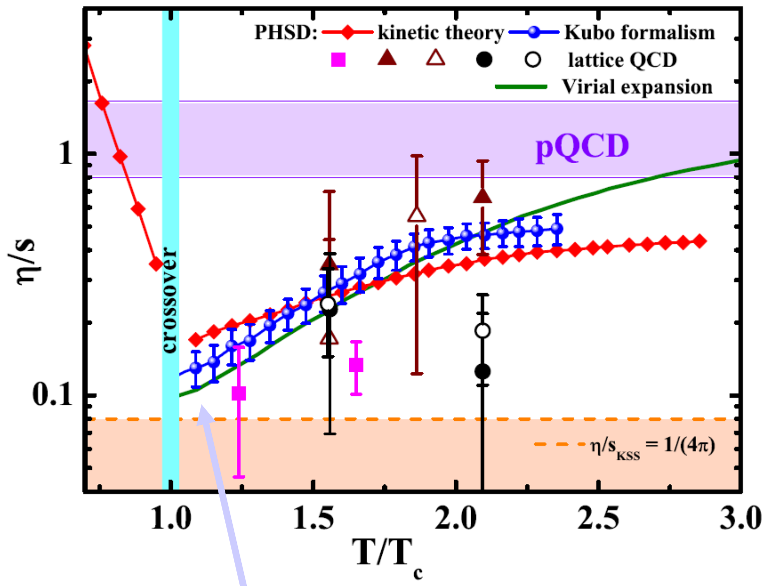
QGP in equilibrium: Transport properties at finite (T, μ_q): η/s

Infinite hot/dense matter = PHSD in a box:



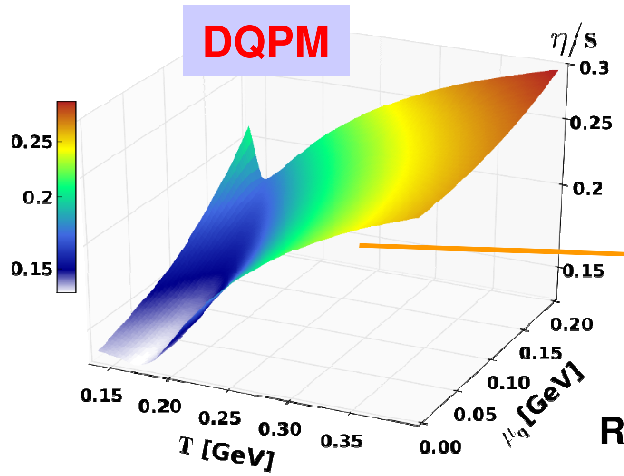
Shear viscosity η/s at finite T

V. Ozvenchuk et al., PRC 87 (2013) 064903



Shear viscosity η/s at finite (T, μ_q)

lQCD:
$$\frac{T_c(\mu_q)}{T_c(\mu_q=0)} = \sqrt{1-\alpha\,\mu_q^2} \approx 1-\alpha/2\,\mu_q^2 + \cdots$$



QGP in PHSD = strongly-interacting liquid

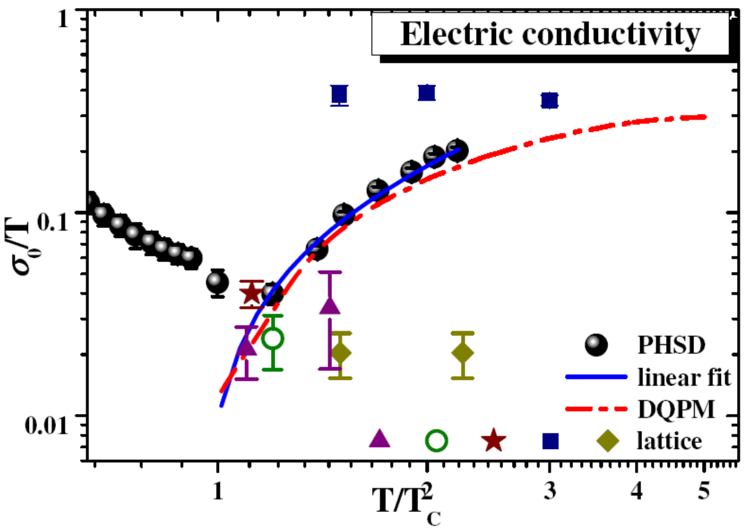
η/s: μ_q=0 ➔ finite μ_q: smooth increase as a function of (T, μ_q)

Review: H. Berrehrah et al. Int.J.Mod.Phys. E25 (2016) 1642003

Transport properties at finite (T, μ_q): σ_e/T

PHSD in a box:
Electric conductivity σ_e/T at finite T

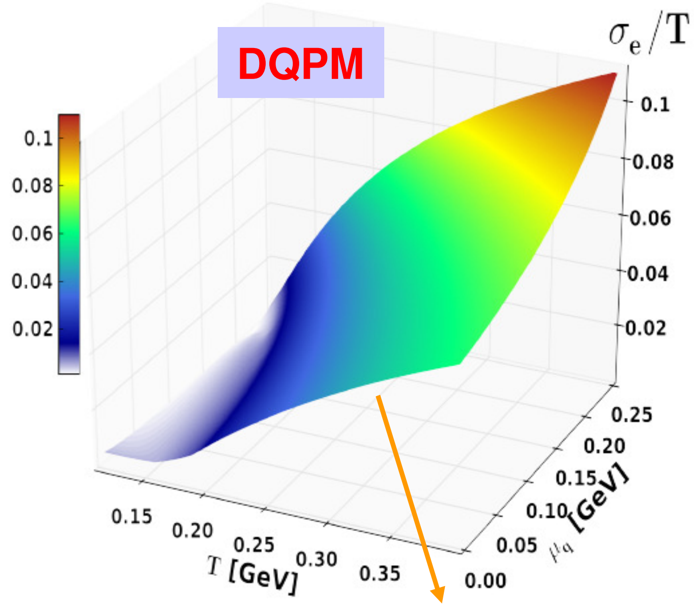
W. Cassing et al., PRL 110(2013)182301



- the QCD matter even at T~ T_c is a **much better electric conductor than Cu or Ag** (at room temperature) by a factor of 500 !

Electric conductivity σ_e/T at finite (T, μ_q)

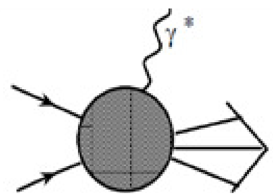
Review: H. Berrehrah et al. Int.J.Mod.Phys. E25 (2016) 1642003



σ_e/T : μ_q=0 ➔ finite μ_q: smooth increase as a function of (T, μ_q)

- **Photon emission:** rates at $q_0 \to 0$ are related to **electric conductivity σ_0**

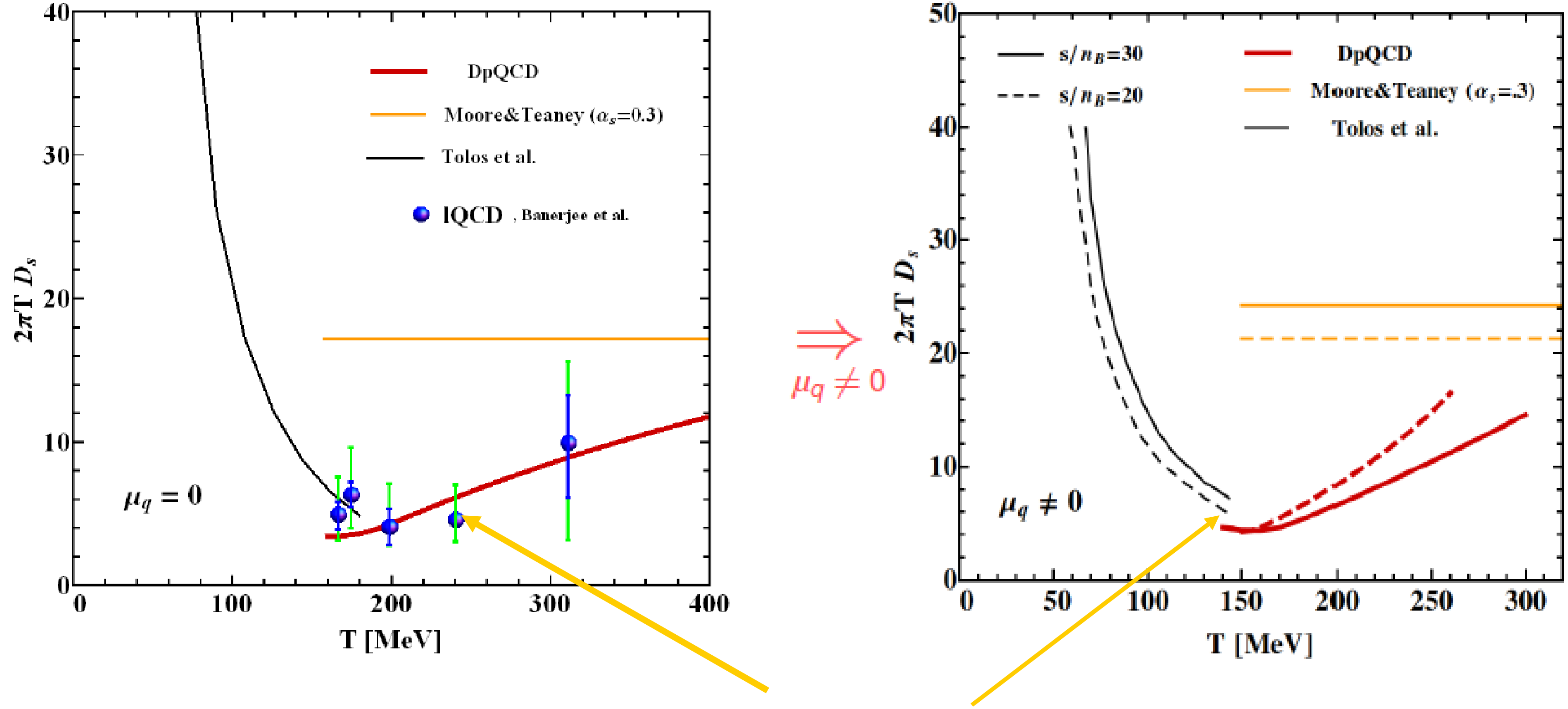
$$q_0 \frac{dR}{d^4x\, d^3q}\bigg|_{q_0 \to 0} = \frac{T}{4\pi^3}\sigma_0$$



σ_0 ➔ Probe of electric properties of the QGP

Charm spatial diffusion coefficient D_s in the hot medium

- D_s for heavy quarks as a function of T for $\mu_q=0$ and finite μ_q



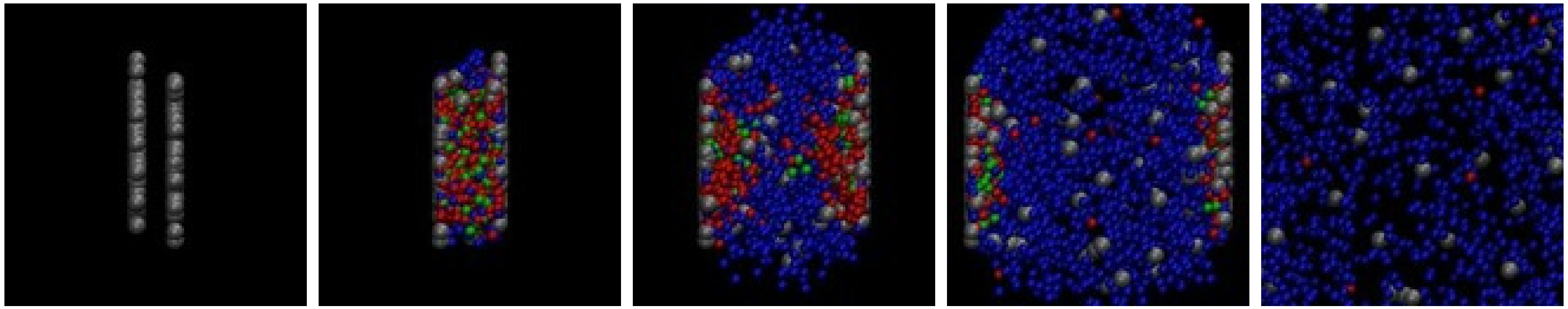
➔ Continuous transition at T_C!

❑ $T < T_c$: hadronic D_s

L. Tolos , J. M. Torres-Rincon, PRD 88 (2013) 074019
V. Ozvenchuk et al., PRC90 (2014) 054909

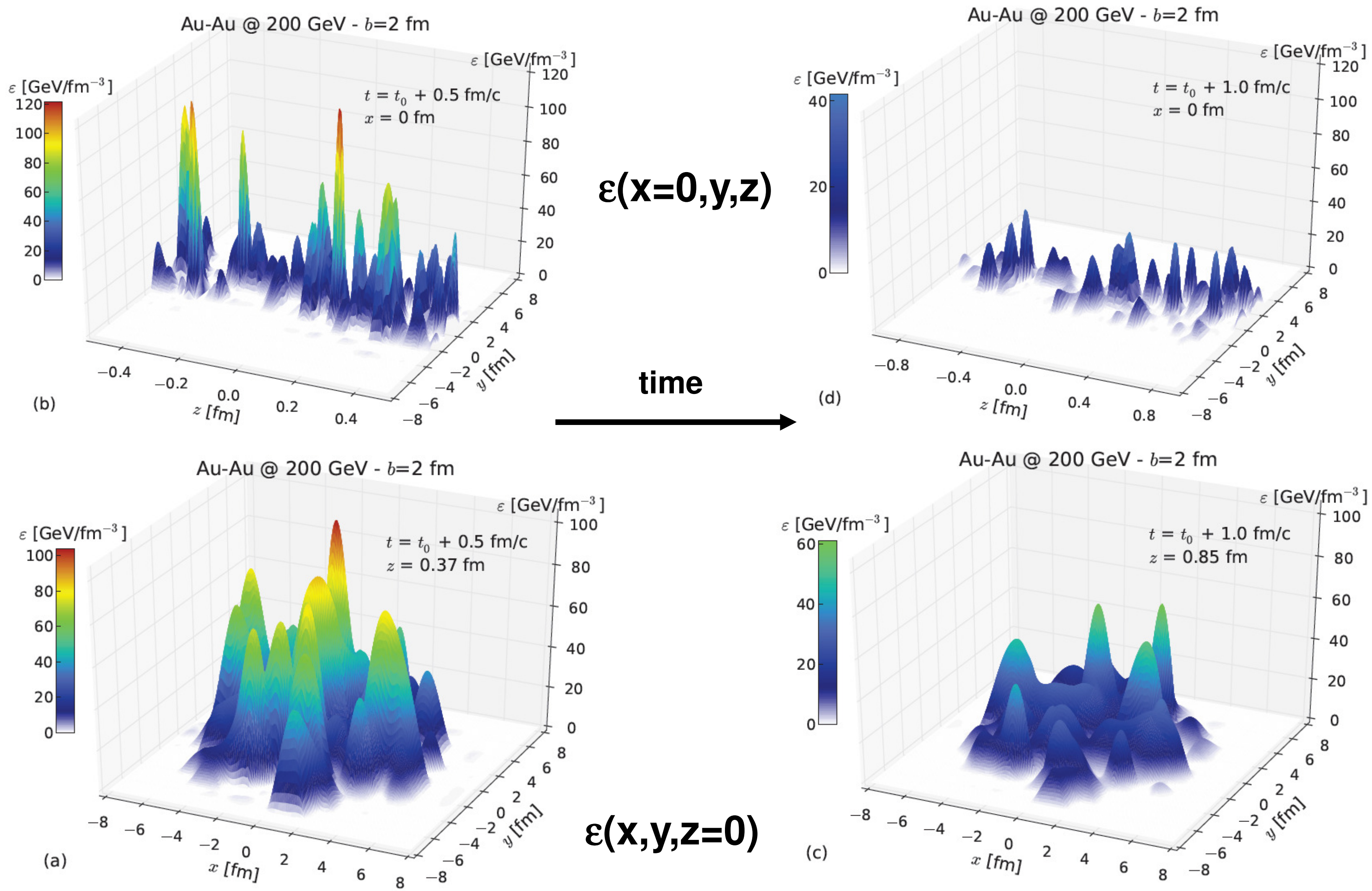
H. Berrehrah et al, PRC 90 (2014) 051901, arXiv:1406.5322

‚Bulk‘ properties in A+A



Time evolution of energy density

PHSD: 1 event Au+Au, 200 GeV, b = 2 fm

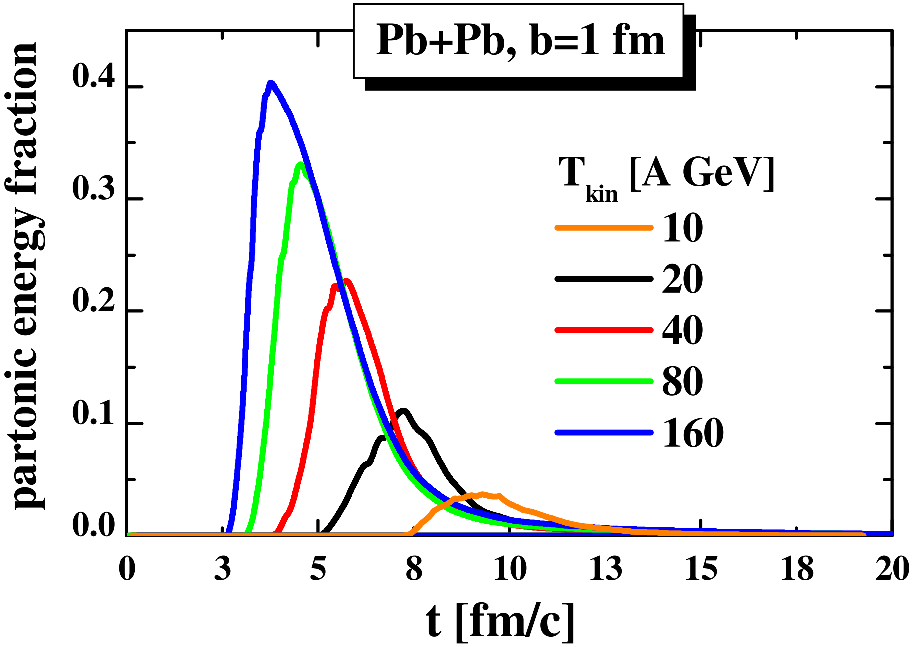


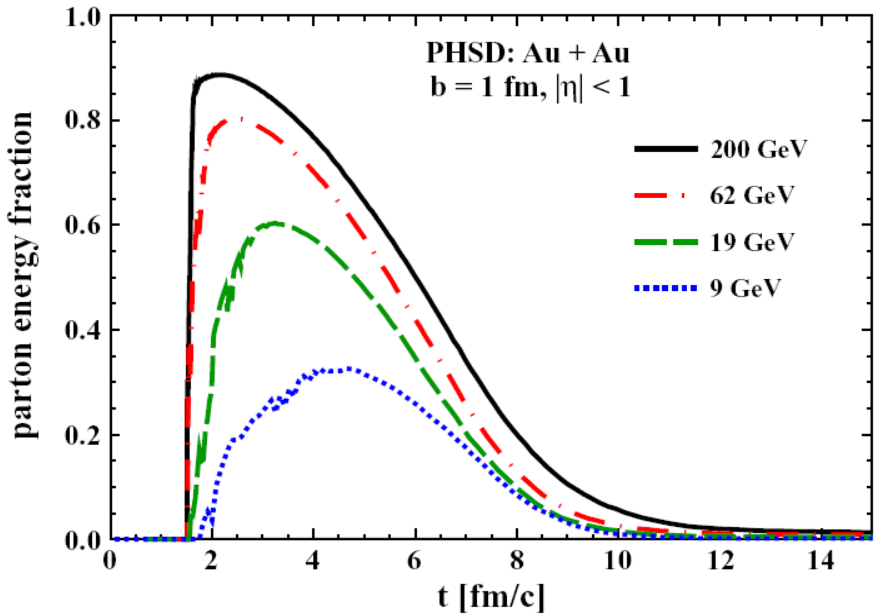
ΔV: Δx=Δy=1fm, Δz=1/γ fm

R. Marty et al, PRC92 (2015) 015201

Partonic energy fraction in central A+A

Time evolution of the partonic energy fraction vs energy

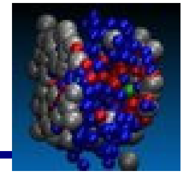




- ❑ Strong increase of partonic phase with energy from AGS to RHIC

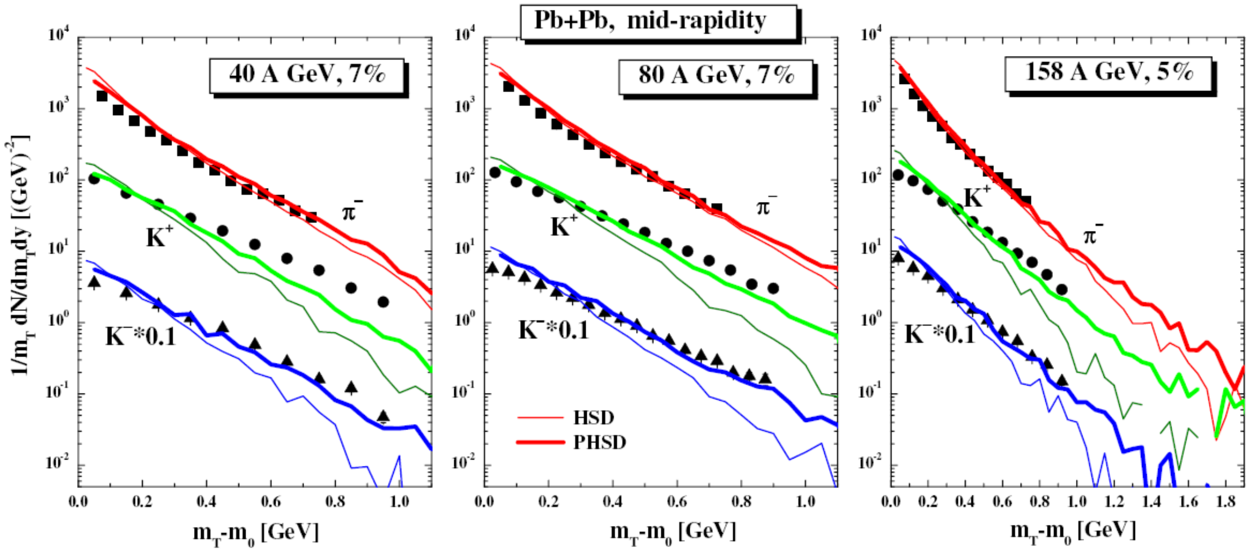
- ❑ SPS: Pb+Pb, 160 A GeV: only about 40% of the converted energy goes to partons; the rest is contained in the large hadronic corona and leading partons
- ❑ RHIC: Au+Au, 21.3 A TeV: up to 90% - QGP

W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
V. Konchakovski et al., Phys. Rev. C 85 (2012) 011902

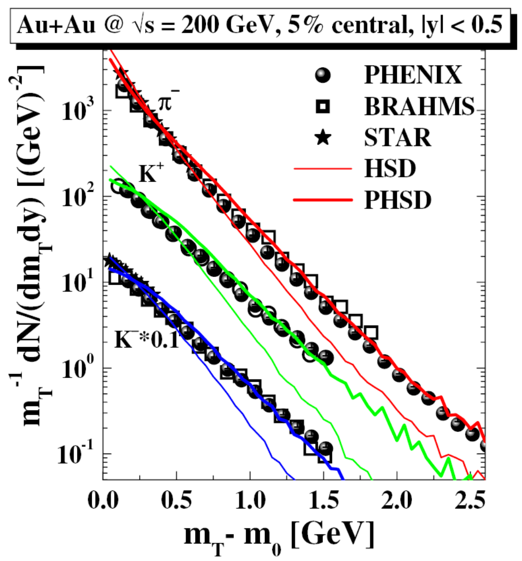


Transverse mass spectra from SPS to RHIC

Central Pb + Pb at SPS energies



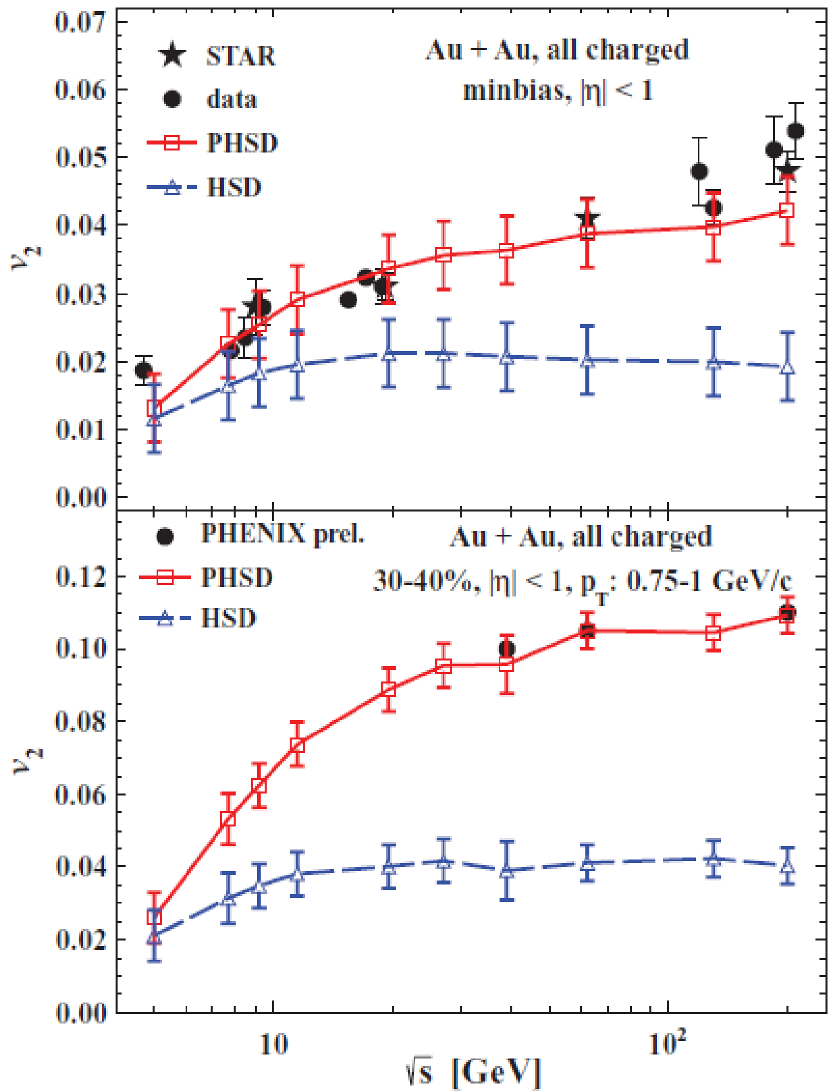
Central Au+Au at RHIC



- **PHSD gives harder m_T spectra and works better than HSD (wo QGP) 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**

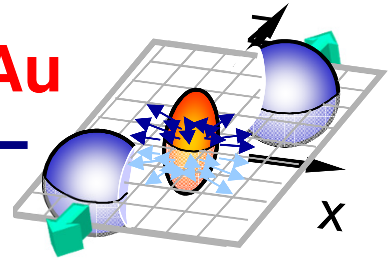
W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

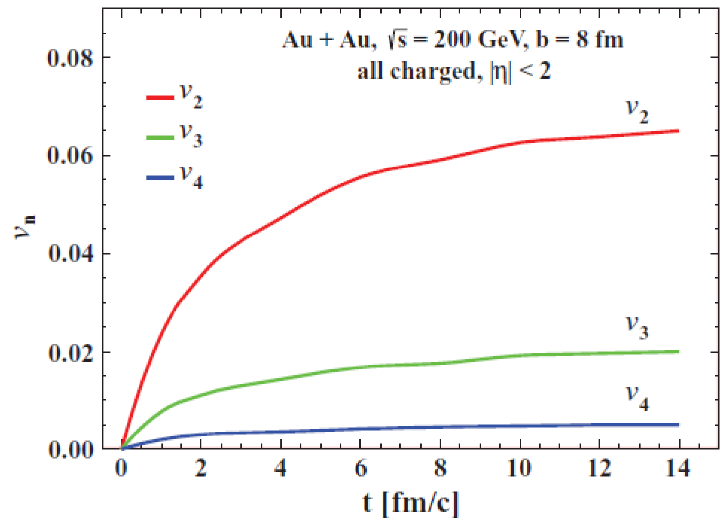
Elliptic flow v_2 vs. collision energy for Au+Au



$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \psi_n)\right]\right)$$

$$v_n = \left\langle \cos n\left(\varphi - \psi_n\right)\right\rangle, \quad n = 1, 2, 3..,$$

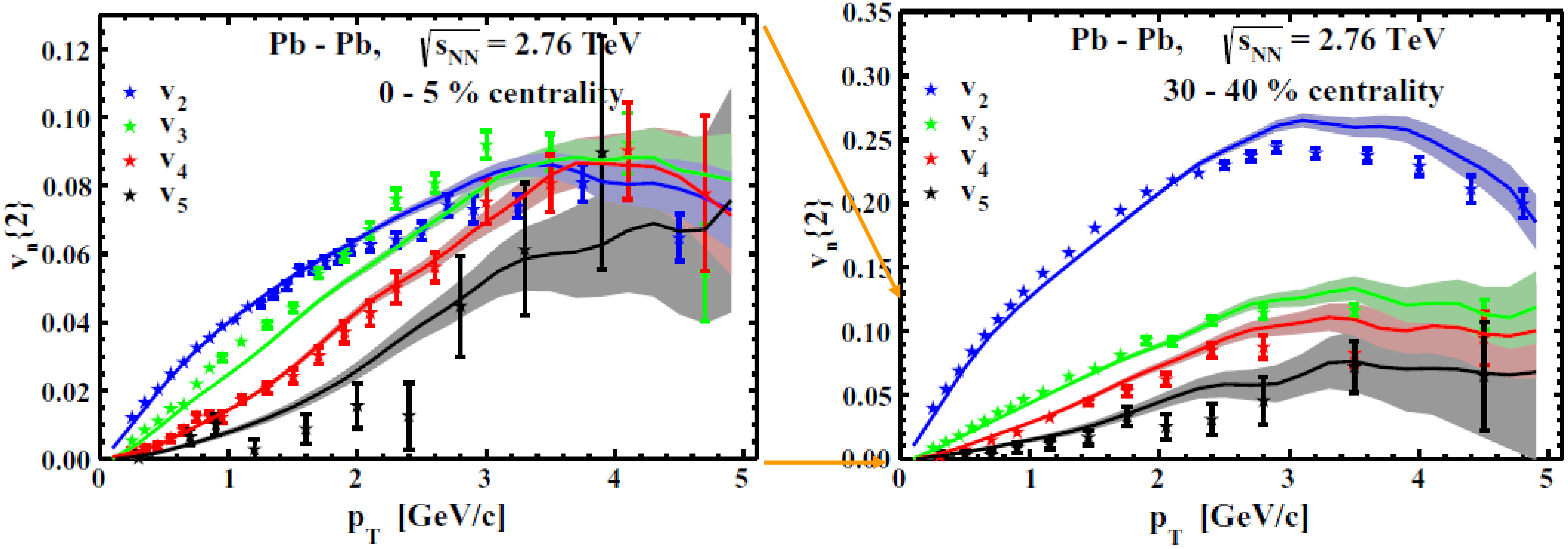




- v_2 in PHSD is larger than in HSD due to the repulsive scalar mean-field potential $U_s(\rho)$ for partons
- v_2 grows with bombarding energy due to the increase of the parton fraction

V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys. Rev. C 85 (2012) 011902

V_n (n=2,3,4,5) of charged particles from PHSD at LHC



symbols – ALICE

PRL 107 (2011) 032301

lines – PHSD (e-by-e)

- PHSD: increase of v_n (n=2,3,4,5) with p_T
- v_2 increases with decreasing centrality
- v_n (n=3,4,5) show weak centrality dependence

V. Konchakovski, W. Cassing, V. Toneev, J. Phys. G: Nucl. Part. Phys 42 (2015) 055106

Messages from the study of spectra and collective flow

- PHSD gives harder m_T spectra than HSD (without QGP) at high energies – LHC, RHIC, SPS

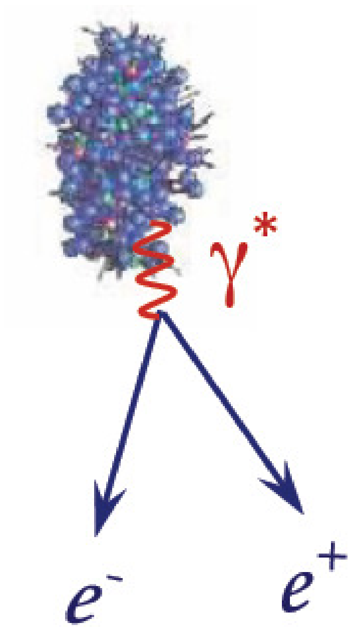
- at RHIC and LHC the QGP dominates the early stage dynamics

- at low SPS (and low FAIR, NICA) energies the effect of the partonic phase decreases (influence of the finite quark chemical potential μ_q ?!)

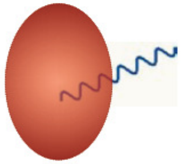
- Anisotropy coefficients v_n as a signal of the QGP:

  - quark number scaling of v_2 at ultrarelativistic energies – signal of deconfinement
  - growing of v_2 with energy – partonic interactions generate a larger pressure than the hadronic interactions
  - v_n, n=3,.. – sensitive to QGP

Electromagnetic probes of the QGP: thermal photons and dileptons



Thermal photons



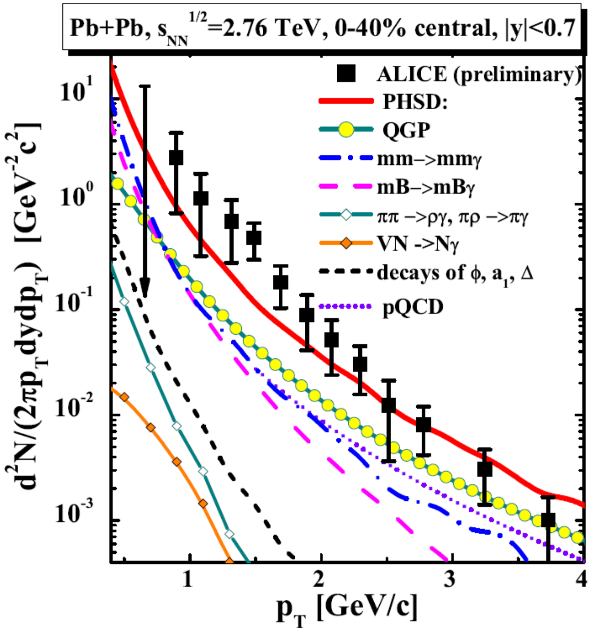
❑ **Thermal photons:**

- **QGP**
- **Hadron gas**

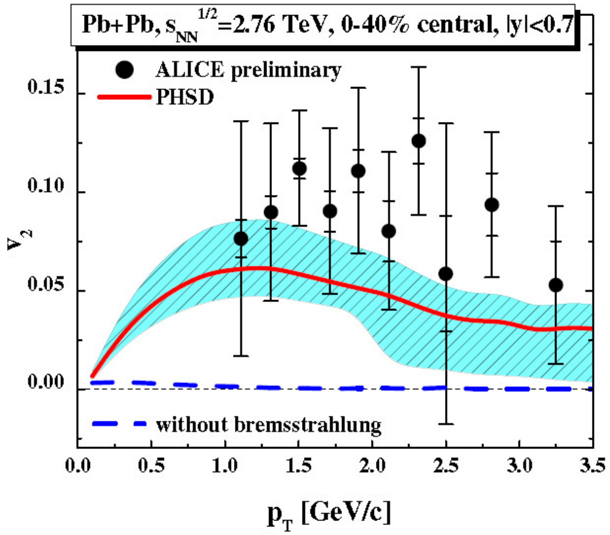
❑ **v_2 'puzzle':**

PHENIX and ALICE - exp. observation of strong elliptic flow of direct photons $v_2(\gamma^{dir}) \sim v_2(\pi)$

Problem: QGP radiation occurs at early times when flow is not yet developed ➔ theor. expected $v_2(\gamma^{QGP}) \rightarrow 0$



photon elliptic flow



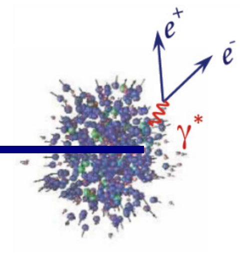
➔ **Strong elliptic flow has a hadronic origin: mm, mB bremsstrahlung and binary reactions mm→mγ**

➔ **The QGP causes the strong elliptic flow of photons indirectly, by enhancing the v_2 of final hadrons due to the partonic interactions**

➔ **LHC (similar to RHIC): PHSD: hadronic photons dominate spectra and v_2**

O. Linnyk et al., Phys. Rev. C 88 (2013) 034904; Phys. Rev. C 89 (2014) 034908

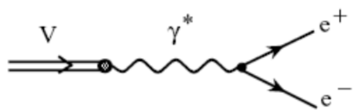
Dilepton sources



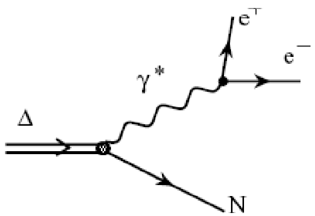
- **from the QGP via partonic (q,qbar, g) interactions:**

- **from hadronic sources:**

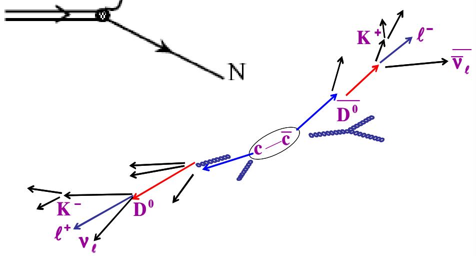
•direct decay of vector mesons (ρ,ω,φ,J/Ψ,Ψ')



•Dalitz decay of mesons and baryons (π^0,η, Δ,…)

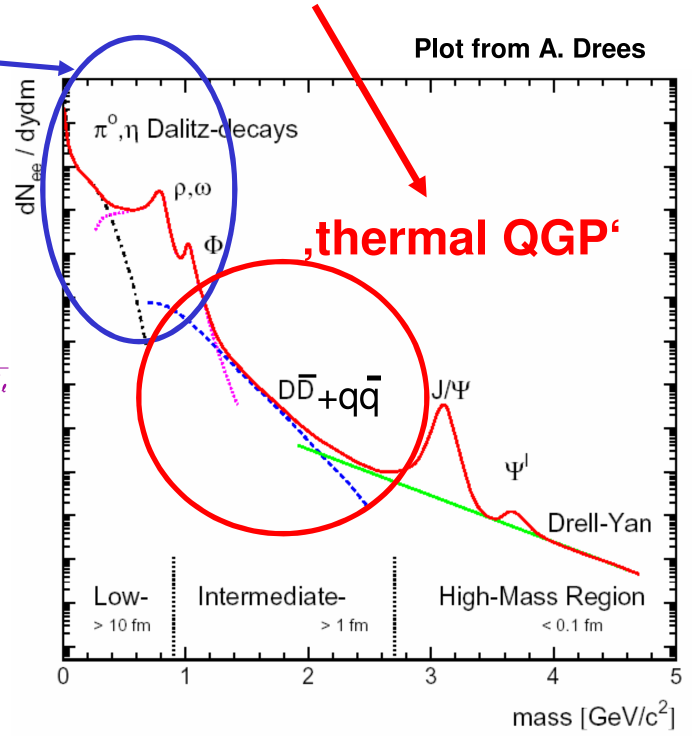


•correlated D+Dbar pairs



•radiation from multi-meson reactions ($\pi+\pi$, $\pi+\rho$, $\pi+\omega$, $\rho+\rho$, $\pi+a_1$) - ‚4π'

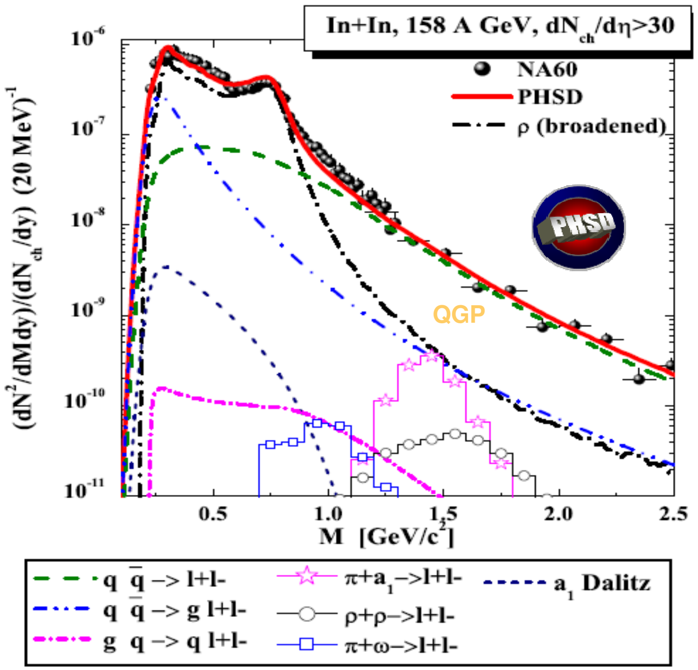
Plot from A. Drees



! Advantage of dileptons:
additional „degree of freedom" (*M*) allows to disentangle various sources

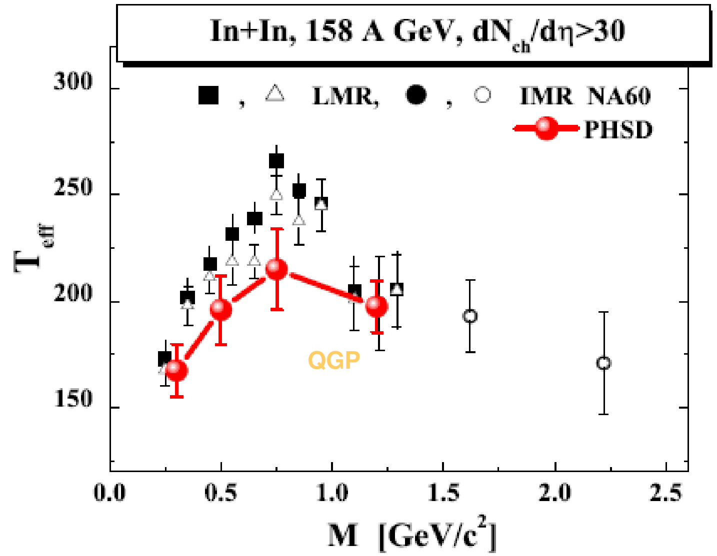
Lessons from SPS: NA60

❑ **Dilepton invariant mass spectra:**

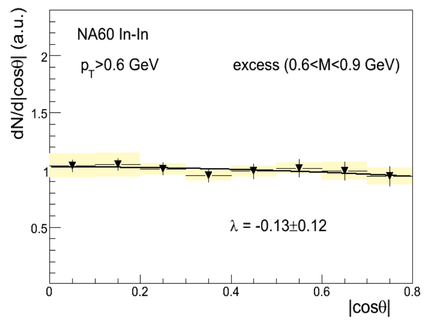


NA60: Eur. Phys. J. C 59 (2009) 607

❑ **Inverse slope parameter T_{eff}:**
spectrum from QGP is softer than from hadronic phase since the QGP emission occurs dominantly before the collective radial flow has developed



PHSD:
Linnyk et al, PRC 84 (2011) 054917

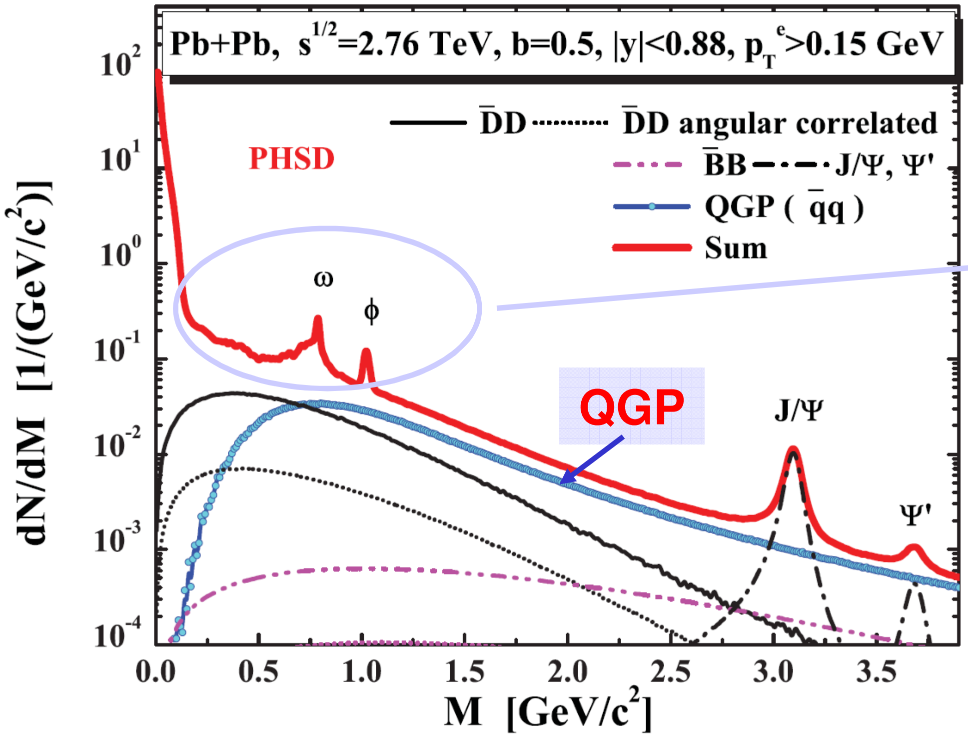


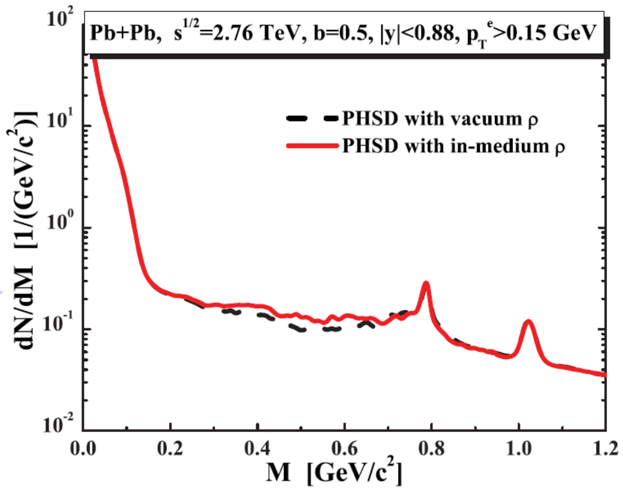
PRL 102 (2009) 222301

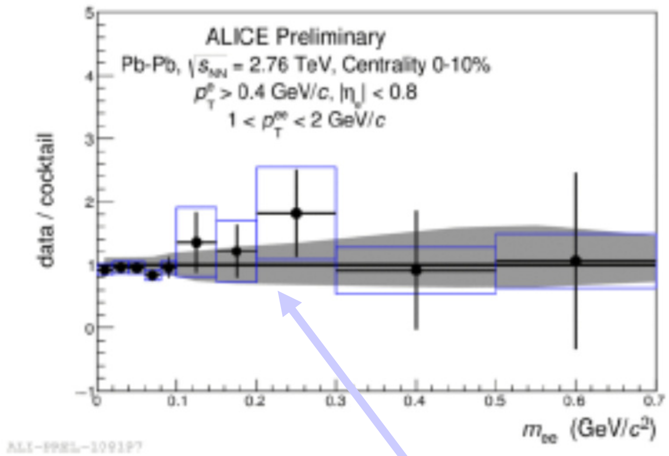
Message from SPS: (based on NA60 and CERES data)

1) Low mass spectra - evidence for the in-medium broadening of ρ-mesons
2) Intermediate mass spectra above 1 GeV - dominated by partonic radiation
3) The rise and fall of T_{eff} – evidence for the thermal QGP radiation
4) Isotropic angular distribution – indication for a thermal origin of dimuons

Dileptons at LHC







O. Linnyk, W. Cassing, J. Manninen, E.B., P.B. Gossiaux, J. Aichelin, T. Song, C.-M. Ko, Phys.Rev. C87 (2013) 014905; arXiv:1208.1279

Message:

- low masses - hadronic sources: in-medium effects for ρ mesons are small
- QGP(qbar-q) dominates at M>1.2 GeV → clean signal of QGP at LHC!

Messages from electrmagnetic probes

I. Direct photons - the photons produced in the QGP contribute up to 50% to the observed spectrum, but have small v_2

- **Large direct photon v_2 – comparable to that of hadrons – is attributed to the intermediate hadronic bremsstrahlung and hadronic scattering channels not subtracted from the data**

- **The QGP phase causes the strong elliptic flow of photons indirectly, by enhancing the v_2 of final hadrons due to the partonic interaction in terms of explicit parton collisions and the partonic mean-field potentials**

II. Dilepton spectra - according to the PHSD predictions - show sizeable changes due to the different in-medium scenarios (as collisional broadening and dropping mass) which can be observed experimentally

- **In-medium effects can be observed at all energies from SIS to LHC**
- **At SPS, RHIC and LHC the QGP (qbar-q) dominates at M>1.2 GeV**

Review: O. Linnyk et al., Prog. Part. Nucl. Phys., (2016)

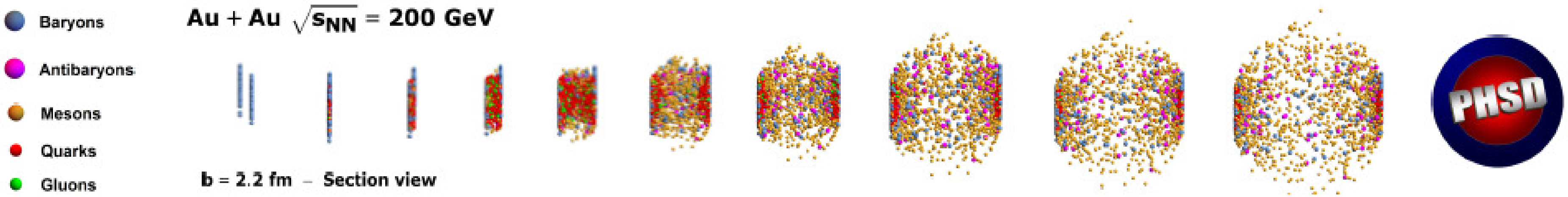
Summury

Theory versus experimental observables:

evidence for strong partonic interactions in the early phase of relativistic heavy-ion reactions

⇔ high density QCD

⇒ formation of the sQGP!



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Angel Ramos

GSI
GOETHE UNIVERSITÄT FRANKFURT AM MAIN
FIAS Frankfurt Institute for Advanced Studies
HIC for FAIR Helmholtz International Center
HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research
Bundesministerium für Bildung und Forschung
DFG Deutsche Forschungsgemeinschaft
DAAD
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN
Subatech
TEXAS A&M UNIVERSITY
JINR
UAB Universitat Autònoma de Barcelona

Thank you!


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