

# Biro's Big Bang: from RHIC to FAIR

Horst Stoecker



# Pioneering work on chemical equilibration in quark-gluon plasma

PHYSICAL REVIEW C

VOLUME 48, NUMBER 3

SEPTEMBER 1993

## Parton equilibration in relativistic heavy ion collisions

T. S. Biró,<sup>1,3</sup> E. van Doorn,<sup>1</sup> B. Müller,<sup>1</sup> M. H. Thoma,<sup>1,2</sup> and X.-N. Wang<sup>1,3</sup>

<sup>1</sup>*Department of Physics, Duke University, Durham, North Carolina 27708*

<sup>2</sup>*Institut für Theoretische Physik, Universität Giessen, D-35392 Giessen, Germany*

<sup>3</sup>*Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, California 94720*

(Received 5 March 1993)

We investigate the processes leading to phase-space equilibration of parton distributions in nuclear interactions at collider energies. We derive a set of rate equations describing the chemical equilibration of gluons and quarks including medium effects on the relevant QCD transport coefficients, and discuss their consequences for parton equilibration in heavy ion collisions.

➡ light-quark production rate in gluon-dominated plasma:

$$n_g \langle v \sigma_{gg \rightarrow q\bar{q}} \rangle \simeq 1.2 \alpha_s^2 \lambda_g T \ln \frac{1.65}{\alpha_s \lambda_g} \quad (\lambda_g = e^{\mu_g/T} \rightarrow \text{gluon fugacity})$$

# Equations of (1+1)-dimensional hydrodynamics: partons with chemical nonequilibrium

T. Biro et al (1993)

Equation of fluid dynamics in Bjorken approximation [ $\varepsilon(t, \mathbf{x}) = \varepsilon(\tau)$ ,  $\tau = \sqrt{t^2 - z^2}$ ]:  $\tau \dot{\varepsilon} + \varepsilon + p = 0$

Equation of state for massless partons in baryon-free matter:  $\varepsilon = 3p = \left( \frac{8\pi^2}{15} \lambda_g + \frac{7\pi^2 N_f}{20} \lambda_q \right) T^4$  ( $N_f = 2.5$ )

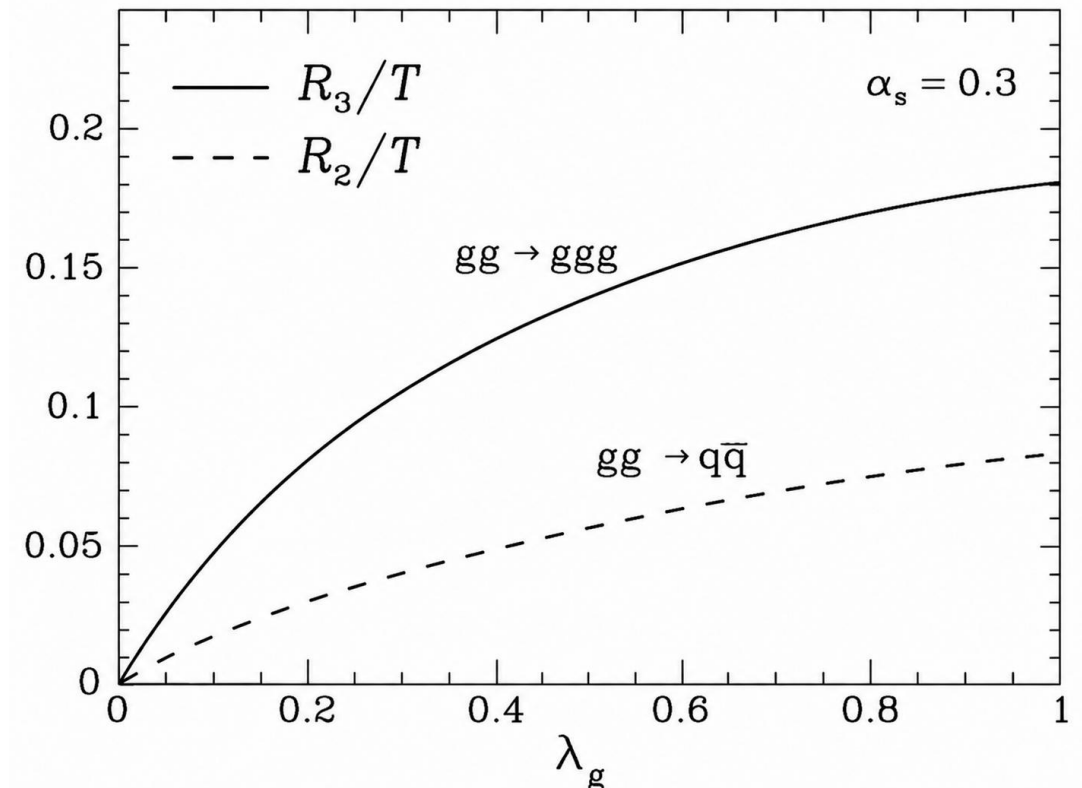
Rate equations for gluon ( $\lambda_g$ ) and (anti)quark ( $\lambda_q = \lambda_{qbar}$ ) fugacities:

$$\frac{\dot{\lambda}_g}{\lambda_g} + \frac{3\dot{T}}{T} + \frac{1}{\tau} = R_3(1 - \lambda_g) - 2R_2 \left( 1 - \frac{\lambda_q^2}{\lambda_g^2} \right)$$

$$\frac{\dot{\lambda}_q}{\lambda_q} + \frac{3\dot{T}}{T} + \frac{1}{\tau} = \frac{32}{9} R_2 \left( \frac{\lambda_g}{\lambda_q} - \frac{\lambda_q}{\lambda_g} \right)$$

- ➔ solutions for  $\lambda_g(\tau)$ ,  $\lambda_q(\tau)$ ,  $T(\tau)$
- ➔ chemical equilibrium at  $\tau \rightarrow \infty$ :  $\lambda_i \rightarrow 1$ ,  $T \propto \tau^{-1/3}$

Gluon ( $R_3$ ) and quark ( $R_2$ ) production rates:



Thermalization of gluons in ultrarelativistic heavy ion collisions by including three-body interactions in a parton cascade

Zhe Xu<sup>1,2,\*</sup> and Carsten Greiner<sup>2,†</sup>

parton cascade BAMPS:

based on the model suggested by Biro et al (1993)

→ the transport approach which includes both  $gg \leftrightarrow gg$  and  $gg \leftrightarrow ggg$  processes

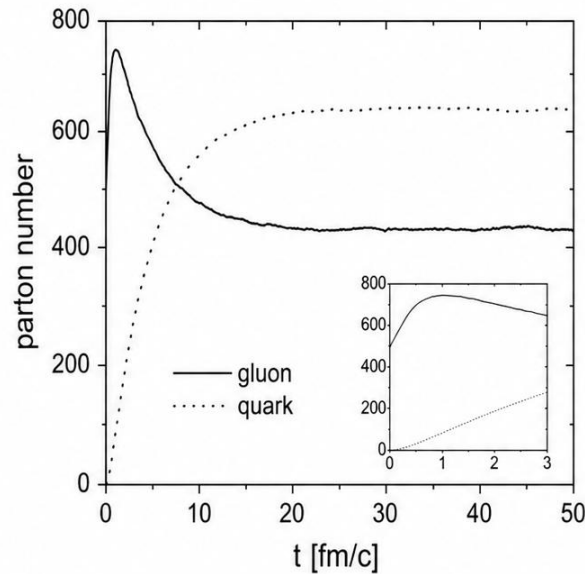


FIG. 12. Time evolution of the gluon and quark number in box calculations. We consider here gluons and quarks with two flavors.

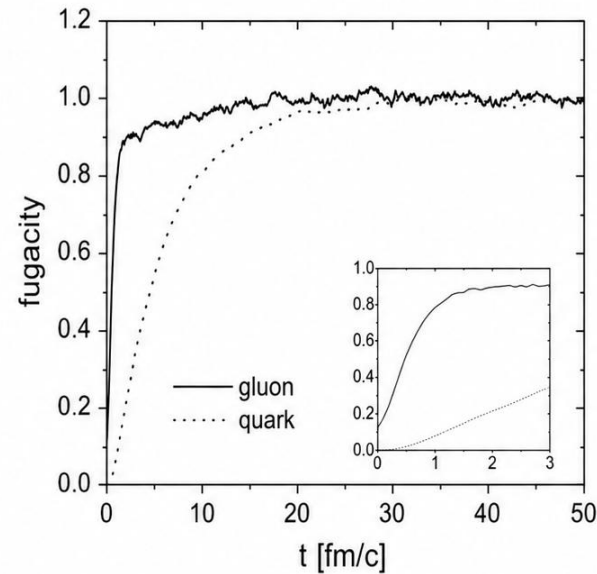


FIG. 16. Time evolution of the fugacity for gluons and quarks from the same calculation as in Fig. 12.

→ 3x3x3 fm - box calculation with initial momentum distribution of gluons expected at RHIC energy  $\sqrt{s_{NN}} = 200$  GeV

→ BAMPS: chemical equilibration time at LHC energies  $\tau_* \sim 5$  fm/c

My recent articles with Tamás



## Under-saturation of quarks at early stages of relativistic nuclear collisions: The hot glue initial scenario and its observable signatures

H. Stöcker<sup>1,2,3,\*</sup>, M. Beitel<sup>2</sup>, I. S. Bíró<sup>4</sup>, D. P. Csernai<sup>5</sup>, K. Gallmeister<sup>2</sup>, M. I. Gorenstein<sup>3,6</sup>,  
C. Greiner<sup>2</sup>, I. N. Mishustin<sup>3,7</sup>, M. Panero<sup>8</sup>, S. Raha<sup>9</sup>, L. M. Satarov<sup>3,7</sup>, S. Schramm<sup>2,3</sup>, F. Senzel<sup>2</sup>,  
B. Sinha<sup>10</sup>, J. Steinheimer<sup>3</sup>, J. Struckmeier<sup>1,3</sup>, V. Vovchenko<sup>1,3,11</sup>, Z. Xu<sup>12</sup>, K. Zhou<sup>2,3</sup>, and P. Zhuang<sup>12</sup>

<sup>1</sup> GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany

<sup>2</sup> Institut für Theoretische Physik, Goethe Universität Frankfurt, D-60438 Frankfurt Main, Germany

<sup>3</sup> Frankfurt Institute for Advanced Studies, D-60438 Frankfurt am Main, Germany

<sup>4</sup> Institute for Particle and Nuclear Physics, Wigner RCP, Budapest, Hungary

<sup>5</sup> Institute for Physics and Technology, University of Bergen, 5007 Bergen, Norway

<sup>6</sup> Bogolyubov Institute for Theoretical Physics, 03680 Kiev, Ukraine

<sup>7</sup> National Research Center “Kurchatov Institute”, 123182 Moscow, Russia

<sup>8</sup> University of Turin and INFN, Turin, Italy

<sup>9</sup> Bose Institute, Kolkata, India

<sup>10</sup> Variable Energy Cyclotron Centre, Kolkata, India

<sup>11</sup> Taras Shevchenko National University of Kiev, 03022 Kiev, Ukraine

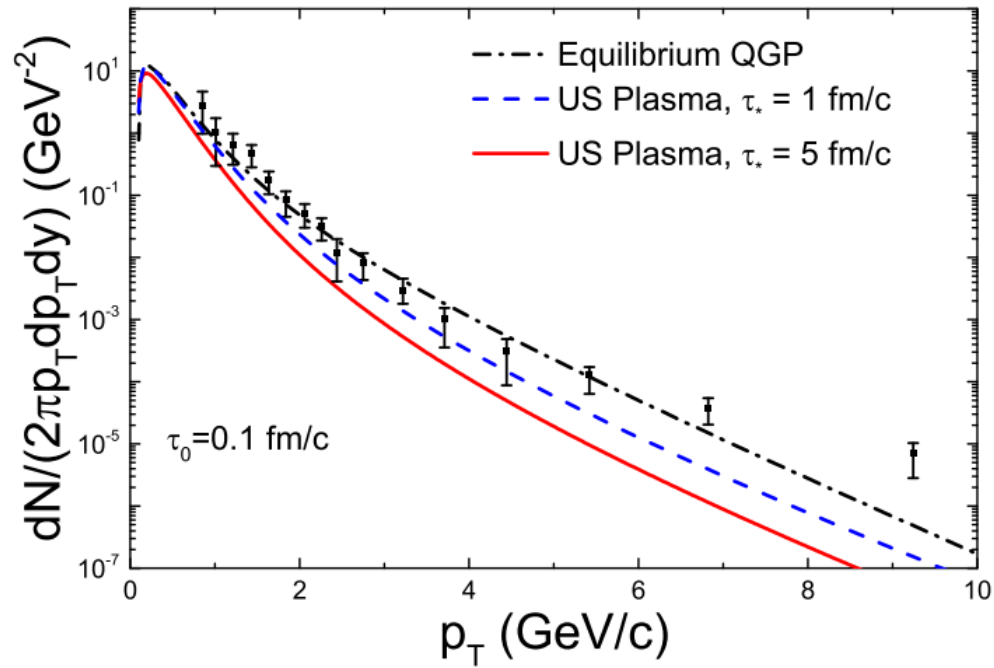
<sup>12</sup> Department of Physics, Tsinghua University, Beijing, China

Received 2015 Oct 02, accepted 2015 Oct 10

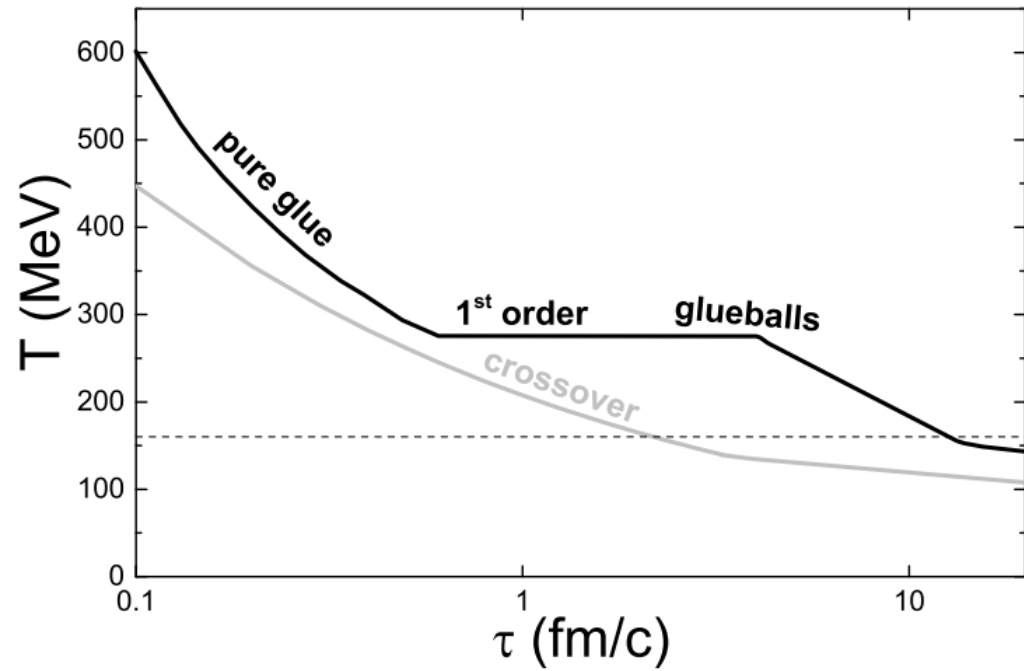
Published online 2015 Nov 20

**Key words** elementary particles – glueball – photon – quark-gluon plasma

The early stage of high multiplicity nuclear collisions is represented by a nearly quarkless, hot, deconfined pure gluon plasma. This new scenario should be characterized by a suppression of high  $p_T$  photons and dileptons as well as by reduced baryon to meson ratios. We present the numerical results for central Pb+Pb collisions at the LHC energies by using the ideal Bjorken hydrodynamics with time-dependent quark fugacity. It is shown that about 25 % of final total entropy is generated during the hydrodynamic evolution of chemically undersaturated quark-gluon plasma.



**Fig. 5** Spectrum of the thermal photons as a function of transverse momentum in central Pb+Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. The solid and dashed lines correspond, respectively, to  $\tau_* = 1$  fm/c and 5 fm/c. Dots show experimental data (Lohner et al. 2013) for 0–40 % most central events.



**Fig. 6** Schematic picture of the temperature evolution of a high-energy collision in the pure glue scenario with the Yang-Mills first order phase transition to glueballs.

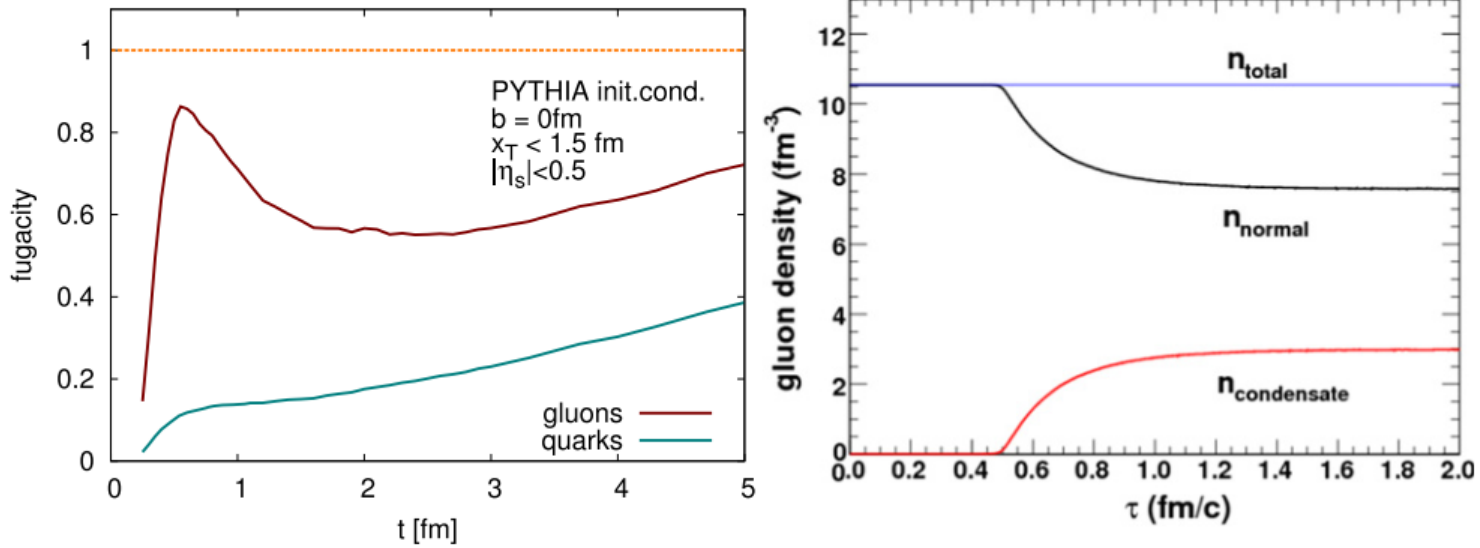
# Glueballs amass at the RHIC and LHC! The early quarkless first-order phase transition at $T = 270 \text{ MeV}$ —from pure Yang–Mills glue plasma to Hagedorn glueball states

Horst Stoecker<sup>1,2,3</sup>, Kai Zhou<sup>2,3</sup>, Stefan Schramm<sup>2,3</sup>,  
Florian Senzel<sup>2</sup>, Carsten Greiner<sup>2</sup>, Maxim Beitel<sup>2</sup>,  
Kai Gallmeister<sup>2</sup>, Mark Gorenstein<sup>3,6</sup>, Igor Mishustin<sup>3,11</sup>,  
David Vasak<sup>3</sup>, Jan Steinheimer<sup>3</sup>, Juergen Struckmeier<sup>1,3</sup>,  
Volodymyr Vovchenko<sup>1,3</sup>, Leonid Satarov<sup>3,11</sup>, Zhe Xu<sup>4</sup>,  
Pengfei Zhuang<sup>4</sup>, Laszlo P Csernai<sup>5</sup>, Bikash Sinha<sup>7</sup>,  
Sibaji Raha<sup>8</sup>, **Tamás Sándor Biró**<sup>9</sup> and Marco Panero<sup>10</sup>

<sup>1</sup> GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, D-64291 Darmstadt, Germany

<sup>2</sup> Institut für Theoretische Physik, Goethe Universität Frankfurt, Max-von-Laue Str. 1, D-60438 Frankfurt Main, Germany

<sup>3</sup> Frankfurt Institute for Advanced Studies, Ruth-Moufang-Str. 1, D-60438 Frankfurt am Main, Germany



(a) Fugacity of gluons and quarks, respectively.

(b) number density of gluons and gluon condensate in overpopulated case.

**Figure 1.** (a) Time evolution of fugacity of gluons and quarks calculated by using the Boltzmann approach to multi-parton scatterings (BAMPS). Within BAMPS, partons scatter via  $2 \leftrightarrow 2$  interactions in leading-order pQCD and via inelastic  $2 \leftrightarrow 3$  processes calculated by the improved Gunion–Bertsch approximation while considering a running coupling for each scattering evaluated at the microscopic level. The depicted time evolutions are calculated for a cylindrical tube of  $x_T < 1.5$  fm and space-time rapidity  $\eta_s < 0.5$  in Au+Au collisions with  $\sqrt{s} = 200$  AGeV and zero impact parameter. (b) Time evolution of number density of gluons and gluon condensate starting with an overpopulated initial distribution function  $f_0 = 0.4\theta(Q_s - p)$  within BAMPS box calculation.



ELSEVIER

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla



## Laser wake field collider

NAPLIFE Collaboration

István Papp<sup>a,b,\*</sup>, Larissa Bravina<sup>c</sup>, Mária Csete<sup>d</sup>, Igor N. Mishustin<sup>e,f</sup>, Dénes Molnár<sup>g</sup>,  
Anton Motorenko<sup>e</sup>, Leonid M. Satarov<sup>e</sup>, Horst Stöcker<sup>e,h,i</sup>, Daniel D. Strottman<sup>j</sup>,  
András Szenes<sup>d</sup>, Dávid Vass<sup>d</sup>, Tamás S. Biró<sup>a</sup>, László P. Csernai<sup>a,b,e</sup>, Norbert Kroó<sup>a,k</sup>

<sup>a</sup> Wigner Research Centre for Physics, Budapest, Hungary

<sup>b</sup> Dept. of Physics and Technology, University of Bergen, 5007 Bergen, Norway

<sup>c</sup> Department of Physics, University of Oslo, Norway

<sup>d</sup> Dept. of Optics and Quantum Electronics, Univ. of Szeged, Hungary

<sup>e</sup> Frankfurt Institute for Advanced Studies, 60438 Frankfurt/Main, Germany

<sup>f</sup> National Research Center "Kurchatov Institute" Moscow, Russia

<sup>g</sup> Dept. of Physics, Purdue University, West Lafayette, 47907 IN, USA

<sup>h</sup> Inst. für Theoretische Physik, Goethe Universität Frankfurt, 60438 Frankfurt/Main, Germany





<sup>i</sup> GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany

<sup>j</sup> Los Alamos National Laboratory, Los Alamos, 87545 NM, USA

<sup>k</sup> Hungarian Academy of Sciences, 1051 Budapest, Hungary



## Crater formation and deuterium production in laser irradiation of polymers with implanted nano-antennas

László P. Csernai <sup>1,2,3,4</sup> Igor N. Mishustin,<sup>3</sup> Leonid M. Satarov <sup>3</sup> Horst Stöcker <sup>3,5,6</sup> Larissa Bravina,<sup>7</sup> Mária Csete,<sup>8,9</sup>  
Judit Kámán,<sup>1,8</sup> Archana Kumari,<sup>1,8</sup> Anton Motornenko,<sup>3</sup> István Papp,<sup>1,8</sup> Péter Rácz,<sup>1,8</sup> Daniel D. Strottman,<sup>10</sup>  
András Szenes,<sup>8,9</sup> Ágnes Szokol,<sup>1,8</sup> Dávid Vass,<sup>7,9</sup> Miklós Veres,<sup>1,8</sup> Tamás S. Biró <sup>1,11</sup> and Norbert Kroó<sup>1,12</sup>  
(NAPLIFE Collaboration)

<sup>1</sup>*Wigner Research Centre for Physics, 1121 Budapest, Hungary*

<sup>2</sup>*Department of Physics and Technology, University of Bergen, 5007 Bergen, Norway*

<sup>3</sup>*Frankfurt Institute for Advanced Studies, 60438 Frankfurt am Main, Germany*

<sup>4</sup>*Csernai Consult Bergen, 5119 Ulset, Norway*

<sup>5</sup>*GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*

<sup>6</sup>*Institute für Theoretische Physik, Goethe Universität, 60438 Frankfurt am Main, Germany*

<sup>7</sup>*Department of Physics, University of Oslo, N-0316 Oslo, Norway*

<sup>8</sup>*National Research, Development and Innovation Office of Hungary, 1077 Budapest, Hungary*

<sup>9</sup>*Department of Optics and Quantum Electronics, University of Szeged, 6720 Szeged, Hungary*

<sup>10</sup>*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

<sup>11</sup>*University Babes-Bolyai, 400347 Cluj-Napoca, Romania*

<sup>12</sup>*Hungarian Academy of Sciences, 1051 Budapest, Hungary*



(Received 7 December 2022; accepted 10 July 2023; published 11 August 2023)

# Dilepton mass spectrum in partonic matter

$$\frac{dN_{l+l^-}}{dM} = \int d^4x \frac{d\Gamma_{l+l^-}}{dM}$$

$M^2 \equiv (p_+ + p_-)^2$  - invariant mass of lepton pair squared

$\frac{d\Gamma_{l+l^-}}{dM}$  - local rate of lepton pair production at space-time point  $x^\mu = (t, \vec{r})^\mu$

In thermalized matter with partonic temperature  $T = T(x)$

Rapp et al :

$$\frac{d\Gamma_{l+l^-}}{dM} \propto M^{3/2} \exp(-M/T) \quad (\text{at } T \ll M)$$

- ➡ slope of dilepton mass spectrum is sensitive to temperature (dileptons as ‘thermometer’)
- ➡ smaller slopes correspond to emission from hotter (earlier) stages

# Partonic sources of dilepton production

(in the lowest order in  $\alpha_s$ )

- Compton scattering  $A + g \rightarrow A + l^+l^-$  ( $A = q, \bar{q}$ ) ( $q = u, d, s \dots, l = e, \mu \dots$ )
- Annihilation  $q + \bar{q} \rightarrow l^+l^-, l^+l^- + g$
- Bremsstrahlung (of virtual gluons)  $A + B \rightarrow A + B + l^+l^-$  ( $B = q, \bar{q}, g$ )

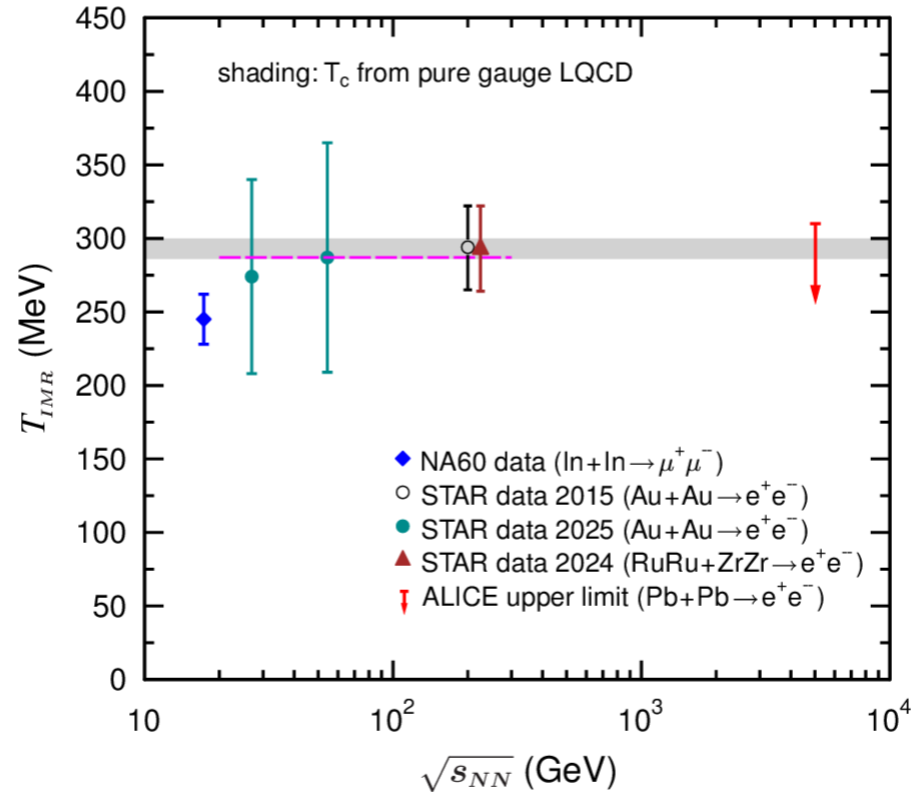
 these processes are most important in the intermediate-mass region (IMR):  $1 \lesssim M \lesssim 3 \text{ GeV}/c^2$

At larger masses charmed meson ( $J/\psi, D, \bar{D} \dots$ ) decays and Drell-Yan radiation of leading partons are important

At lower masses  $M \lesssim 1 \text{ GeV}/c^2$  hadronic sources from decays of  $\pi^0, \eta, \rho, \omega \dots$  mesons dominate

# Observed temperatures of intermediate-mass dileptons in heavy-ion collisions

Stoecker et al, arXiv: 2603.24219



$T_{IMR}$  -> from fit of dilepton spectra  
in the intermediate mass region  
(invariant masses  $M = 1-3$  GeV)

$$\frac{dN_{l+l^-}}{dM} \propto M^{3/2} \exp(-M/T_{IMR})$$

➔ saturating behavior of  $T_{IMR}$  (s) at RHIC and LHC bombarding energies (evidence of Yang-Mills FOPT?)

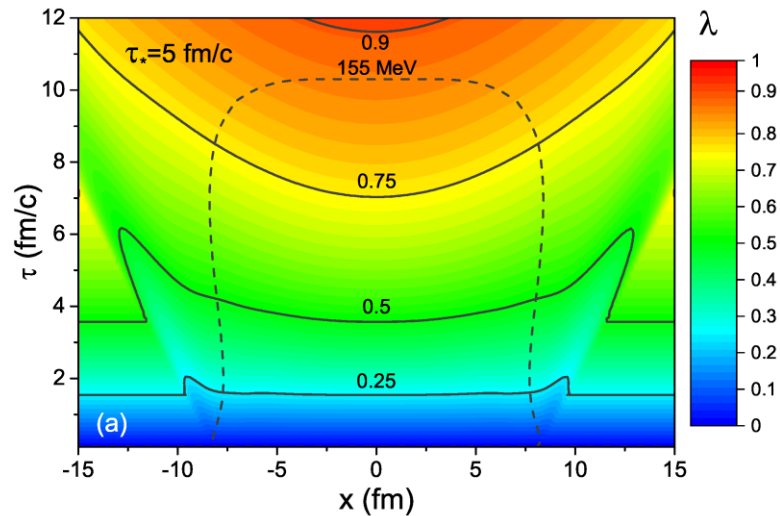
➔  $T_{IMR}$  exceed the QCD crossover temperature (156 MeV in baryon-free matter)

# Hydrodynamical model with chemical nonequilibrium: Pb+Pb central collisions at LHC energy $\sqrt{s_{NN}} = 2.76$ TeV

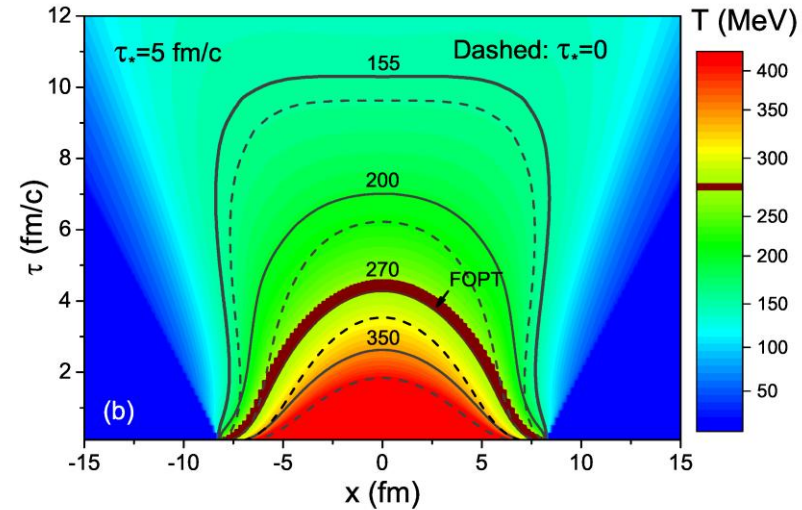
V. Vovchenko, H. Stoecker et al., Phys. Rev. C94 (2016) 024906 (2+1 hydro with Bjorken scaling in t-z variables, initial temperature profiles at  $t = \tau_0, z = 0$  from Glauber calculations)

$$\partial T^{\mu\nu} / \partial x^\nu = 0$$

quark suppression factor  $\lambda$  ( $\tau_* = 5$  fm/c)



temperature ( $\tau_* = 0$  and 5 fm/c)



contour plots  
for most central  
collisions:  
 $\tau$  - proper time  
 $x$  - radial coord.

quark suppression factor:

$$\lambda = 1 - \exp\left(-\frac{\tau_0 - \tau}{\tau_*}\right)$$

model parameter:  
quark equilibration  
time  $\tau_*$

- ➡ our model predicts larger temperatures as compared to chemically equilibrium scenario ( $\tau_* = 0$ )
- ➡ FOPT temperature  $T \approx 270$  MeV is close to the inverse slope of dilepton mass spectra observed by STAR
- ➡ deviations from chemical equilibrium survive even up to hadronization stage (at  $\tau_* \gtrsim 5$  fm/c)

We were younger 10 years ago (workshop in Hungary):



# Our colloquium in 2019 (I)



# Our colloquium in 2019 (II)



Happy Birthday, Tamás!

Backup slides:

# Experimental data on dilepton spectra in nuclear collisions - I

Effective temperatures extracted by fitting dilepton spectra in IMR:

NA60 (2009)  $\rightarrow$  In + In  $\rightarrow \mu^+ \mu^- + X$  at  $\sqrt{s_{NN}} = 17.3$  GeV  $\rightarrow T_{\text{IMR}} = 246 \pm 15$  MeV (semicentral events)

STAR (2023, 2024)  $\rightarrow$  Au + Au  $\rightarrow e^+ e^- + X$  at  $\sqrt{s_{NN}} = \begin{cases} 27 \\ 54.5 \end{cases}$  GeV  $\rightarrow T_{\text{IMR}} = \begin{cases} 280 \pm 60 \\ 300 \pm 60 \end{cases}$  MeV

Significantly smaller temperatures were extracted from dilepton spectra in the low-mass region (LMR):

$$T_{\text{LMR}} = 156 \pm 40 \text{ MeV} \quad (\text{at RHIC and SPS bombarding energies})$$

$\rightarrow$  This value is close to pseudocritical temperature obtained from LQCD for small chemical potentials

$\rightarrow$  Similar temperatures were extracted from chemical freeze-out fits of observed hadron yields

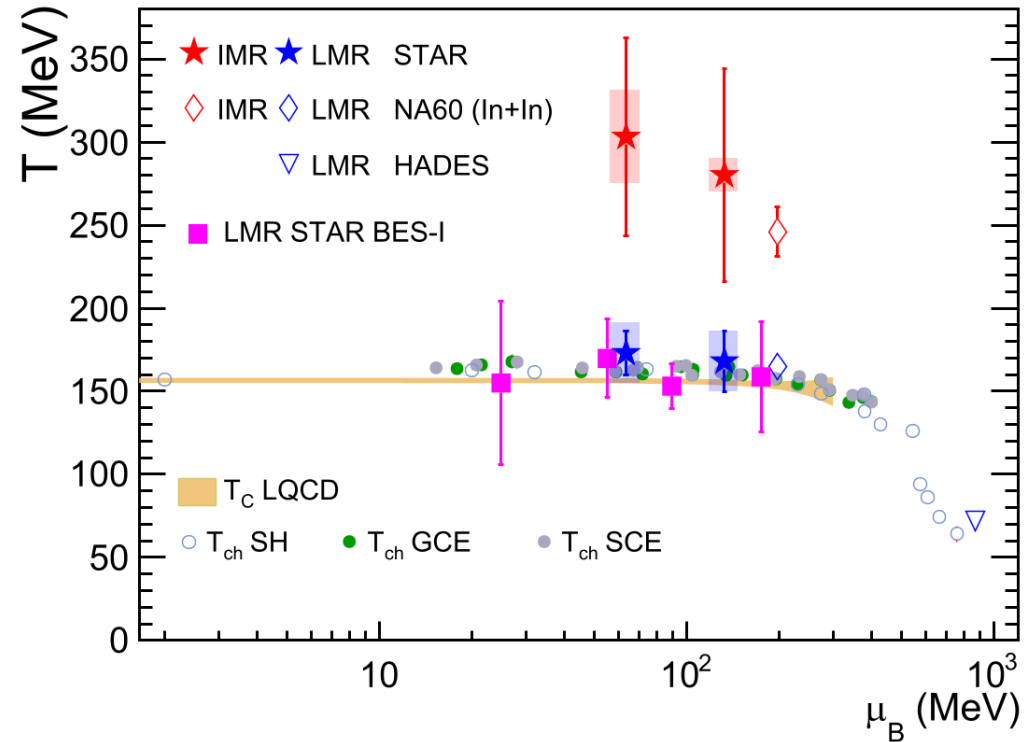
# Experimental data on dilepton spectra in nuclear collisions - II

NA60 Collab. (diamonds)  
Eur. Phys. J. C59 (2009)

STAR Collab. (squares)  
Phys. Rev. C107 (2023)

STAR Collab. (stars)  
arXiv: 2402.01998

HADES Collab. (triangle)  
Nature Phys. 15 (2019)  
(Au+Au at  $\sqrt{s_{NN}} = 2.42$  GeV)



$\mu_B$  – baryon chemical potential

positions of open and full circles are obtained from chemical freeze-out analysis of hadronic yields



STAR and NA60 thermal fits:  $T_{IMR} > T_{LMR}$

# Energy-momentum tensor of chemically nonequilibrated QGP

V. Vovchenko, H. Stoecker et al., Phys. Rev. C94 (2016) 024906 - 2+1 hydro for Pb+Pb at  $\sqrt{s_{NN}} = 2.76$  TeV  
 → w/o dissipation ( $\eta/s=0$ ) and net baryon asymmetry ( $n_q = n_{qbar}$ )

$$T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu} \quad (u^\mu - \text{fluid four-velocity})$$

The energy density ( $\varepsilon$ ) and pressure ( $P$ ) are calculated by introducing the quark suppression factor  $\lambda$ :

$$\begin{pmatrix} \varepsilon \\ P \end{pmatrix} = \lambda \begin{pmatrix} \varepsilon \\ P \end{pmatrix}_{\text{FQ}} + (1 - \lambda) \begin{pmatrix} \varepsilon \\ P \end{pmatrix}_{\text{PG}} \quad (0 \leq \lambda \leq 1)$$

where  $\varepsilon_i$  and  $P_i$  correspond to **pure glue** ( $i=\text{PG}$ ) and **full QCD** ( $i=\text{FQ}$ ) phases (functions of temperature)

We parametrize  $\lambda$  by function of local proper time  $\tau$  (for each fluid element)

$$\tau = \tau(\eta, r_\perp)$$

$$\lambda = 1 - \exp\left(-\frac{\tau_0 - \tau}{\tau_*}\right)$$

It is assumed that there were no quarks initially ( $\lambda=0$  at  $\tau=\tau_0=0.1$  fm/c)

where  $\tau_*$  - quark equilibration time

→ model parameter, chosen in the interval 0-5 fm/c

(PG limit:  $\tau_* \rightarrow \infty$ )

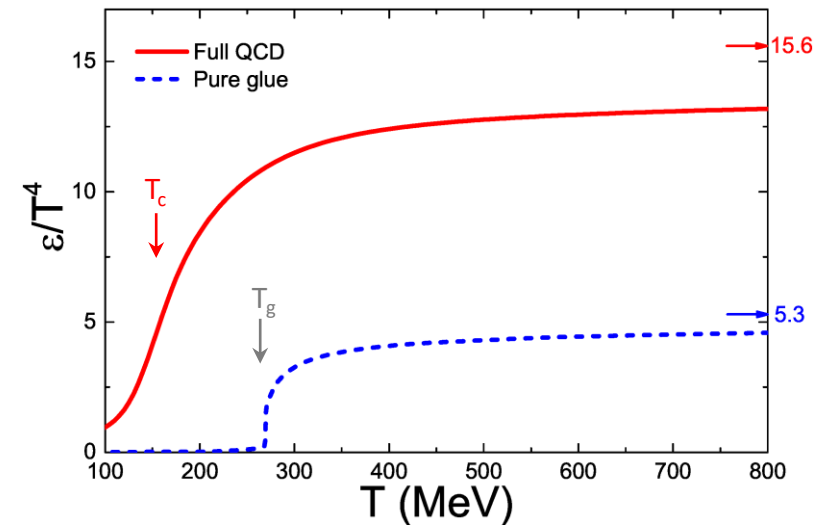
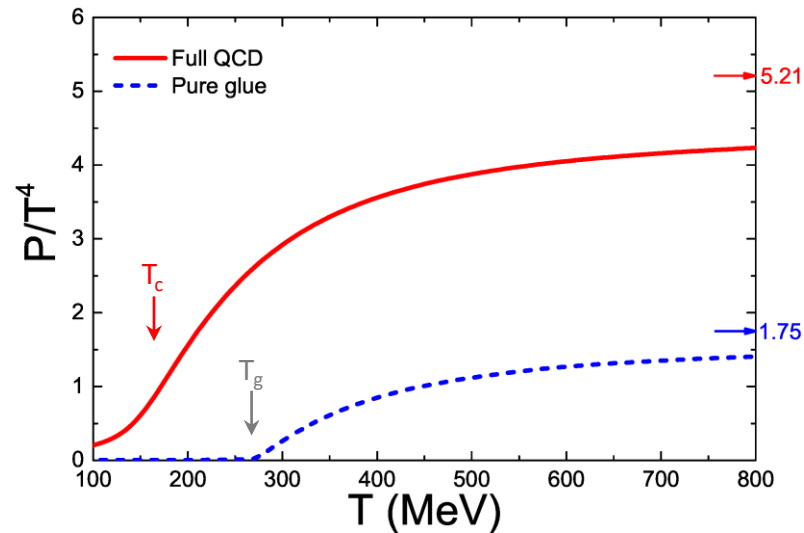
# LQCD results for pure glue (PG) and full QCD (FQ) matter

PG ( $N_f=0$ ): G. Boyd et al., Phys. Rev. Lett. 75 (1995) 4169

→ FOPT at  $T=T_g \approx 270$  MeV

FQ ( $N_f=2+1, \mu_B=0$ ): S. Borsanyi et al., Phys. Lett. B730 (2014) 99

→ crossover at  $T \sim T_c = 155$  MeV



discontinuity  
of  $\varepsilon_{PG}$  at  $T=T_g$

→ larger values of pressure ( $P$ ) and energy density ( $\varepsilon$ ) in FQ calculation due to  $q$ - $\bar{q}$  contribution

→ small  $P$  and  $\varepsilon$  values in PG matter at  $T < T_g$  due to large masses of glueballs (confined states of gluons)