

Probing the High Energy Frontier at the LHC

Part III: Heavy-Ion Physics with ALICE

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- 2 Thermodynamics of the QGP (K. Reygers)
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- 6 Collective Flow (K. Schweda)

Books (I)

Heavy-Ions

Introduction to High-Energy Heavy-Ion Collisions

Cheuk-Yin Wong

World Scientific

**K. Yagi, T. Hatsuda, and Y. Miake, Quark-Gluon Plasma
(Cambridge Monographs, ed. T. Ericson, P.V. Landshoff)**

ISBN 0-521-56108-6

R. Vogt

Ultrarelativistic Heavy-Ion Collisions (Elsevier)

ISBN 978-0-444-52196-5

Quark Gluon Plasma 3

(World Scientific Publishing, ed. R.C. Hwa and X.-N. Wang)

ISBN 981-238-077-9

The Large Hadron Collider, Nature 448 (2007) 269

1. Introduction

Strong Interaction

- **Confinement:**
Isolated quarks and gluons cannot be observed, only color-neutral hadrons
- **Asymptotic freedom:**
Coupling α_s between color charges gets weaker for high momentum transfers, i.e., for small distances
(Perturbative methods applicable for $r < 1/10$ fm)
- Limit of low particle densities and weak coupling experimentally well tested (\rightarrow QCD perturbation theory)
- **Nucleus-Nucleus collisions: QCD at high temperatures and density („QCD thermodynamics“)**



Nobel prize in physics (2004)



David J. Gross



H. David Politzer



Frank Wilczek

Ultrarelativistic Heavy-Ion Physics

Basic, childlike questions addressed in ultrarelativistic heavy-ion physics:

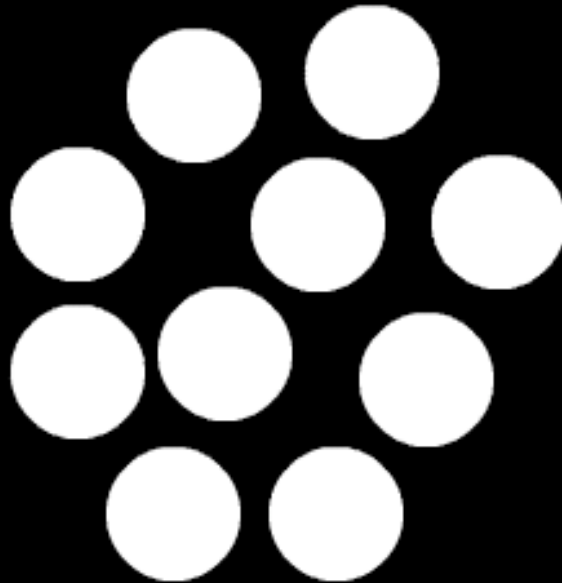
What happens to matter if you make it

- hotter and hotter?
- denser and denser?

With increasing temperature T :

solid \rightarrow liquid \rightarrow gas \rightarrow plasma \rightarrow QGP

Quark-Gluon-Plasma

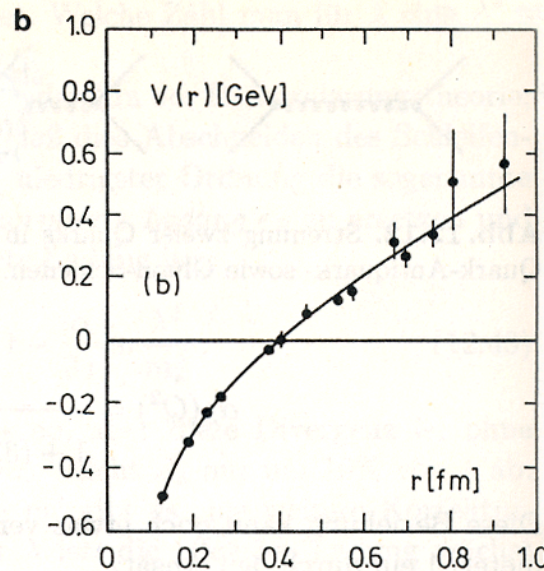
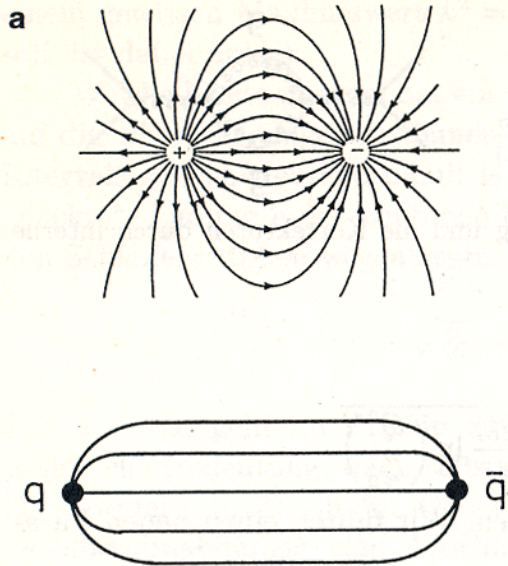


Confinement

$$\text{Quark potential: } V(r) = -\frac{4}{3} \frac{\alpha_s(r) \hbar c}{r} + k \cdot r$$

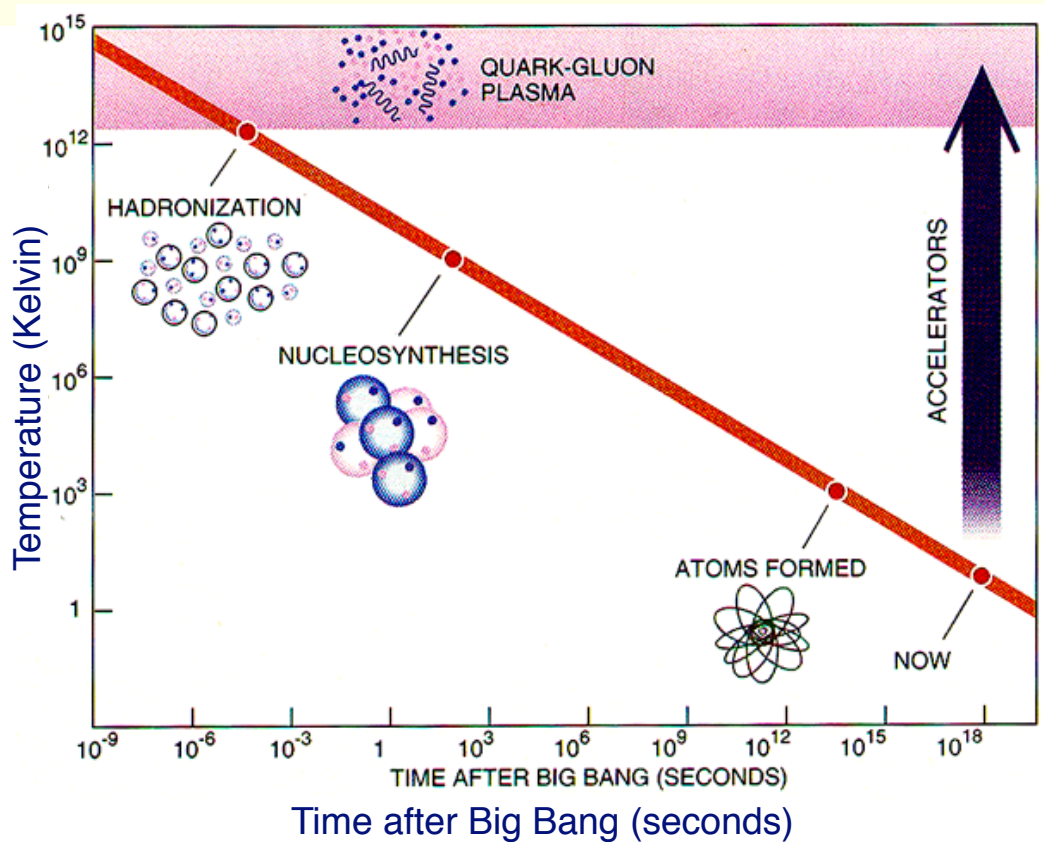
Dominant at small distances
(1-gluon exchange)

Dominant at large distances
(related to confinement)



The long distance term $k \cdot r$ is expected to disappear in the QGP

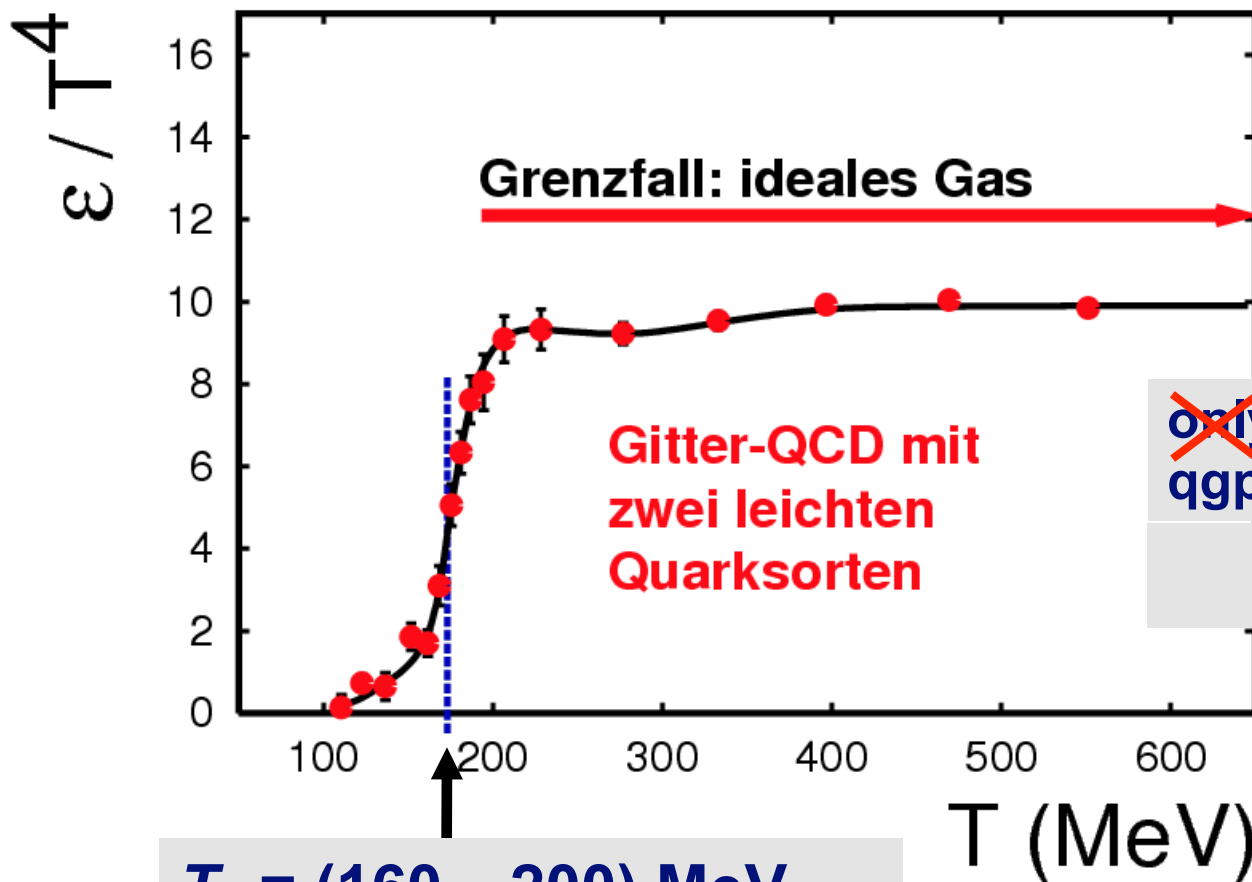
Nucleus-Nucleus Collisions: „Mini Big Bang in the Laboratory“



- Transition from the Quark-Gluon Plasma to a gas of hadrons at $\sim 10^{12} \text{ }^\circ\text{C}$
- 100 000 hotter than the core of the sun
- Early universe: QGP \rightarrow hadron gas a few microseconds after the Big Bang

Predictions from First Principles: Lattice QCD

F. Karsch, E. Laermann, hep-lat/0305025



2 quark flavors:

$$\epsilon_{\text{SB}} = g \cdot \frac{\pi^2}{30} \cdot T^4$$

with $g = 37$

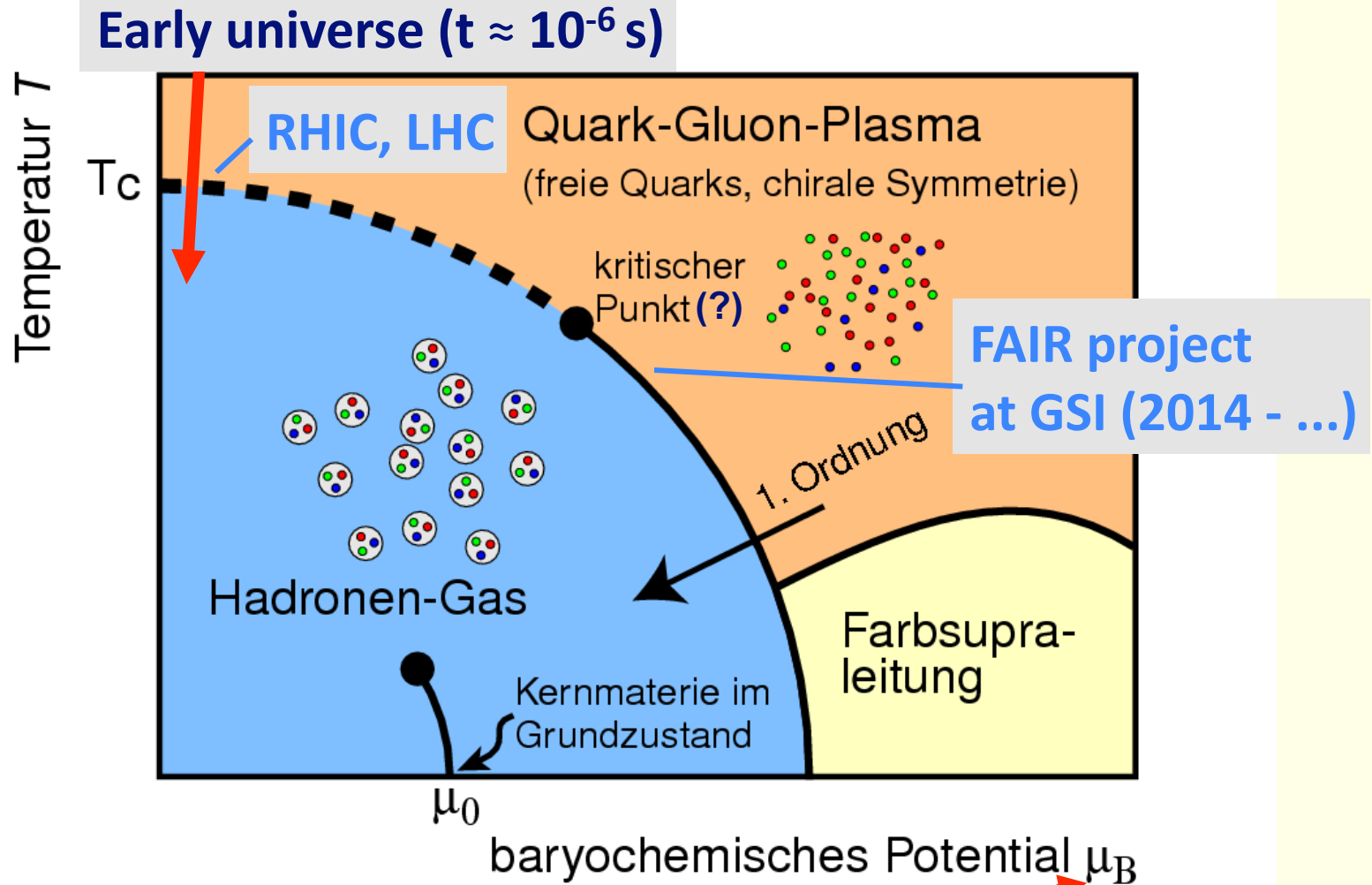
~~only 20% deviation:~~
qgp is an ideal gas

not

$$T_c = (160 - 200) \text{ MeV}$$

$$\epsilon_c \approx 0.7 - 1.0 \text{ GeV/fm}^3$$

Expected QCD Phase Diagram

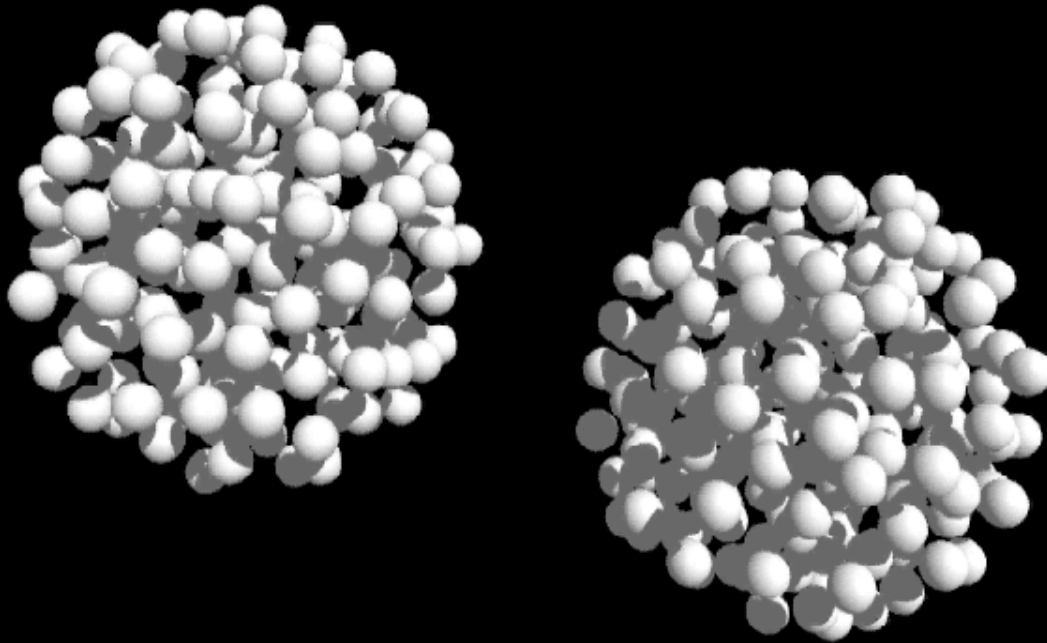


Measure of the net baryon density ρ

Ultra-Relativistische Schwerionenkollision

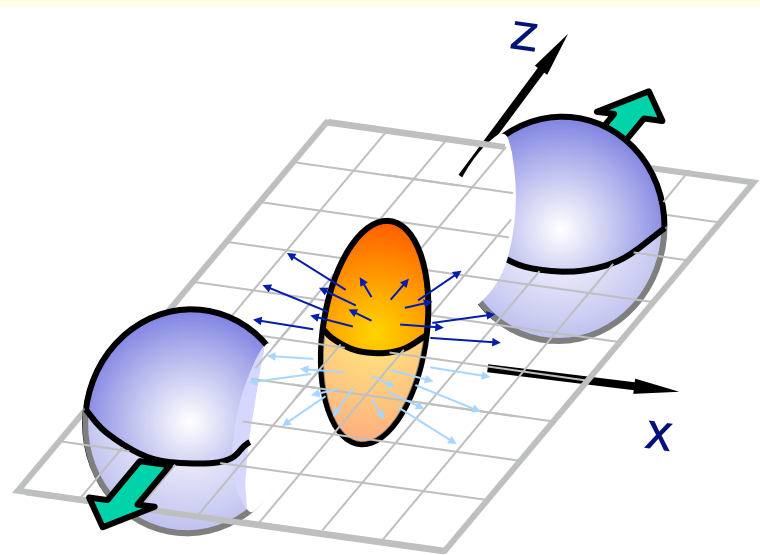
Pb+Pb 160 GeV/A

$t = -0.22 \text{ fm}/c$

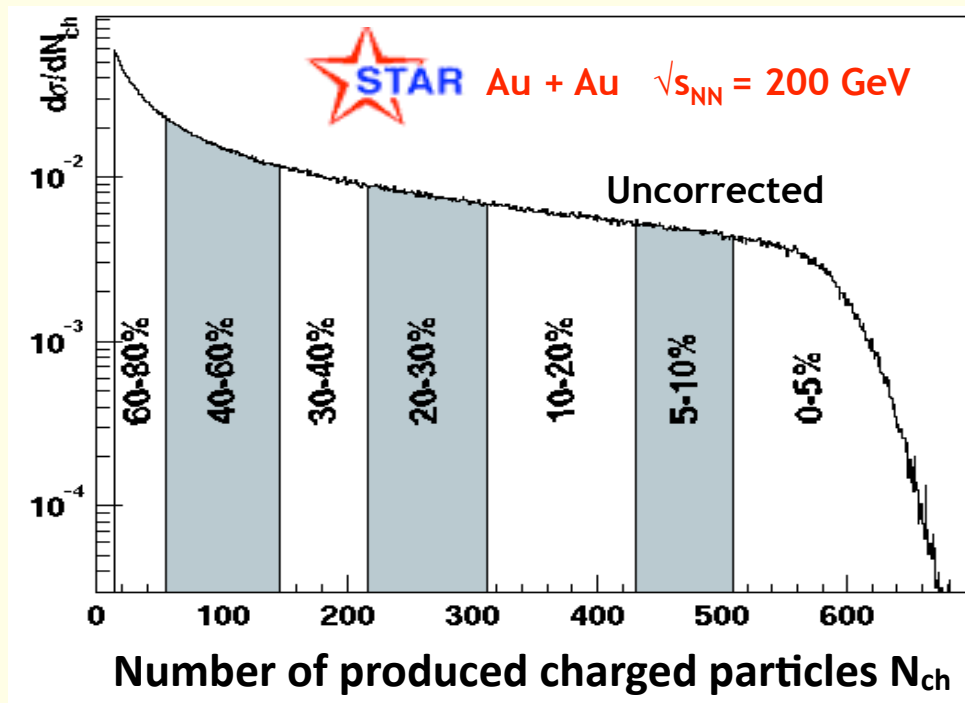


UrQMD Frankfurt/M

Collision Geometry



Non-central Collision



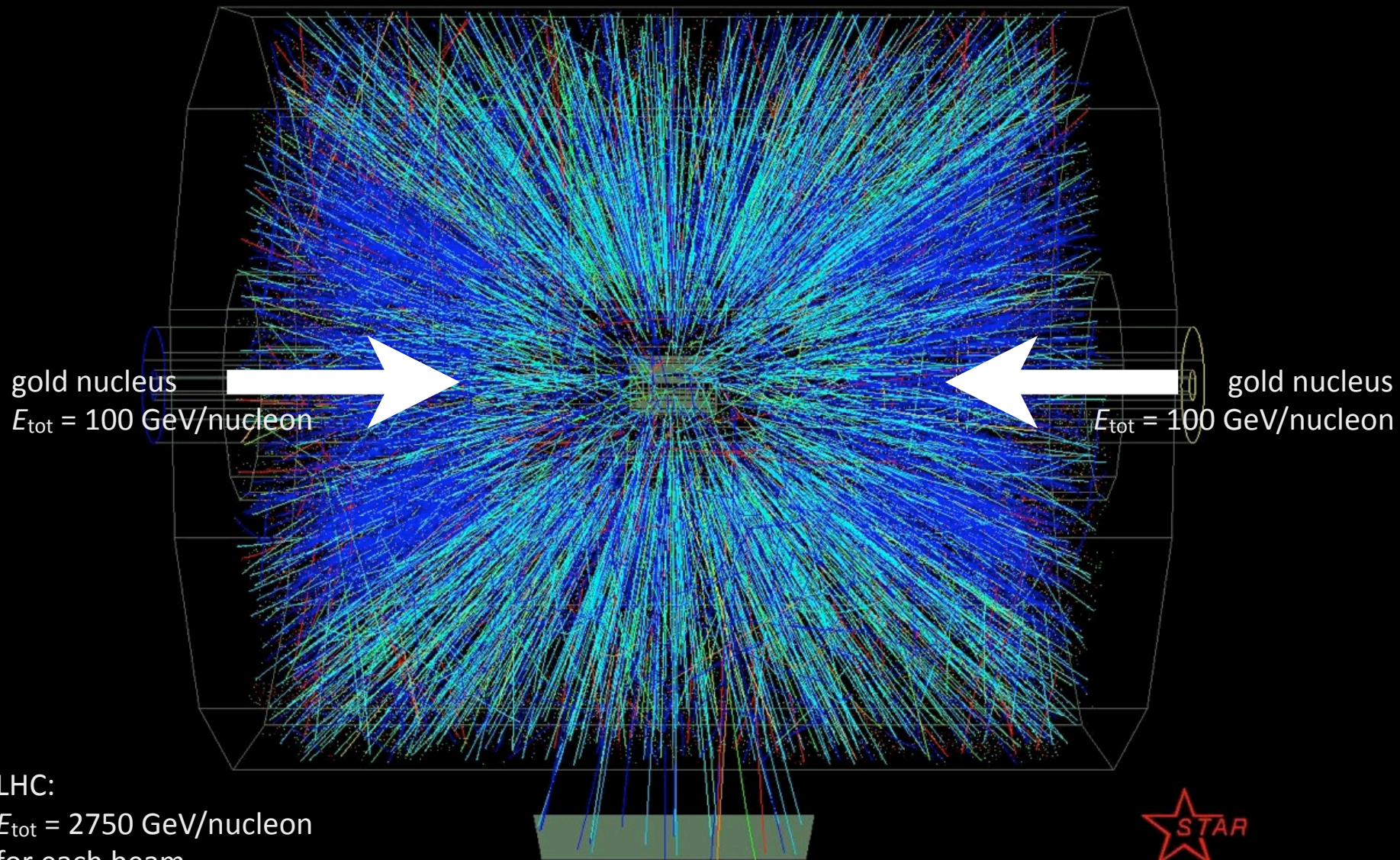
Number of participants: number of nucleons in the overlap region

Number of binary collisions: number of inelastic nucleon-nucleon collisions

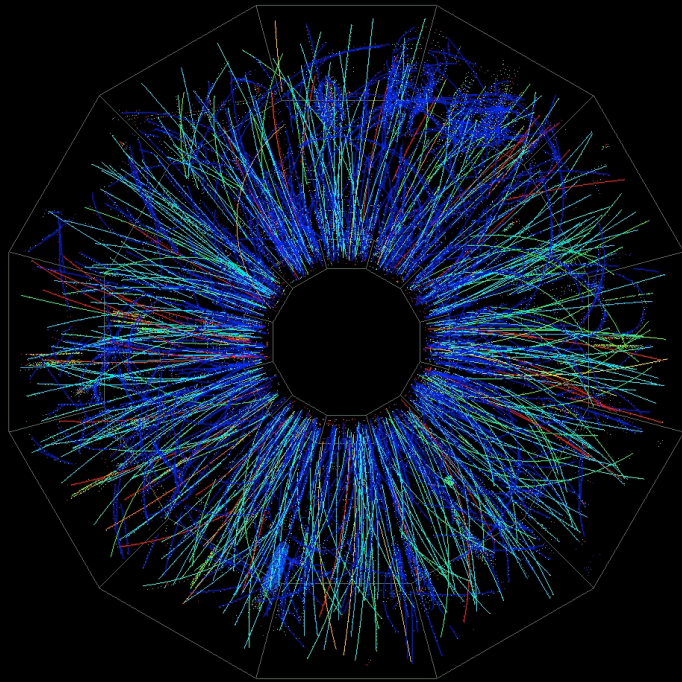
Small impact parameter b corresponds to large particle multiplicity

Reaction plane: x - z plane

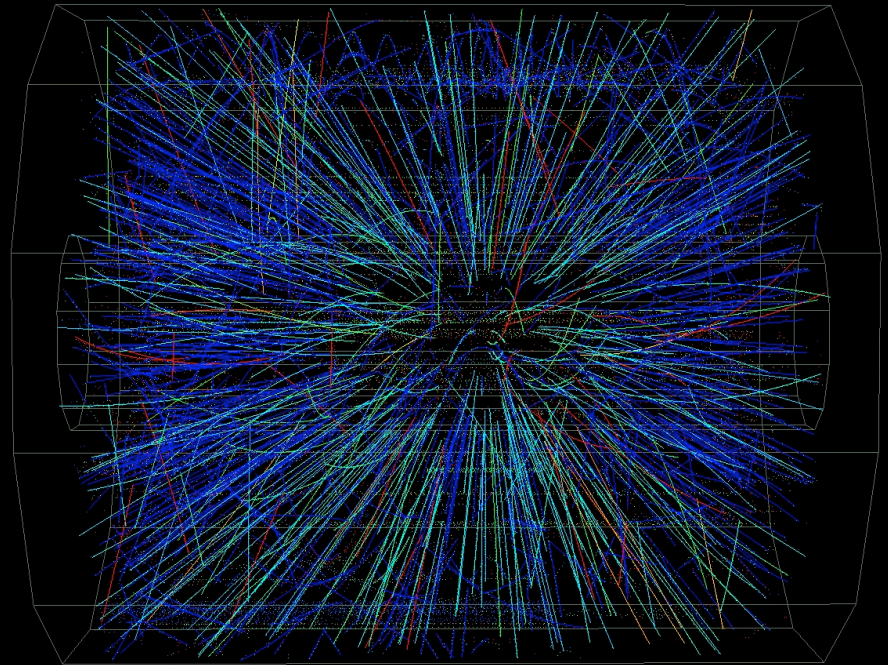
Au+Au Collision at the Relativistic Heavy Ion Collider (RHIC) in the USA



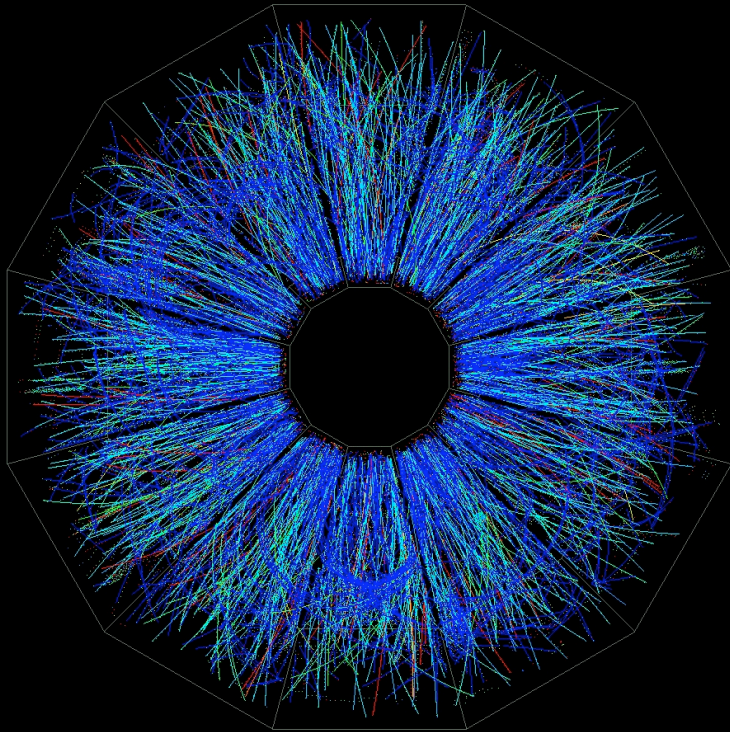
Au + Au Collisions at RHIC



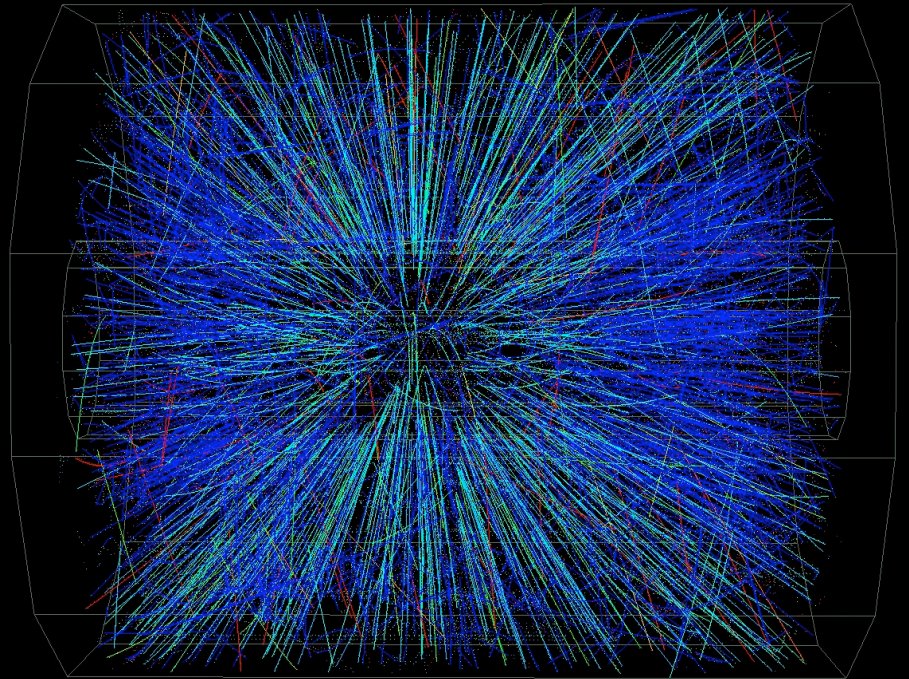
Peripheral Event



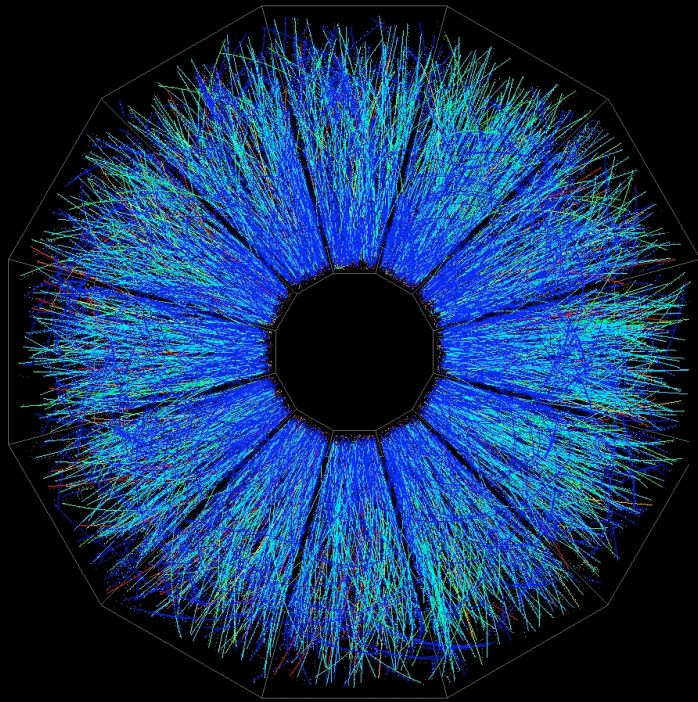
Au + Au Collisions at RHIC



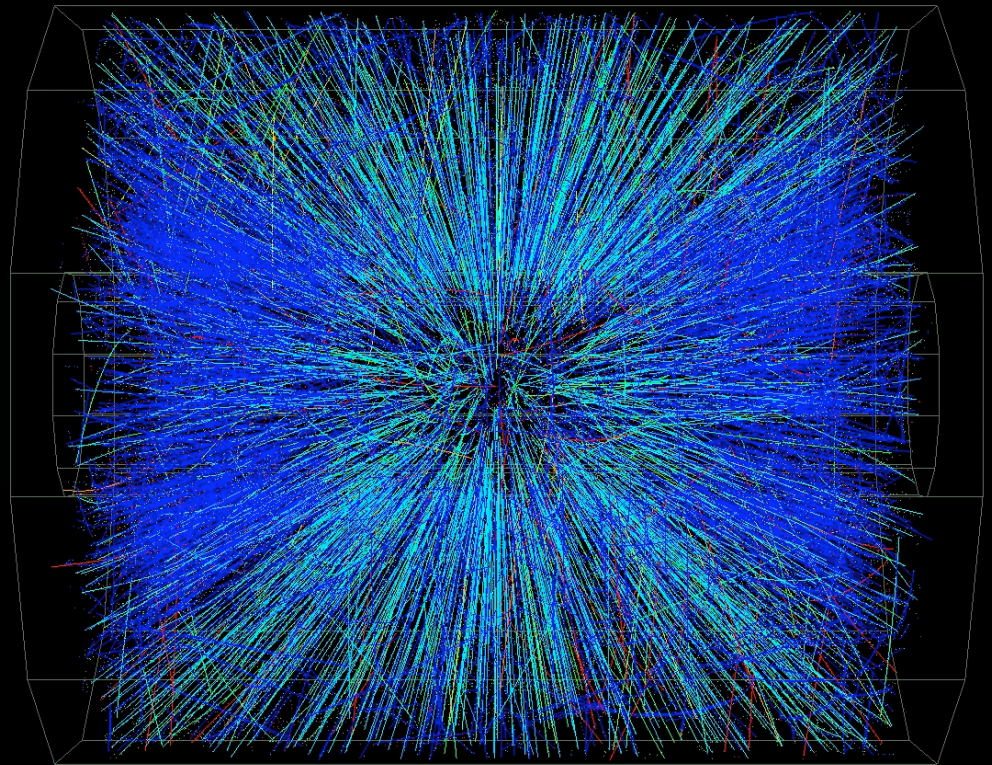
Mid-Central Event



Au + Au Collisions at RHIC

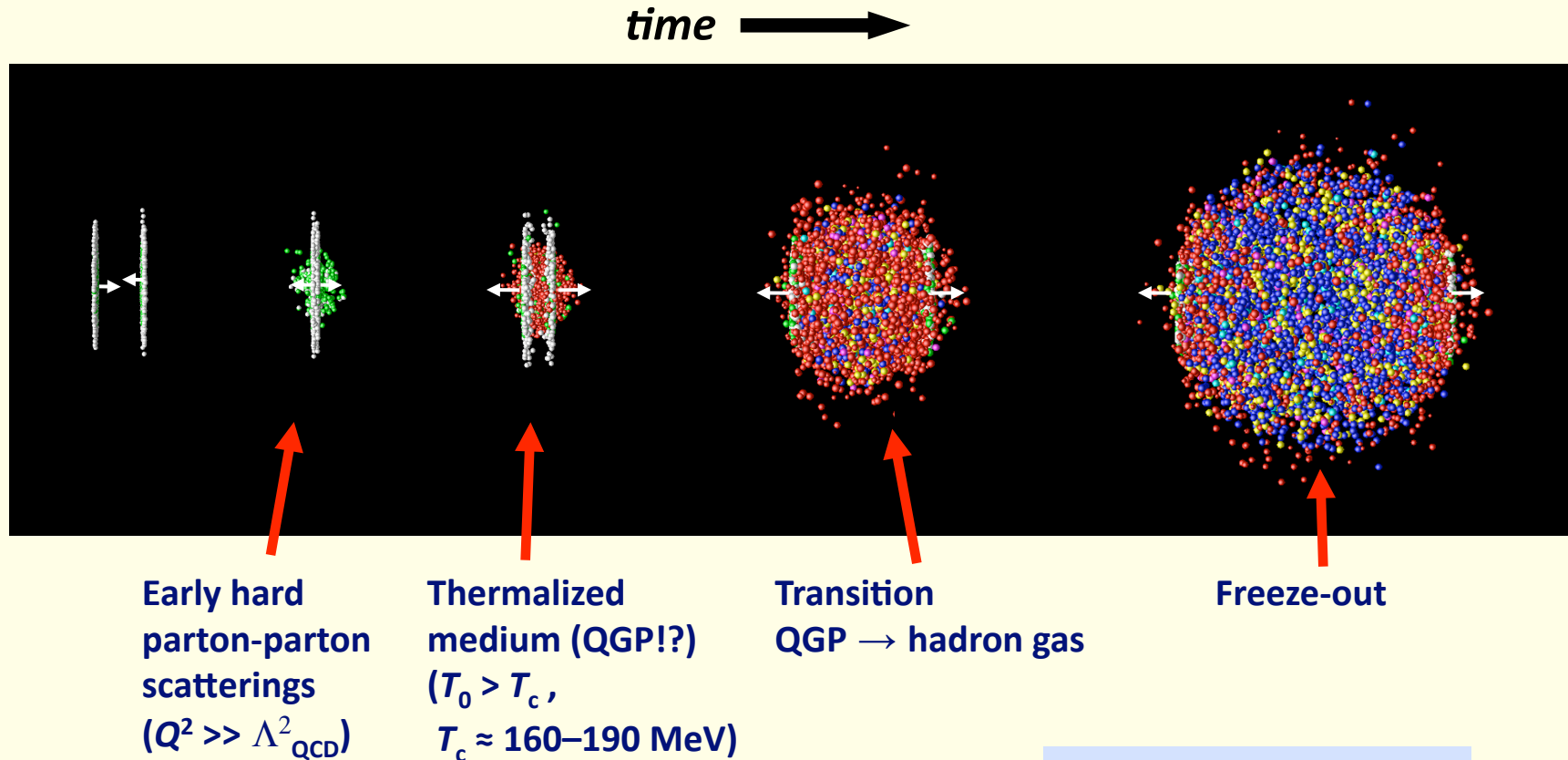


Central Event



about 5000 charged
particles per
central collisions

Ultra-Relativistic Nucleus-Nucleus Collisions



- Time scales (RHIC, $\sqrt{s_{\text{NN}}} = 200$ GeV):

- ◆ Thermalization: $\tau_0 < \sim 1$ fm/c

- ◆ QGP lifetime (center of a central Au+Au coll.): ~ 5 fm/c

Note:

$$1 \text{ fm}/c = 0.33 \cdot 10^{-23} \text{ s}$$

Brief History of Heavy-Ion Physics

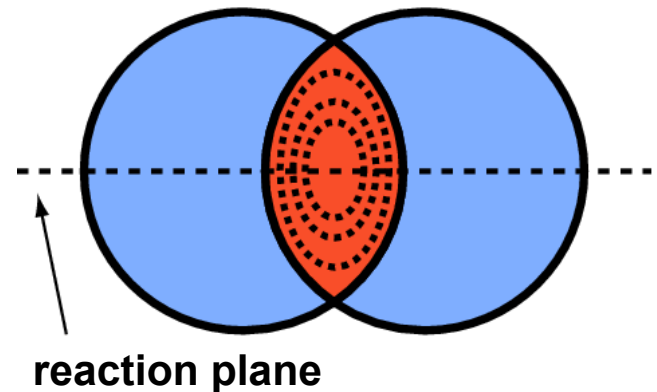
Start	Accelerator	Projectile	Energy (\sqrt{s}) per NN pair
~1985	AGS (BNL)	Si	~5 GeV
~1985	SPS (CERN)	O, S	~20 GeV
1994	SPS (CERN)	Pb	17 GeV
2000	RHIC (BNL)	Au	200 GeV
2008	LHC (CERN)	Pb	5500 GeV

Important Results of the RHIC Heavy-Ion Program

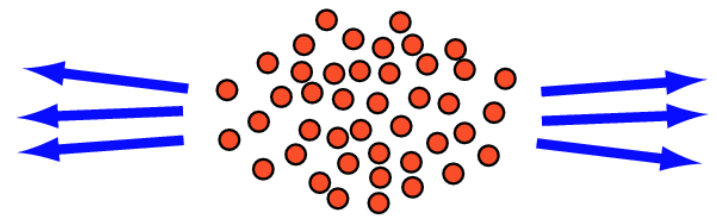
- **Hadron suppression at high p_T**
 - Medium is to large extent opaque for jets ("jet quenching")
- **Elliptic Flow at low p_T**
 - Ideal hydro close to data
⇒ Small viscosity: "perfect liquid"
 - Evidence for early thermalization
($\tau < \sim 1 \text{ fm}/c$)
- **All hadron species in chemical equilibrium**
($T \approx 160 \text{ MeV}$, $\mu_B \approx 20 \text{ MeV}$)

Elliptic flow:

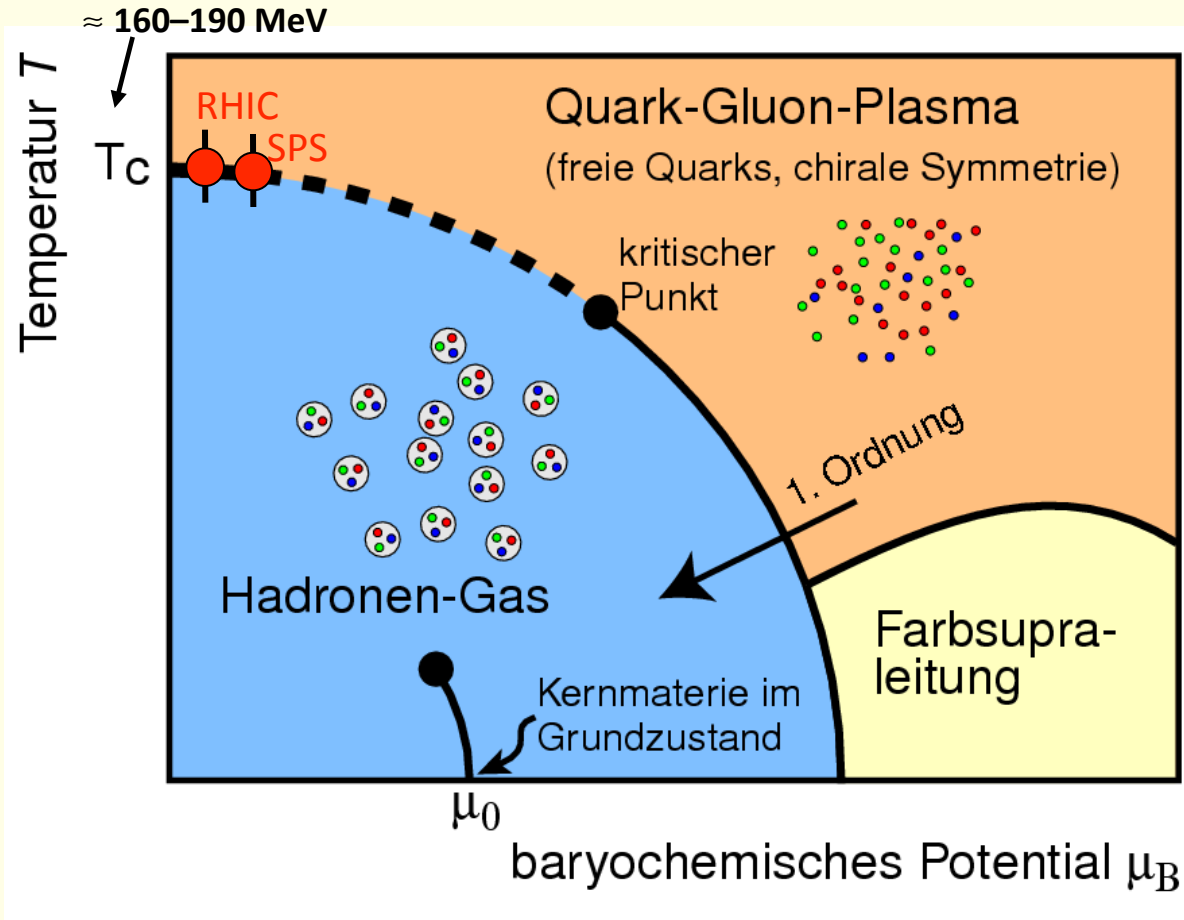
Anisotropy in position space



Anisotropy in momentum space



Nucleus-Nucleus Collisions: Freeze-out Parameters



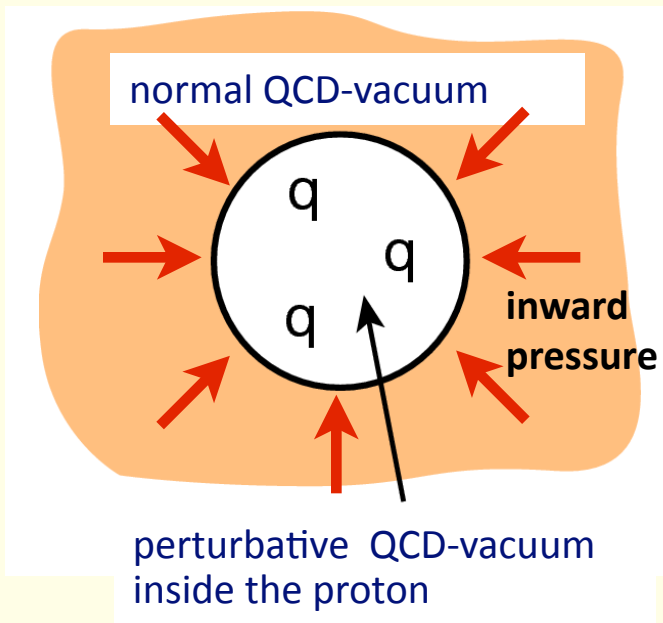
Freeze-out parameters T and μ_B approximately at expected phase boundary

Points to Take Home

- Ultrarelativistic Heavy-Ion Collisions:
Study of QCD in the regime of extreme temperatures and densities
- Goal: Characterization of the Quark-Gluon Plasma
- Transition QGP \rightarrow hadrons about 10^{-6} s after the Big Bang
- QCD phase diagram: QGP reached
 - ▶ at high temperature (about 160-200 MeV [$\sim 2 \cdot 10^{12}$ K])
 - ▶ and/or add high baryochemical potential μ_B
- RHIC/LHC: $\mu_B \approx 0$
- Experiments at FAIR:
 $\mu_B > 0$ search for critical point

2. Thermodynamics of the QGP

Bag Model



- Hadron = „bag“ filled with quarks
- Two kinds of vacuum
 - ◆ Normal QCD-Vacuum outside of the bag
 - ◆ Perturbative QCD-Vacuum within the bag

Energy density: $\varepsilon = E / V$

Energy density in the bag is higher than in the vacuum: $\varepsilon_{\text{BAG}} - \varepsilon_{\text{vacuum}} =: B > 0$

kinetic energy of N particles in a spherical box of radius R

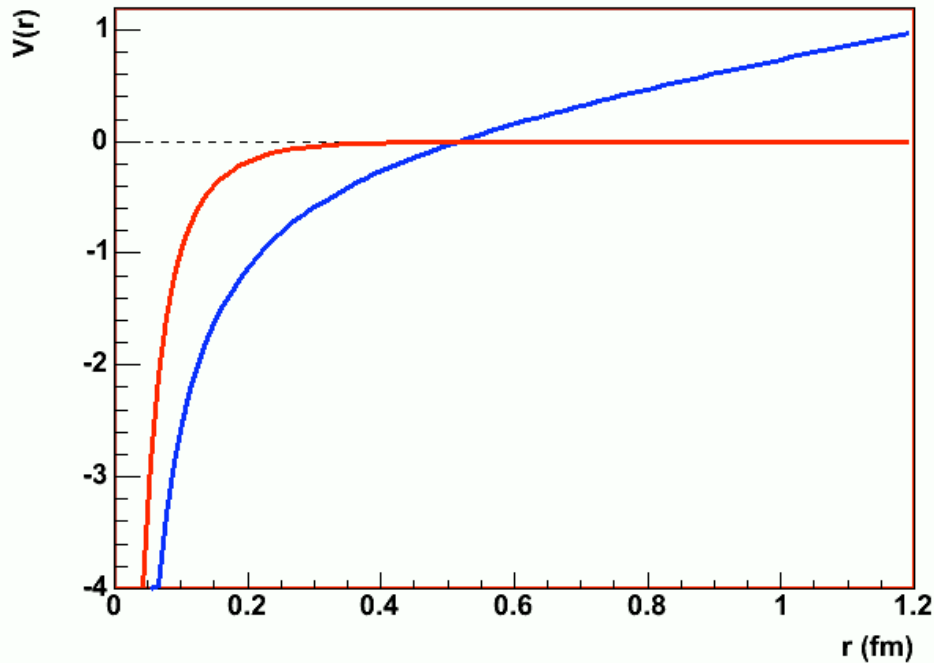
Energy of N quarks in a bag of radius R :

$$E = \frac{2.04N}{R} + \frac{4\pi}{3} \cdot R^3 \cdot B$$

Condition for stability: $dE/dR = 0$ (minimum):

$$B^{1/4} = \left(\frac{2.04N}{4\pi} \right)^{1/4} \cdot \frac{1}{R} \quad \overset{N=3, R=0,8 \text{ fm}}{\Rightarrow} \quad B^{1/4} = 206 \text{ MeV} \quad (\hbar = c = 1)$$

Quark-Antiquark-Potential in the QGP



- Within a QGP, the long-range part of the potential of a quark-antiquark-pair vanishes
- Consequently, at high temperatures the J/ψ cannot exist anymore
- Asymptotic freedom ($\alpha_s(q^2) \rightarrow 0$ for $q^2 \rightarrow \infty$): QGP is an ideal gas of quarks and gluons at very high temperatures

QCD-vacuum:
$$V(r) = -\frac{4}{3} \frac{\alpha(r)}{r} + kr$$

QGP:
$$V(r) = -\frac{4}{3} \frac{\alpha(r)}{r} \cdot \exp\left(-\frac{r}{\lambda_d}\right)$$

Debye-screening-length, approx. 0,1 fm

Particles in a Box: Number of States

Number of states between momentum p and $p+dp$
(each state occupies a volume h^3 in phase space):

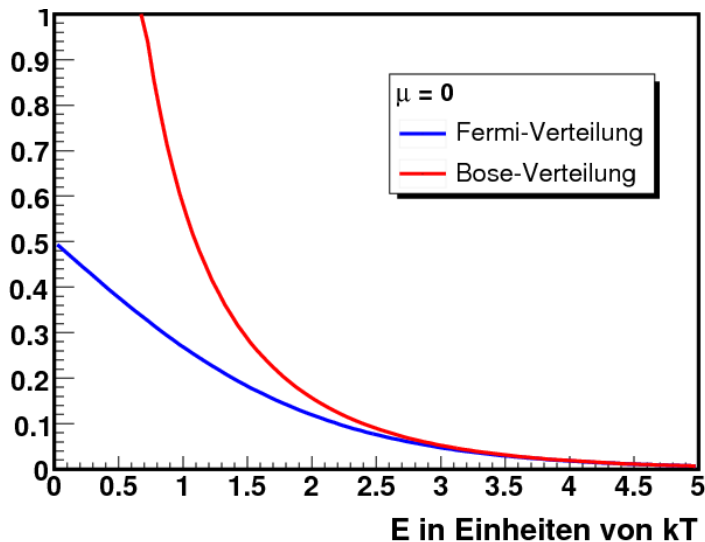
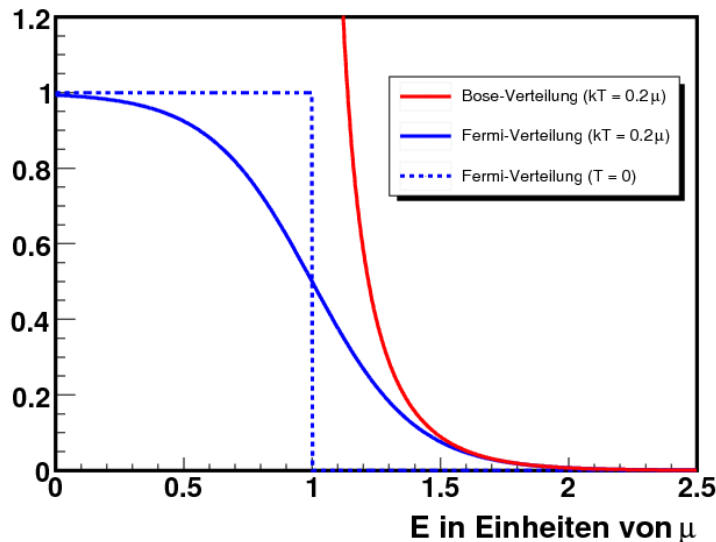
number of states

$$dN = \frac{V}{h^3} 4\pi p^2 dp$$

physical volume

volume of a spherical shell with radius p
and thickness dp in momentum space

Fermi-Dirac and Bose-Einstein Distribution



Number of particles with energy E
 ... for fermions (half-integer spin):

$$n(E) = \frac{g}{1 + e^{(E-\mu)/kT}}$$

(Fermi-Dirac distribution)

... for bosons (integer spin):

$$n(E) = \frac{g}{e^{(E-\mu)/kT} - 1}$$

(Bose-Einstein distribution)

g : # degrees of freedom (degeneracy)

μ : Chemical potential

T : Temperature

Degeneracy

QGP:

$$g_{\text{Bosons}} = 8_{\text{Color}} \times 2_{\text{Polarisation}} = 16$$

$$\begin{aligned} g_{\text{Fermions}} &= g_{\text{Quarks}} + g_{\text{Antiquarks}} = 2 \times g_{\text{Quarks}} \\ &= 2 \times 3_{\text{Color}} \times 2_{\text{Flavour}} \times 2_{\text{Spin}} = 24 \end{aligned}$$

assume only u and d quarks can be produced in the QGP, the rest too heavy

Pion-Gas:

$$g_{\text{Bosons}} = 3_{\text{Type}} \quad g_{\text{Fermions}} = 0$$

(π^+, π^-, π^0)

Integration Yields Total Quark Density in the Ideal (= non interacting) QGP at Temperature T

Massless quarks, Fermi-Dirac distribution:

$$\begin{aligned} dN_q &= g_q \cdot \frac{V}{h^3} \cdot 4\pi p^2 \left(\frac{1}{1 + e^{(E - \mu_q)/kT}} \right) dp \\ &\stackrel{\hbar=k=c=1}{=} g_q \frac{p^2 V}{2\pi^2} \left(\frac{1}{1 + e^{(p - \mu_q)/T}} \right) dp \end{aligned}$$

Quark density:

$$n_q(\mu_q) = \frac{N_q}{V} = g_q \frac{4\pi}{(2\pi)^3} \int_0^\infty \left(\frac{p^2}{1 + e^{(p - \mu_q)/T}} \right) dp$$

holds for massless quarks

Antiquarks ($\mu_{\bar{q}} = -\mu_q$):

$$n_{\bar{q}}(\mu_{\bar{q}}) = \frac{N_{\bar{q}}}{V} = g_q \frac{4\pi}{(2\pi)^3} \int_0^\infty \left(\frac{p^2}{1 + e^{(p + \mu_q)/T}} \right) dp$$

Quark-Gluon Plasma with $\mu = 0$: Quarks

Quark density
($\mu_q = 0$):

$$n_q = n_{\bar{q}} = \frac{N_q}{V} = \frac{3}{2} \zeta(3) \frac{g_q}{2\pi^2} \frac{\pi^2}{30} T^3$$

1,20205

Total energy of the quarks:

$$E_q = \int_0^\infty p dN_q$$

Solution of the integral for vanishing **energy density** and **pressure**
($\mu_q = 0$) yields:

$$\varepsilon_q = \frac{E_q}{V} = \frac{7}{8} g_q \frac{\pi^2}{30} T^4, \quad p_q = \frac{1}{3} \varepsilon_q$$

(identical result for antiquarks ($\mu_q = 0$))

Example: $T = 200 \text{ MeV}, g_q = 12 \Rightarrow n_q = n_{\bar{q}} = 1,71 / \text{fm}^3$

Quark-Gluon Plasma with $\mu = 0$: Gluons

Gluons, Bose-Einstein distribution:

$$dN_g = \frac{V g_g}{2\pi^2} \cdot \frac{p^2}{e^{p/T} - 1} dp, \quad n_g = \frac{N_g}{V} = \frac{1}{V} \int_0^\infty dN_g, \quad E_g = \int_0^\infty p dN_g$$

Solution:

Energy density:

$$\varepsilon_g = \frac{E_g}{V} = g_g \frac{\pi^2}{30} T^4,$$

Pressure:

$$p_g = \frac{1}{3} \varepsilon_g,$$

Particle density:

$$n_g = \frac{g_g}{\pi^2} \zeta(3) T^3$$

Example: $T = 200 \text{ MeV}, g_g = 16 \Rightarrow n_g = 2,03 \text{ Gluons / fm}^3$

Quark-Gluon Plasma with $\mu = 0$: Pressure and Energy Density

Pressure and energy density in a Quark-Gluon-Plasma at $\mu = 0$ without particle interactions:

$$p_{\text{QGP}} = \left(g_g + \frac{7}{8}(g_q + g_{\bar{q}}) \right) \frac{\pi^2}{90} T^4$$
$$= 37 \frac{\pi^2}{90} T^4$$
$$\varepsilon_{\text{QGP}} = 3 p_{\text{QGP}}$$
$$= 37 \frac{\pi^2}{30} T^4$$

Example: $T = 200 \text{ MeV} \quad \Rightarrow \quad \varepsilon_{\text{QGP}}^{\text{id. Gas}} = 2,54 \text{ GeV/fm}^3$

Quark-Gluon Plasma with $\mu = 0$: Critical Temperature (I)

Accounting for the QCD-vacuum:

$$\begin{aligned}\epsilon_{\text{QGP}}^{\text{QCD-Vac.}} &= \epsilon_{\text{QGP}} + B \\ p_{\text{QGP}}^{\text{QCD-Vac.}} &= p_{\text{QGP}} - B\end{aligned}$$

$$\begin{aligned}E &= TS - pV \quad (\mu = 0) \\ \Rightarrow p &= Ts - \epsilon, \quad s := \frac{S}{V}\end{aligned}$$

So we have:

$$\begin{aligned}p_{\text{HG}} &= 3aT^4 & \epsilon_{\text{HG}} &= 9aT^4 \\ p_{\text{QGP}}^{\text{QCD-Vac.}} &= 37aT^4 - B & \epsilon_{\text{QGP}}^{\text{QCD-Vac.}} &= 111aT^4 + B\end{aligned} \quad a := \frac{\pi^2}{90}$$

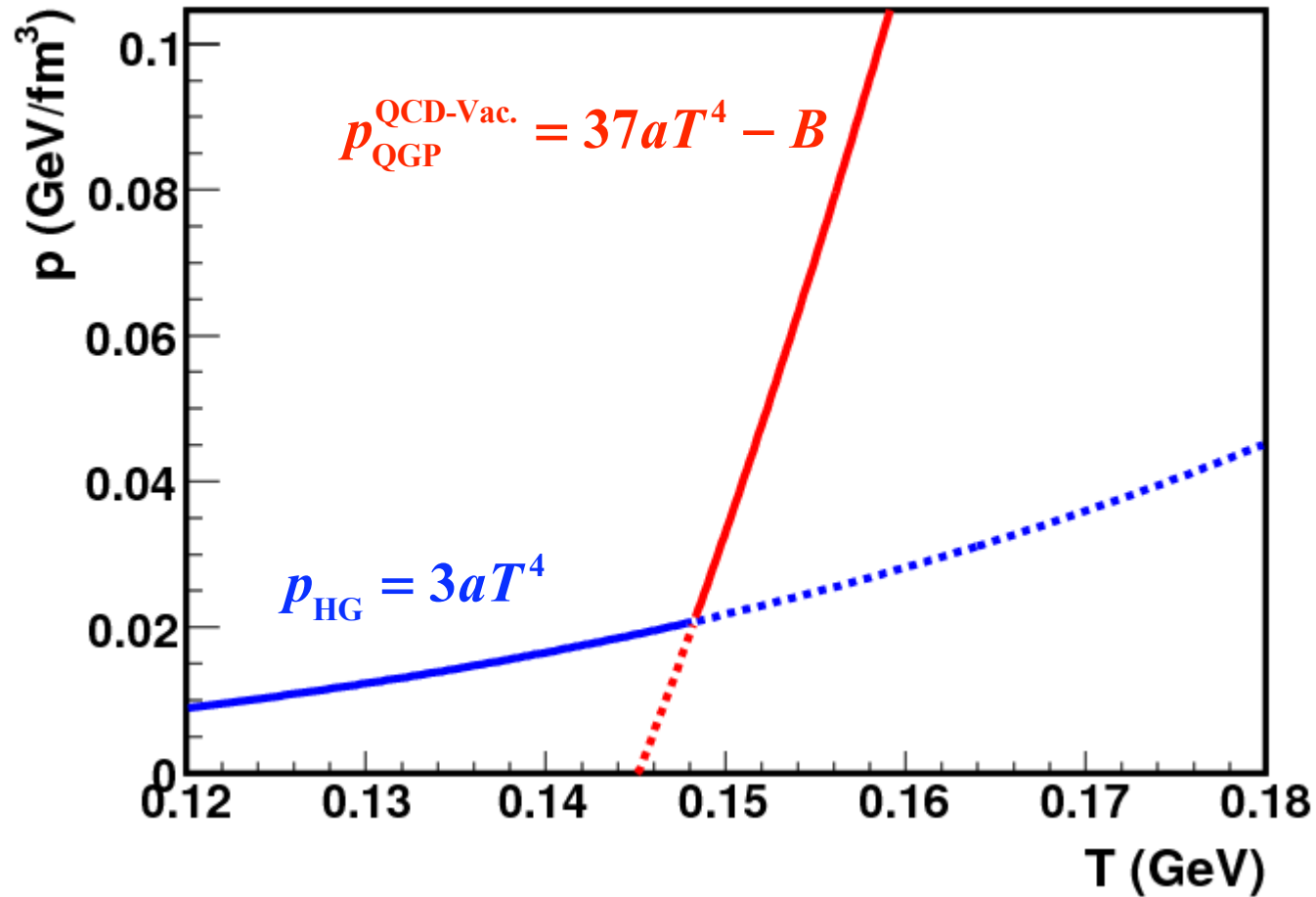
Gibbs criterion for the phase transition:

$$p_{\text{HG}} = p_{\text{QGP}}^{\text{QCD-Vac.}}, \quad T_{\text{HG}} = T_{\text{QGP}} = T_c \quad \Rightarrow \quad T_c = \left(\frac{B}{34a} \right)^{1/4} \approx 150 \text{ MeV}$$

Phase transition in the bag model is of first order. Latent heat:

$$\epsilon_{\text{QGP}}^{\text{QCD-Vac.}}(T_c) - \epsilon_{\text{HG}}(T_c) = 102aT_c^4 + B = 4B$$

Quark-Gluon Plasma with $\mu = 0$: Critical Temperature (II)



Quark-Gluon Plasma mit $\mu = 0$: Entropy

Entropy density for constant temperature and pressure:

$$E = TS - pV \quad (\mu = 0) \quad \Rightarrow \quad \frac{S}{V} = s = \frac{\varepsilon + p}{T} = 4 \frac{p}{T}$$

Ratio of entropy density (QGP / pion gas):

$$s_{\text{QGP}} = 148 a T^3, \quad s_{\text{HG}} = 12 a T^3 \quad \Rightarrow \quad \frac{s_{\text{QGP}}}{s_{\text{HG}}} \approx 12,3$$

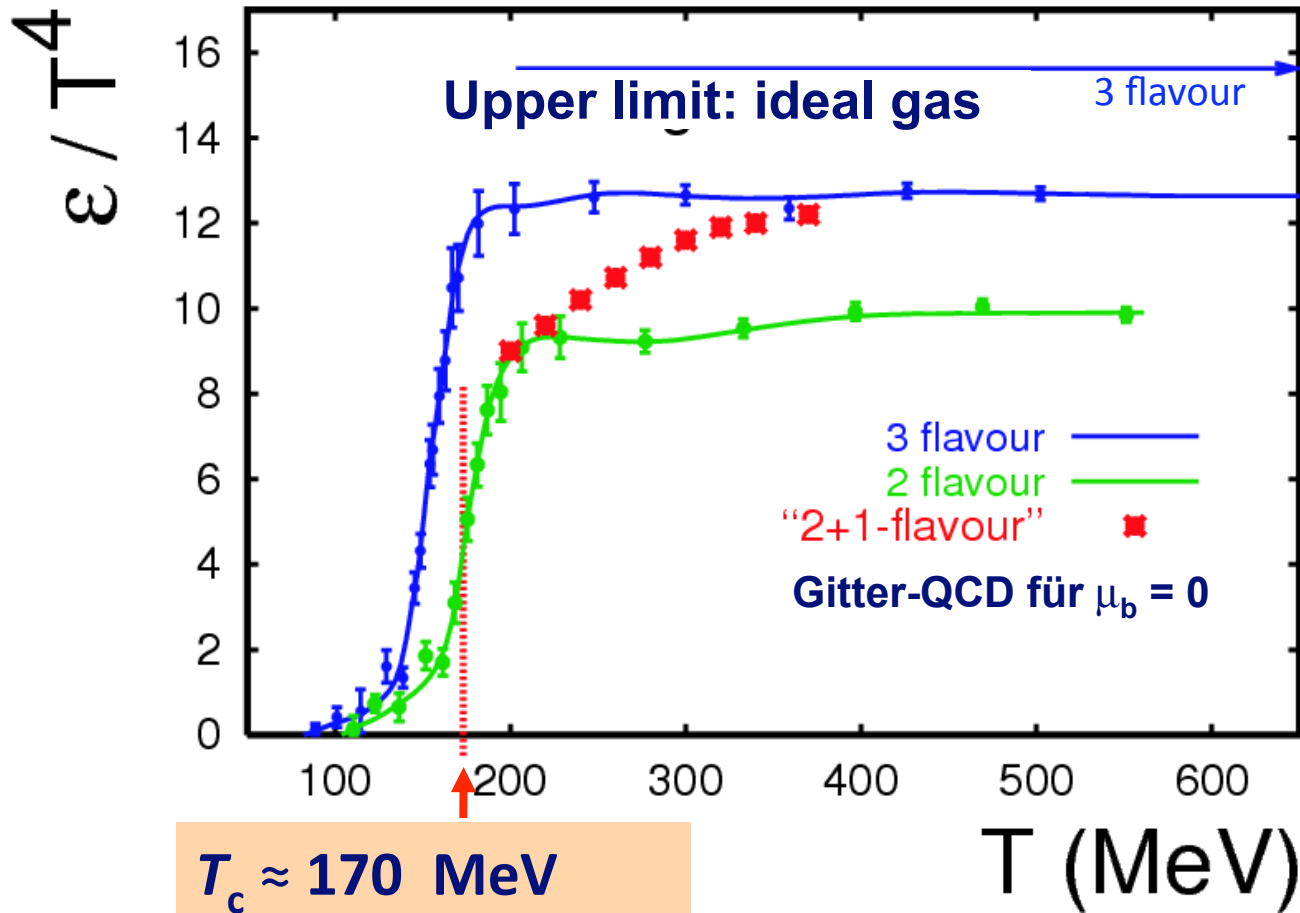
Entropy per particle:

$$\text{Pion gas:} \quad \frac{s_{\text{HG}}}{n_{\pi}} = \frac{12 \pi^2 / 90 \cdot T^3}{g_{\pi} \cdot 1,202 / \pi^2 \cdot T^3} = 3.6$$

$$\text{QGP:} \quad \frac{s_{\text{q}}}{n_{\text{q}}} = 1,4 \quad \frac{s_{\text{g}}}{n_{\text{g}}} = 1,2$$

Quark-Gluon Plasma with $\mu = 0$: QGP with particle interactions (I)

F. Karsch, E. Laermann, hep-lat/0305025



Different calculation yield results
in the range $T_c = 160 - 190$ MeV

Quark-Gluon Plasma with $\mu \neq 0$

Energy and Particle Number Density of the Quarks

For $\mu_q \neq 0$ a solution in closed form can be found for $\varepsilon_q + \varepsilon_{\bar{q}}$ but not for ε_q and $\varepsilon_{\bar{q}}$ separately:

$$\varepsilon_q + \varepsilon_{\bar{q}} = g_q \left(\frac{7\pi^2}{120} T^4 + \frac{1}{4} \mu_q^2 T^2 + \frac{1}{8\pi^2} \mu_q^4 \right)$$

Accordingly one finds for the quark density

$$n_q - n_{\bar{q}} = g_q \left(\frac{1}{6} \mu_q T^2 + \frac{1}{6\pi^2} \mu_q^3 \right), \quad g_q = 12$$

From this the net baryon density can be determined as:

$$n_B = \frac{n_q - n_{\bar{q}}}{3} = \frac{2}{3} \mu_q T^2 + \frac{2}{3\pi^2} \mu_q^3 = \frac{2}{9} \mu_B T^2 + \frac{2}{81\pi^2} \mu_B^3 \quad (\mu_B = 3\mu_q)$$

Quark-Gluon Plasma with $\mu \neq 0$: Critical Temperature and Critical Quark Potential

Energy density in a QGP with $\mu \neq 0$ (without particle interactions):

$$\varepsilon_{\text{QGP}} = \frac{37}{30} \pi^2 T^4 + 3 \mu_q^2 T^2 + \frac{3}{2\pi^2} \mu_q^4$$

Condition for QGP stability:

$$p_{\text{QGP}} = \frac{1}{3} \varepsilon_{\text{QGP}} = B \Rightarrow T_c(\mu_q)$$

Condition for QGP:
QGP-pressure \geq pressure
of the QCD-vacuum
(similar, but not identical,
to the previous condition
 $p_{\text{HG}} = p_{\text{QGP}}$)

Critical temperature / quark potential:

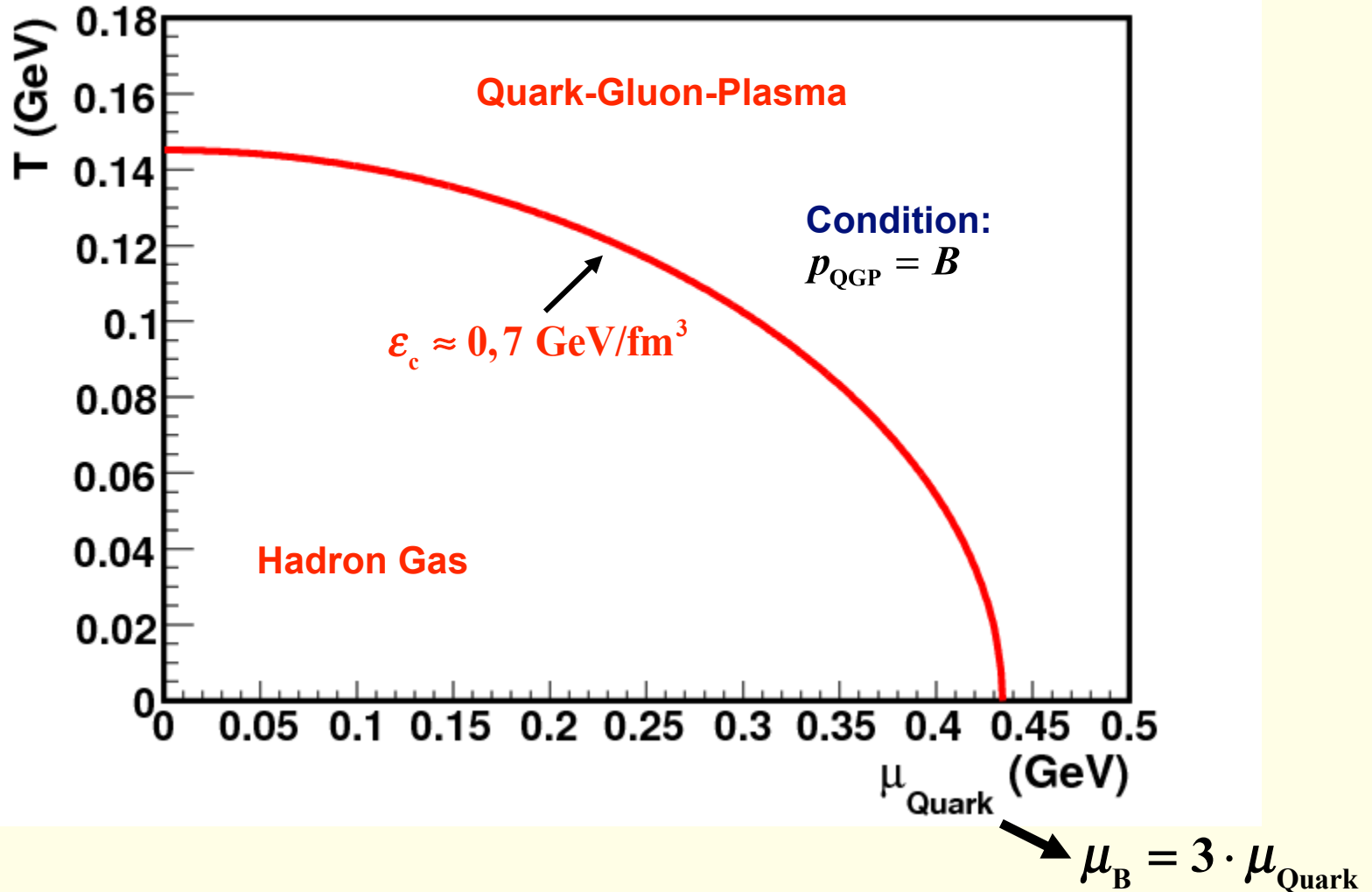
$$T_c(\mu_q = 0) = \left(\frac{90B}{37\pi^2} \right)^{1/4}$$

$$\mu_q^c(T = 0) = \left(2\pi^2 B \right)^{1/4} = 0,43 \text{ GeV}$$

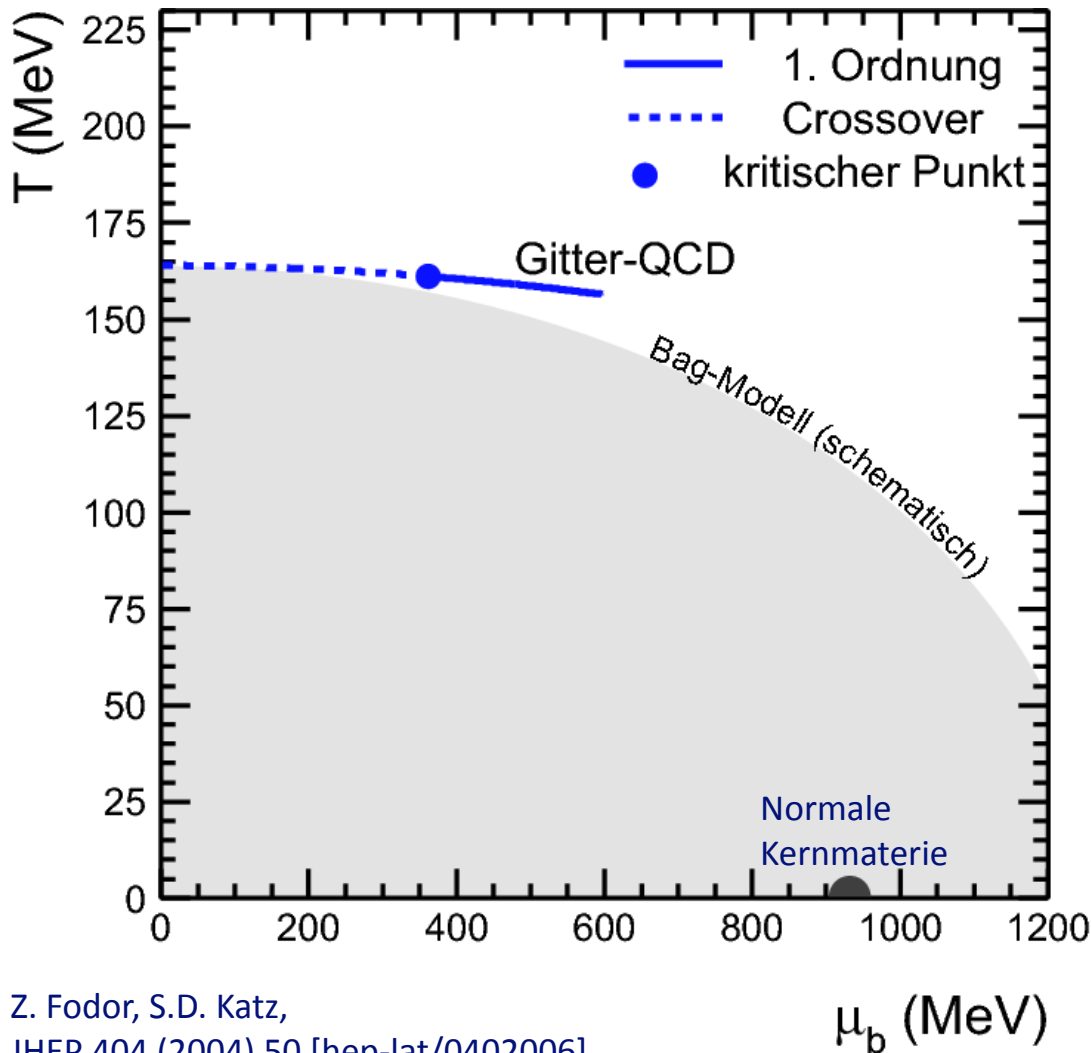
$$n_B^c(T = 0) = \frac{2}{3\pi^2} \left(2\pi^2 B \right)^{3/4} \\ = 0,72 \text{ fm}^{-3} \approx 5 \times n_{\text{nucleus}}$$

Possibly reached
in neutron stars

Quark-Gluon Plasma with $\mu \neq 0$: Phase Diagram of the Non-Interacting QGP



Quark-Gluon Plasma with $\mu \neq 0$: Phase Diagram from Lattice-QCD



Z. Fodor, S.D. Katz,
JHEP 404 (2004) 50 [hep-lat/0402006].

- Lattice-calculations for $\mu_b \neq 0$
- Transition temperature for $\mu_b = 0$: $T_c = 164$ MeV
- Critical point:
 - ▶ $T = 162$ MeV
 - ▶ $\mu_b = 340$ MeV

The existence and exact position of the critical point remains an open question

Points to Take Home

- When treated as a relativistic ideal gas, parameters for the transition Hadron Gas \leftrightarrow QGP are:
 - ▶ $T_c (\mu_b=0) \approx 150 \text{ MeV}$
 - ▶ $\mu_b(T=0) = 3 \mu_{\text{Quark}}(T=0) \approx 1,3 \text{ GeV}$ (this is approximately five times the density of „normal“ nuclear matter)
- Lattice QCD calculations show that for temperatures up to several times T_c the assumption of an ideal gas is a poor approximation
- Transition temperature from Lattice QCD:
 $T_c (\mu_b=0) = 160 - 190 \text{ MeV}$

Points to Take Home