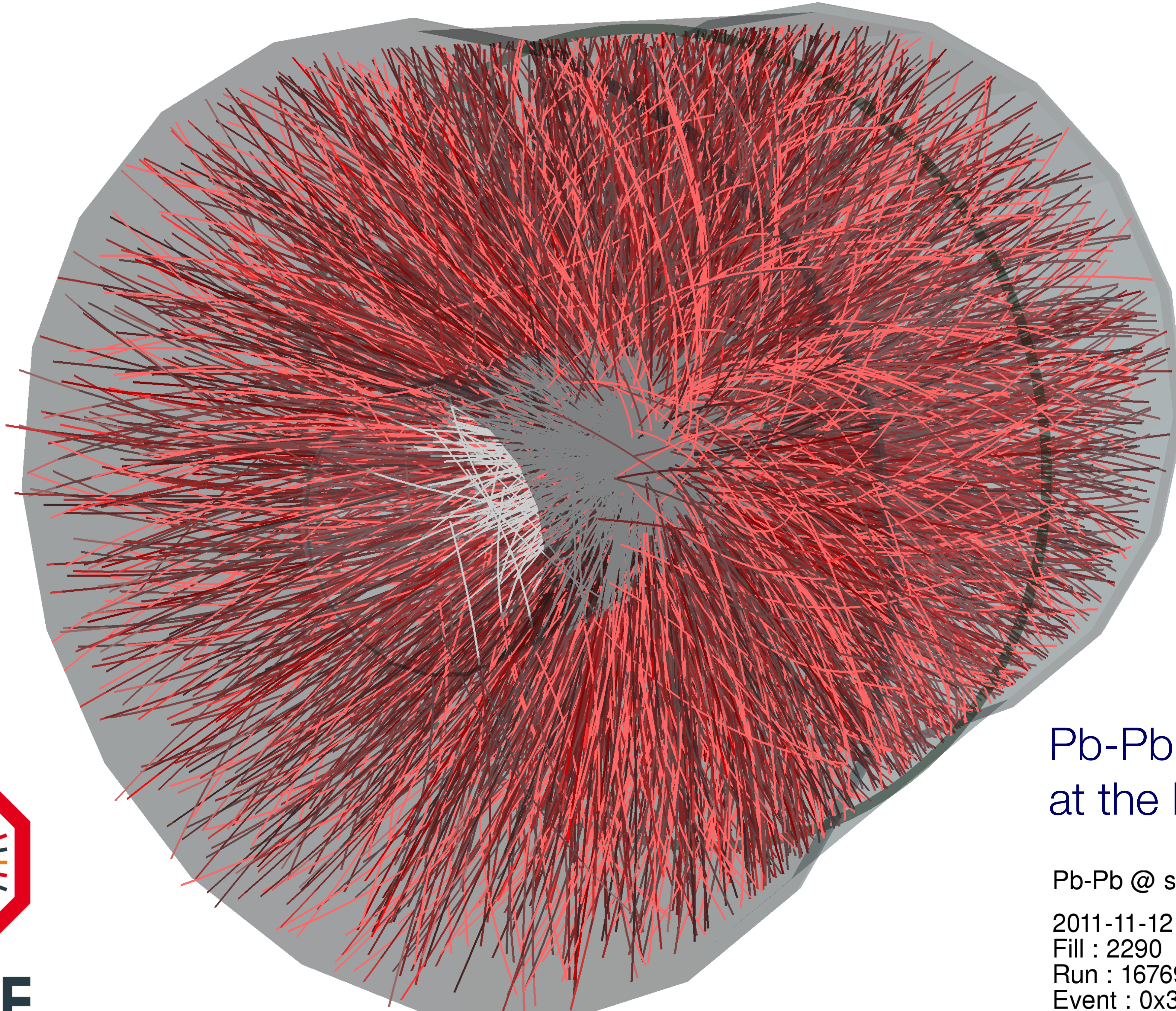
Quark-Gluon Plasma Physics

1. Introduction

Prof. Dr. Klaus Reygers
Heidelberg University
SS 2017



ALICE
A JOURNEY OF DISCOVERY

Pb-Pb collision at the LHC

Pb-Pb @ sqrt(s) = 2.76 ATeV

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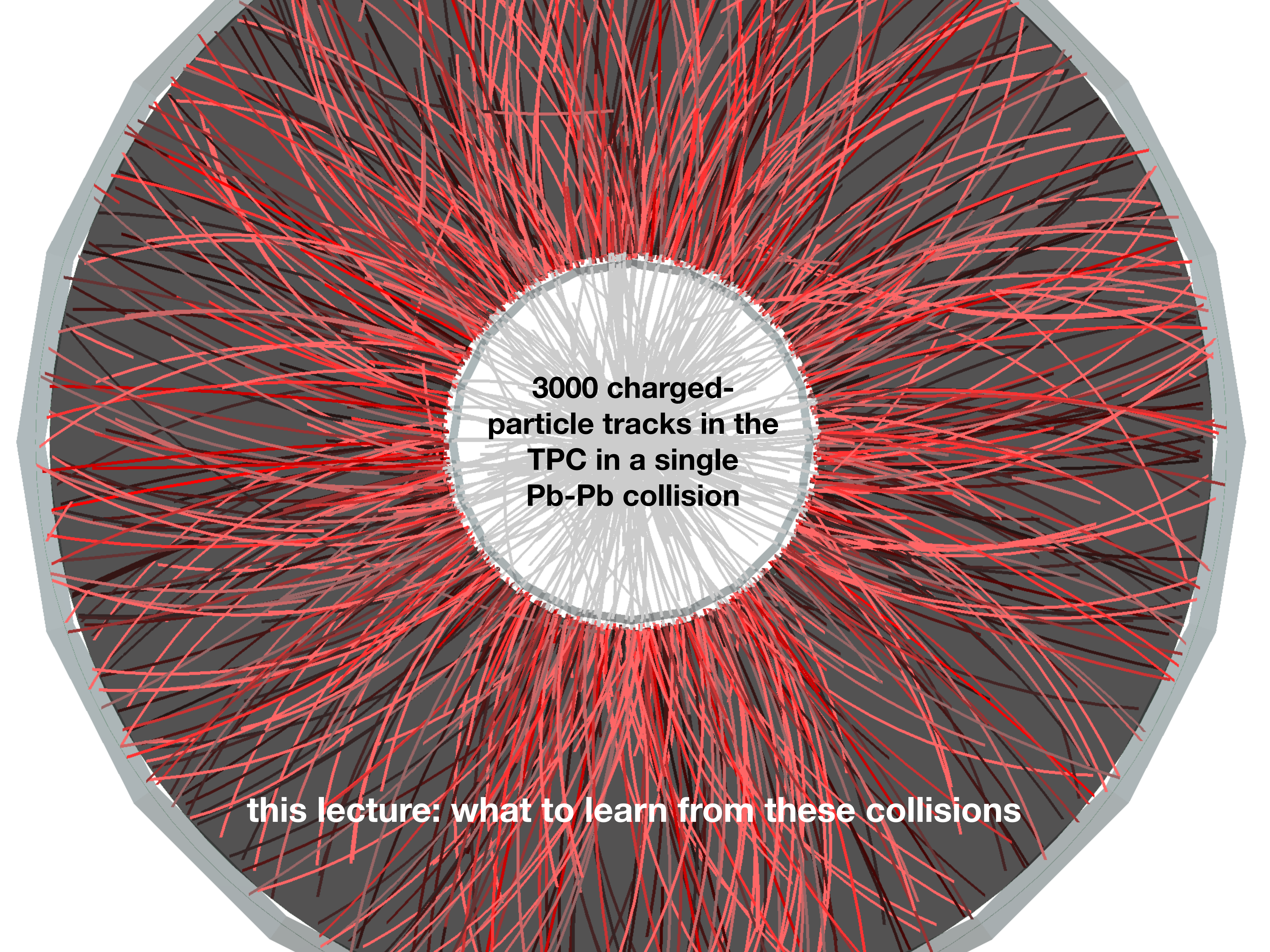
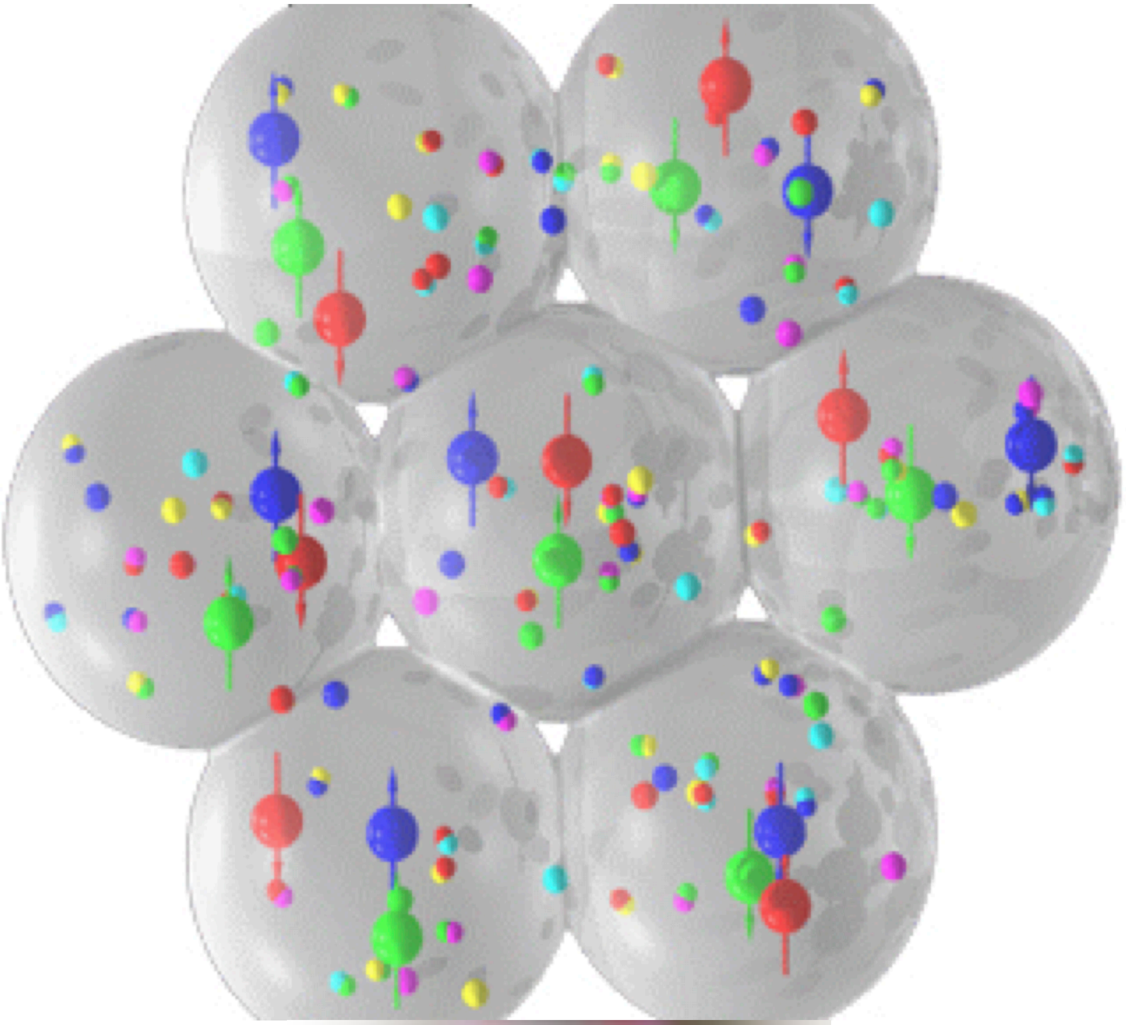

3000 charged-particle tracks in the TPC in a single Pb-Pb collision
this lecture: what to learn from these collisions

What is the question?



What happens to matter if you make it

- hotter and hotter?
- denser and denser?

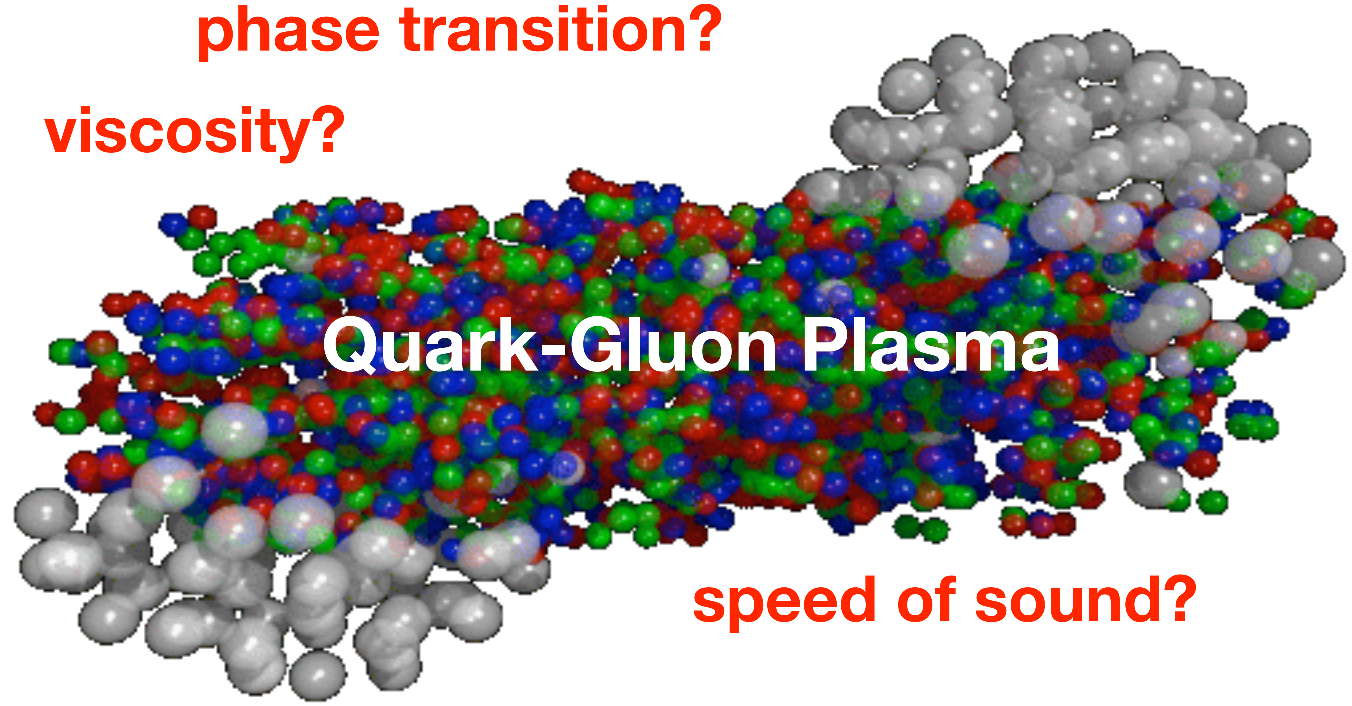
solid → liquid → gas → plasma → hadron gas → QGP

Slightly more precise: "material properties" of the QGP?

- Particle physics: reductionism
- Heavy-ion physics: **emergent** properties of QCD

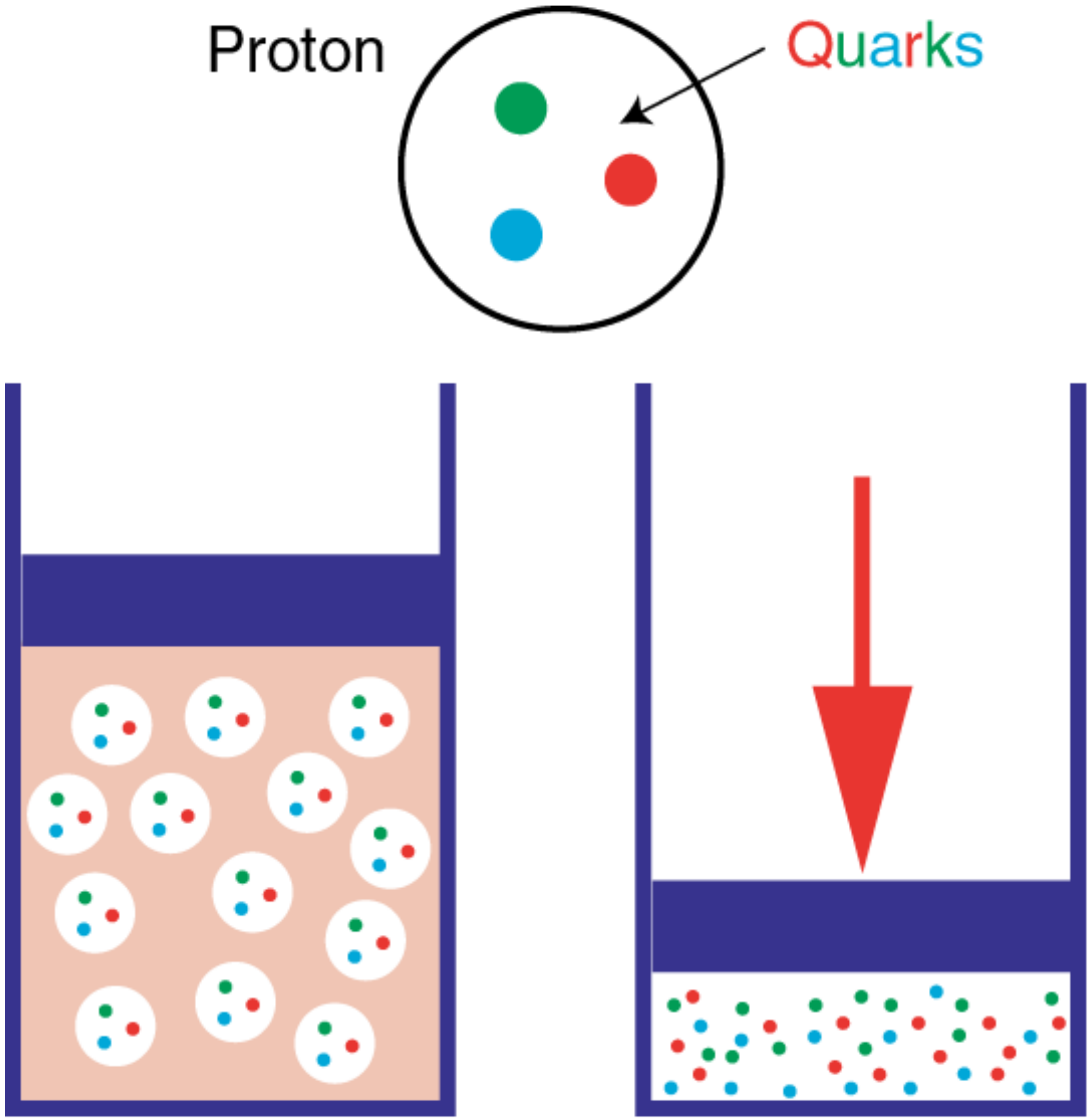
„More is different“

Philip W. Anderson,
Science, 177, 1972, S. 393

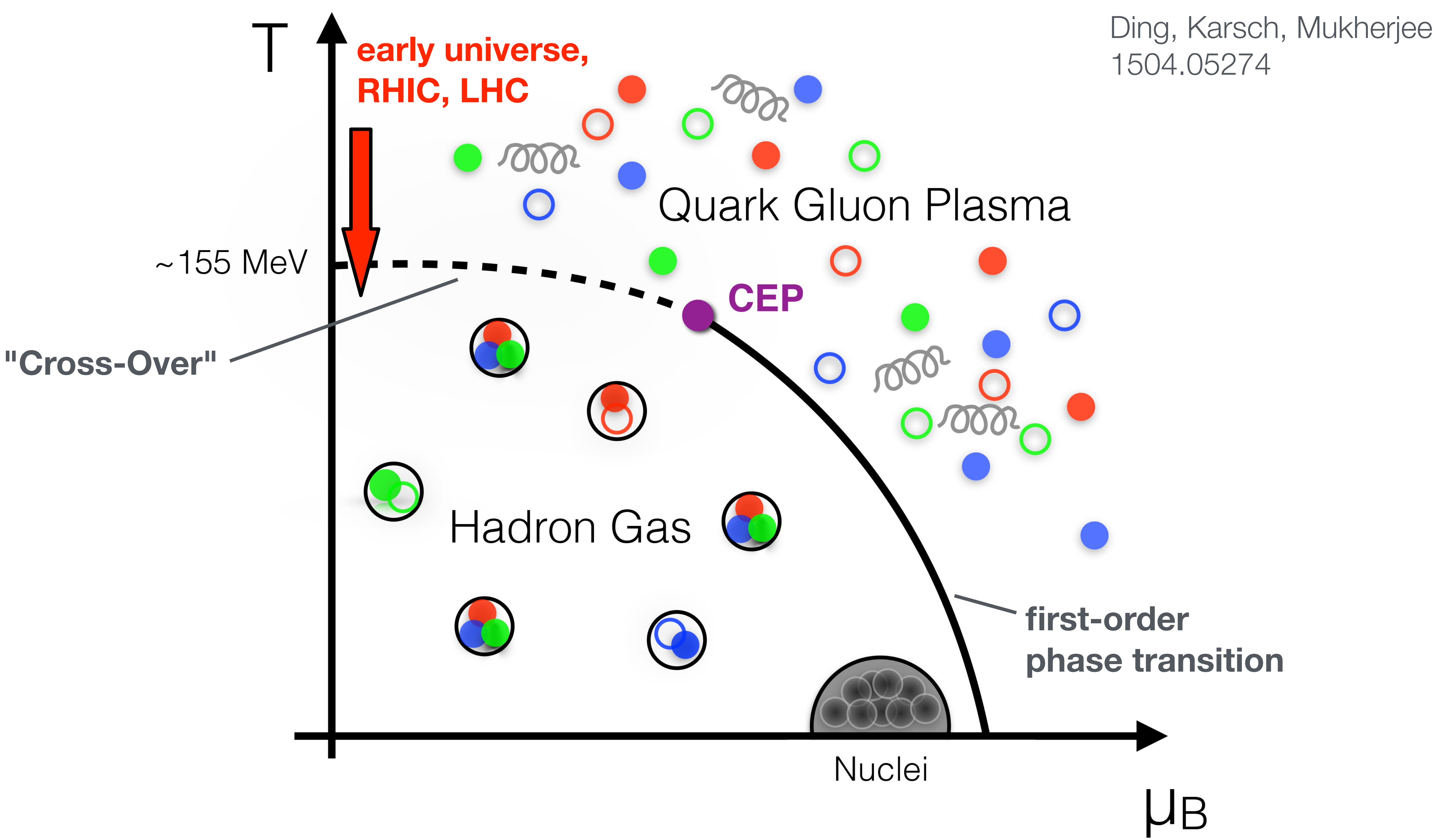


Quelle: urqmd.org

The other path to the QGP: Compression

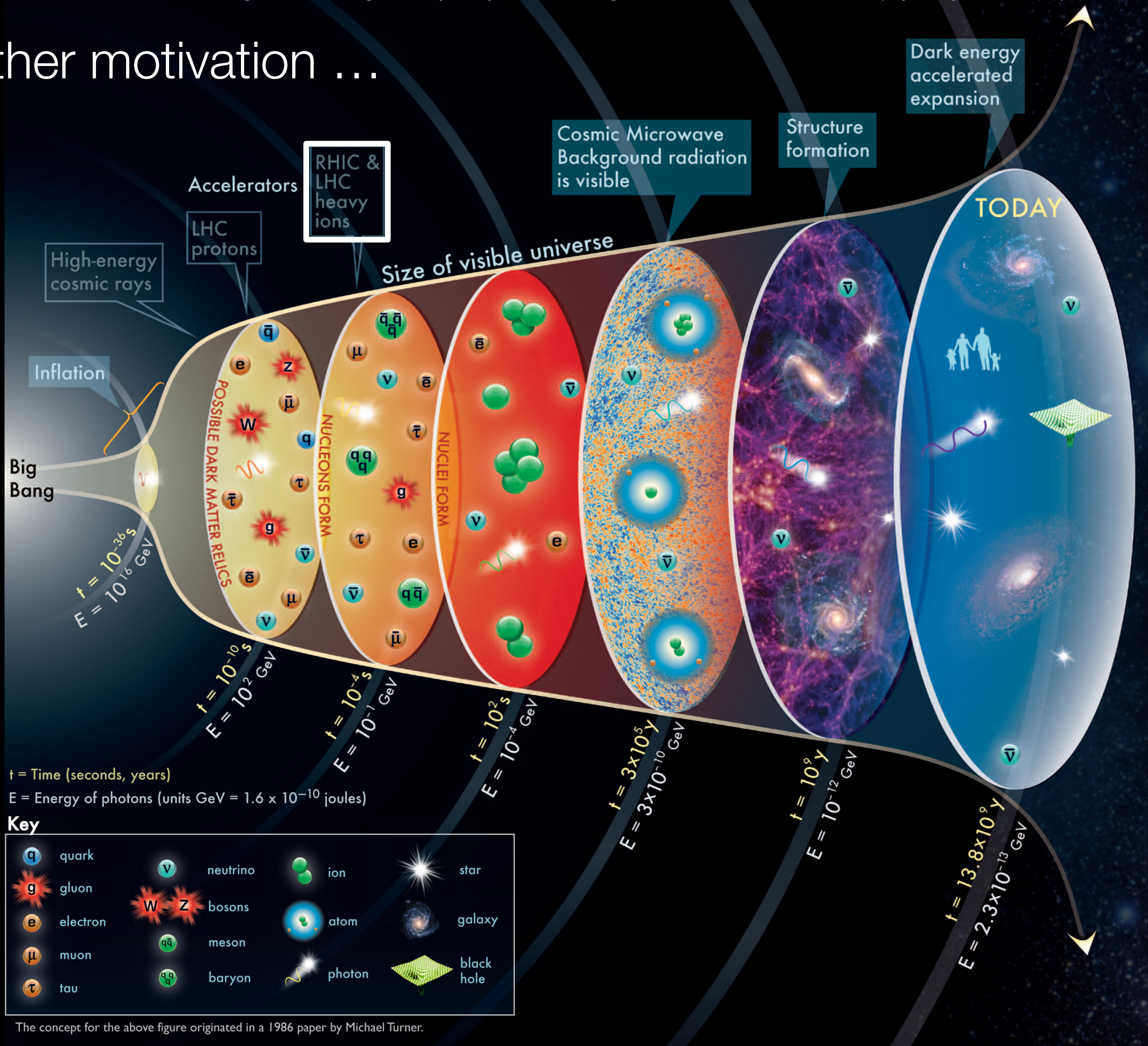


(Conjectured) QCD phase diagram



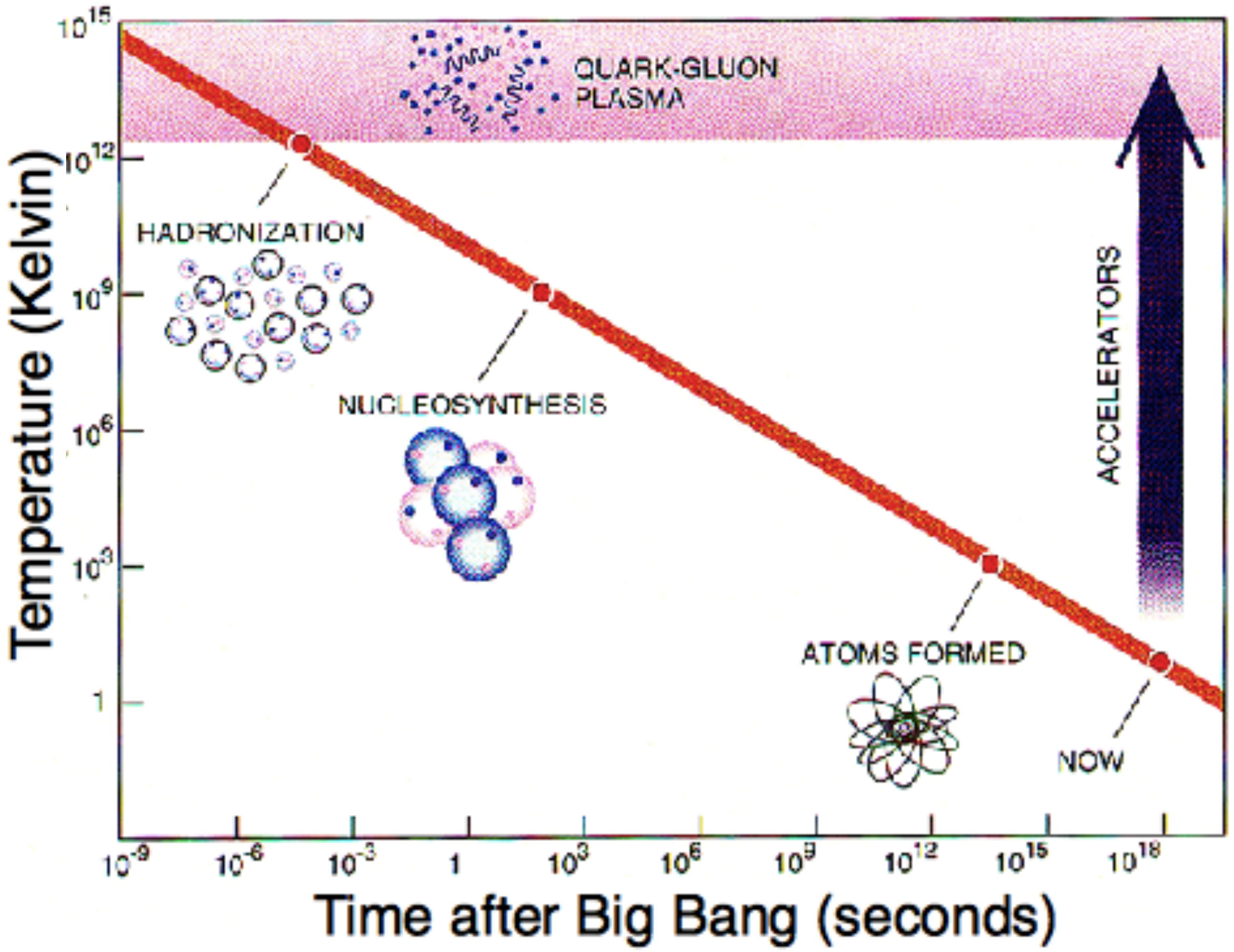
ultimate goal: contact with first-principles QCD calculations

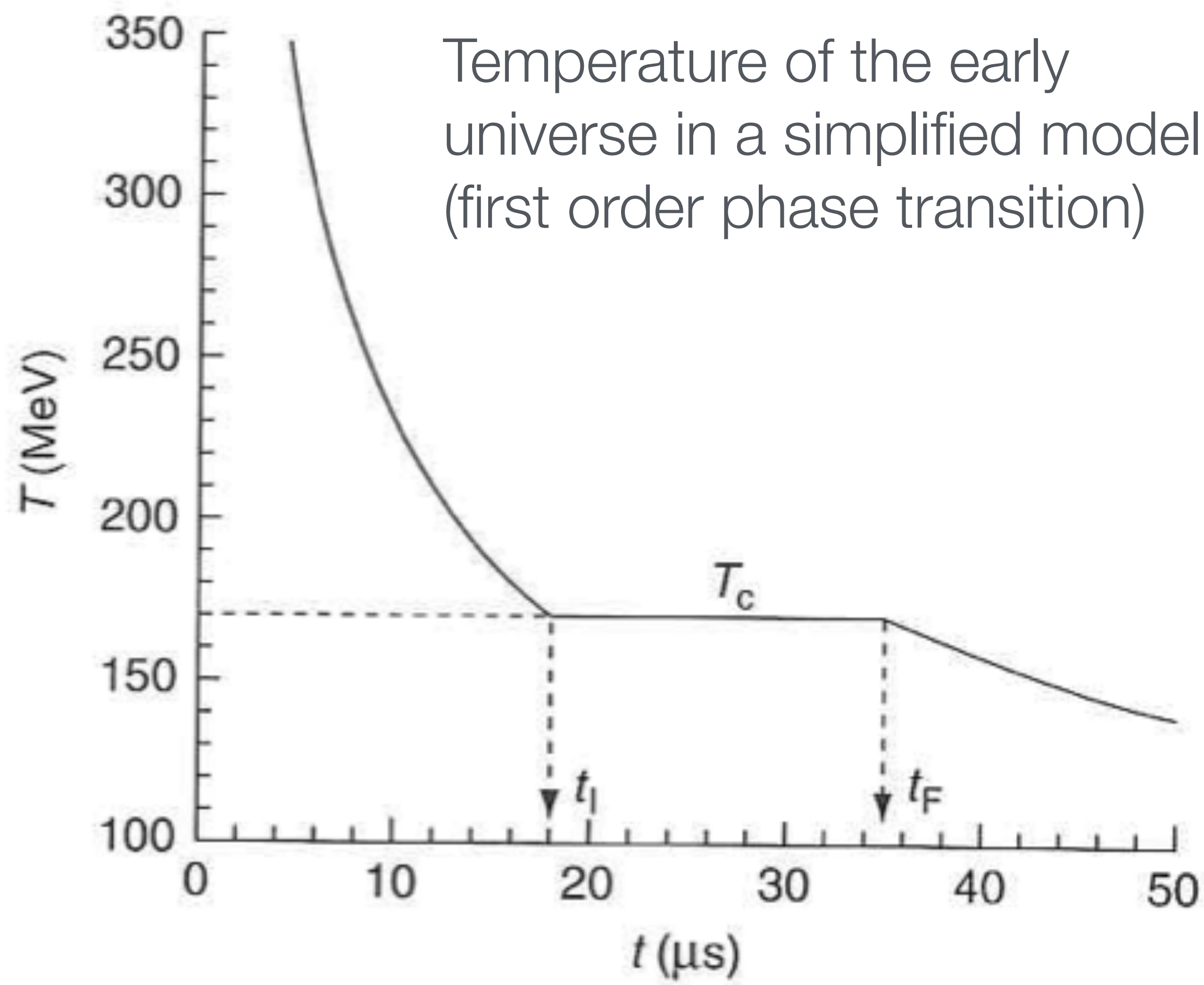
A further motivation …



The concept for the above figure originated in a 1986 paper by Michael Turner.

QGP in the early universe





Temperature of the early universe in a simplified model (first order phase transition)

- Transition from the quark-gluon plasma to a gas of hadrons at a temperature of $T_C \approx 1.8 \times 10^{12}$ K
- 100 000 hotter than the core of the sun
- Early universe: QGP → hadron gas a few microseconds after the Big Bang

Outline

not a theory lecture: focus is on experimental results and phenomenology

Website

Slides will be posted here
(ideally before the lecture)

Quark-Gluon Plasma Physics (SS 2017)

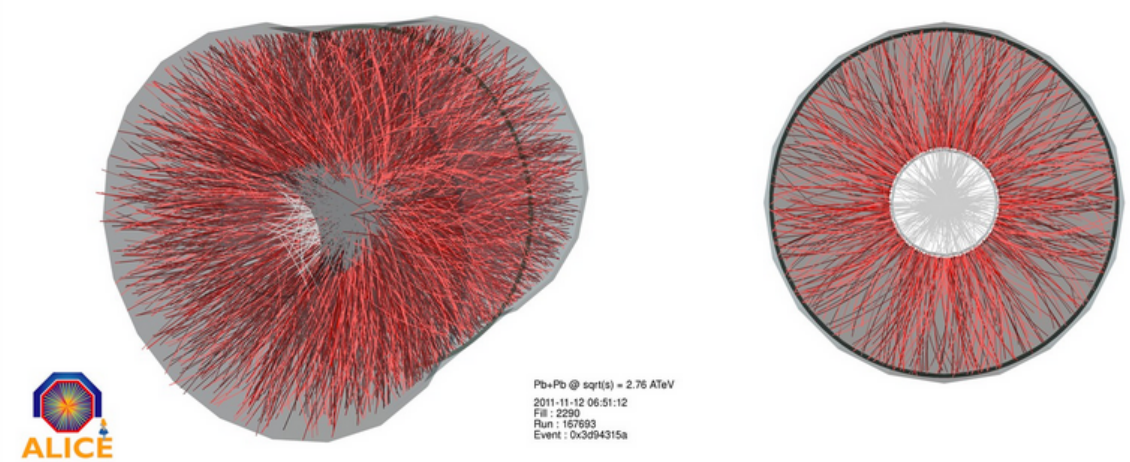
Prof. Dr. Klaus Reygers.

Welcome Contents Literature

close close others view more

Welcome

LAST MODIFIED 19 APRIL 2017



Central collisions of two lead nuclei at the LHC at a center-of-mass energy of 2.76 TeV per nucleon-nuclon pair measured with the ALICE experiment.

Lecturers / Dates

Quark-Gluon Plasma Physics: from fixed target to the LHC (SS 2017, LSF link)
Prof. Dr. Klaus Reygers
INF 226 (KIP), SR 2.404, Thursday, 11:15 - 12:45
first lecture: Thursday, April 20, 2017
ECTS points for this lecture: 2

Contents, schedule, and slides will be made available on this webpage.
We have assembled a list of **textbooks on quark-gluon plasma and heavy-ion physics** for these lectures.

Format of the lectures

In addition to the classical lecture form, we are planning on giving some lectures in form of the so-called inverted or flipped classroom. That is, material, e.g. slides or screencasts, will be provided before the lecture. The lecture itself will then be used to discuss conceptual questions or to consolidate and deepen the acquired knowledge.

Audience

This lecture gives an introduction into ultra-relativistiv heavy-ion collisions and the physics of the quark-gluon plasma. It is aimed at Bacherlor, Master, and Diploma students as well as graduate students. Knowledge on the level of "Experimentalphysik IV" (PEP4) is sufficient for this basic introduction.

Quark-Gluon Plasma Physics, SS 2017

http://www.physi.uni-heidelberg.de/~reygers/lectures/2017/qgp/qgp_lecture_ss2017.html

Audience

- Bachelor/Master students
  - deepen knowledge about nuclear and particle physics
  - relativistic kinematics, thermodynamics, basics of QCD, hydrodynamics, …
  - obtain overview of ultra-relativistic heavy-ion physics
  - obtain/apply programming skills as part of solving homework assignments (root, Mathematica, jupyter notebooks, …)
- (Early) doctoral students
  - Update on developments in areas besides own research topic

Requirement for the successful participation (I)

- no written exam
- a number of homework problems will be provided
- students present solutions (part of the lecture time will be devoted to this)
- homework assignments may include small programming problems
- dates for presentation of solution will be announced beforehand (check also lecture web page)
- 2 ECTS points

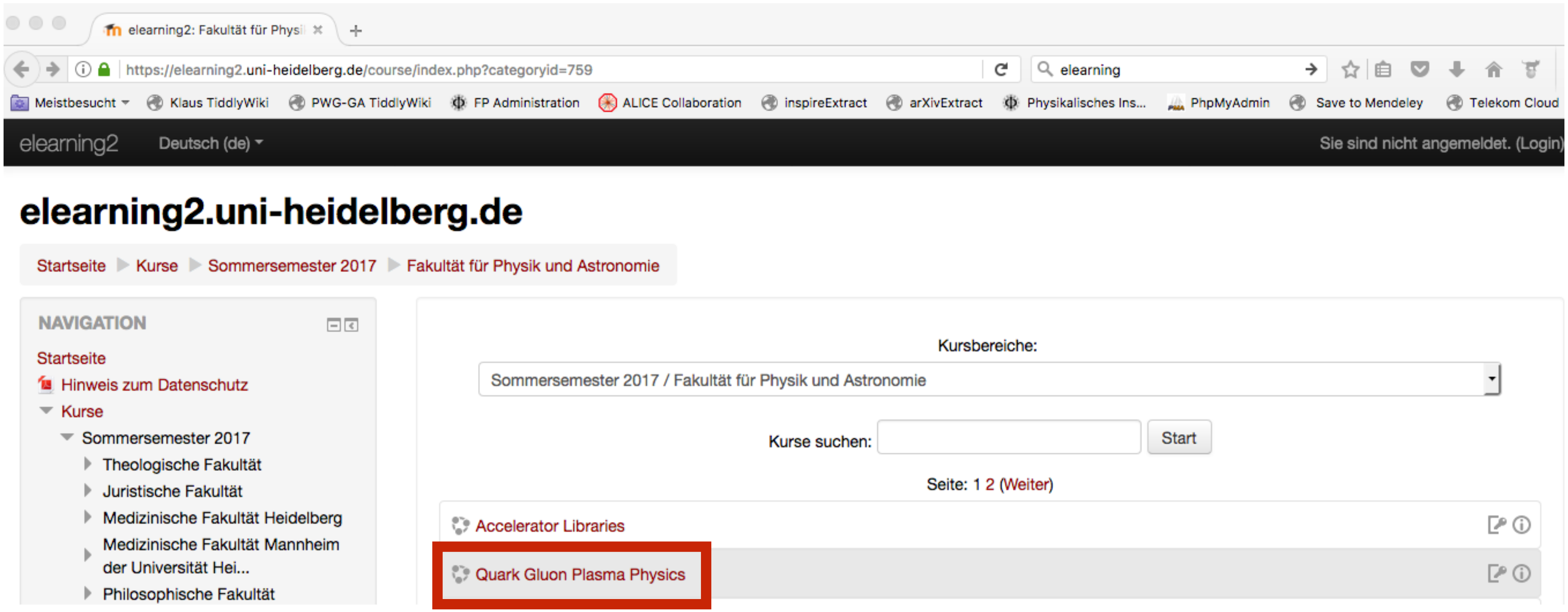
Contents | Schedule | Homework Assignments | Mathematica notebooks

Schedule

Week	Date	Chapter
1	20-Apr-2017	Introduction
2	27-Apr-2017	
3	04-May-2017	
4	11-May-2017	
5	18-May-2017	
6	25-May-2017	no lecture (Ascension Day)
7	01-Jun-2017	
8	08-Jun-2017	
9	15-Jun-2017	no lecture (Corpus Christi)
10	22-Jun-2017	
11	29-Jun-2017	
12	06-Jul-2017	
13	13-Jul-2017	
14	20-Jul-2017	
10	20-Jul-2017	no lecture

http://www.physi.uni-heidelberg.de/~reygers/lectures/2017/qgp/qgp_lecture_ss2017.html

Requirement for the successful participation (II)



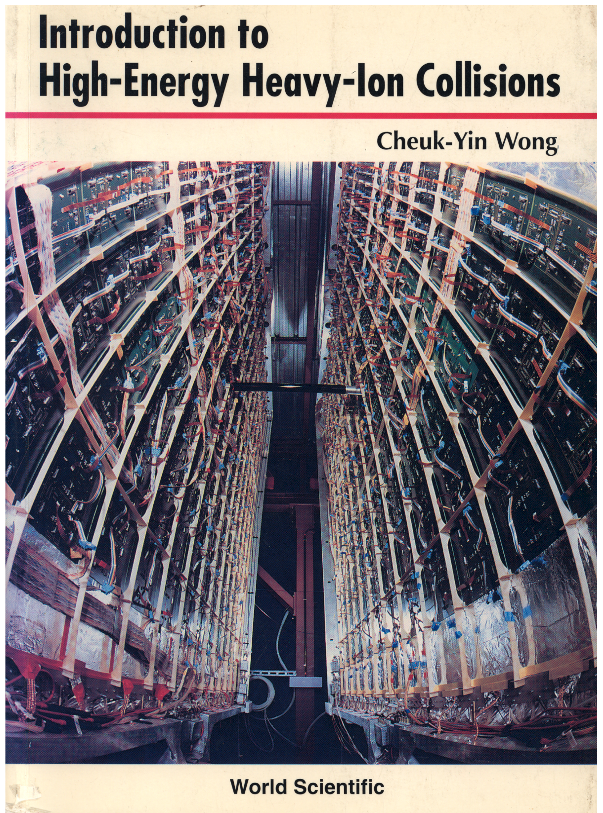
- Online quizzes for each topic
  - on moodle
  - https://elearning2.uni-heidelberg.de/course/view.php?id=15377
  - Requirement: At least 80% correct answers in each quiz
  - Can be repeated as many times as you like, best result counts

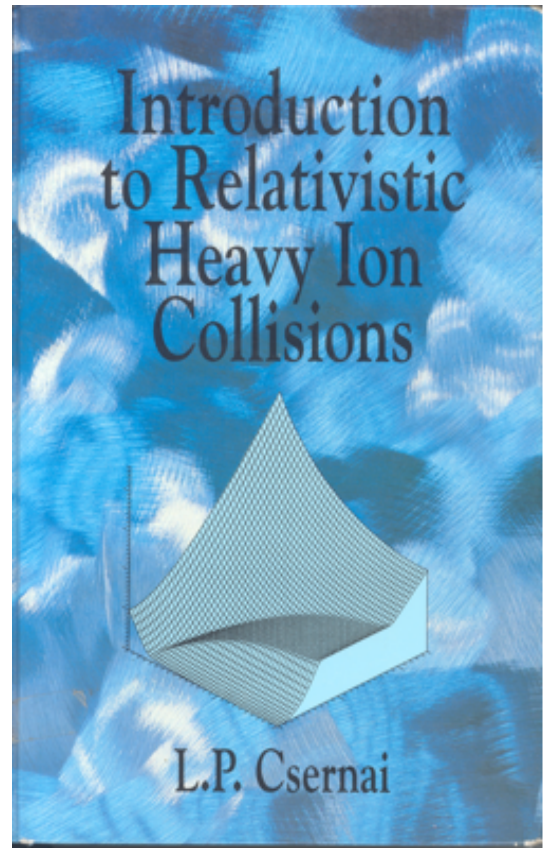
- Summary: successful participation
  - Present one homework problem
  - Pass all quizzes

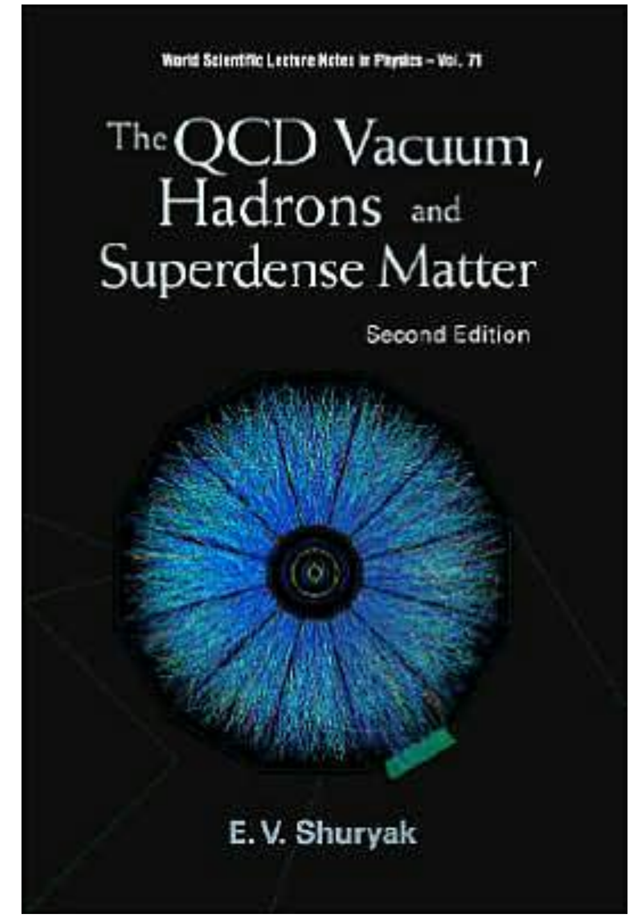
Inverted classroom

- Towards the second half of the semester we'll may try the "inverted classroom"
  - lecture we be provided in form of screencast beforehand
  - lecture time will be devoted to quizzes / deepening of certain points
- Let's see how this goes …

Books (I)

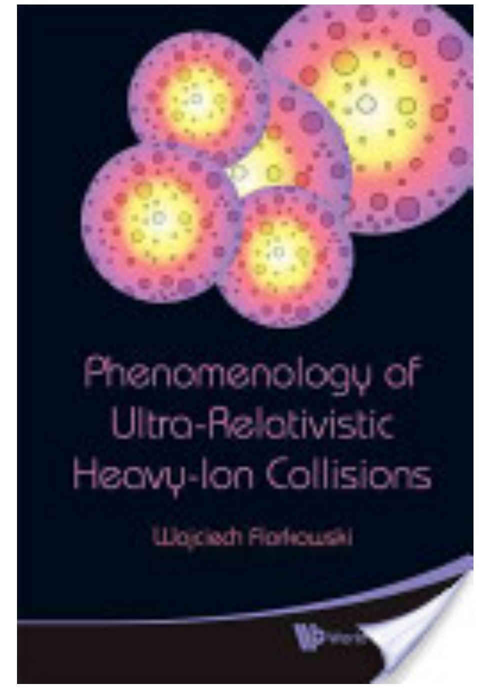


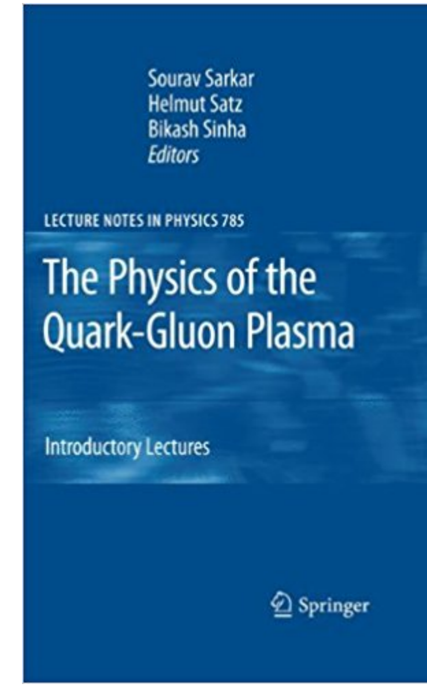




- Wong, Introduction to High-Energy Heavy-Ion Collisions,World Scientific, 1994
- Csernai, Introduction to Relativistic Heavy-Ion Collisions, 1994, book is now freely available as pdf (→ link)
- Shuryak, The QCD vacuum, hadrons, and superdense matter, World Scientific, 2004

Books (II)





- Yagi, Hatsuda, Miake, Quark-Gluon Plasma,Cambridge University Press, 2005
- Vogt, Ultrarelativistic Heavy-Ion Collisions,Elsevier, 2007
- Florkowski, Phenomenology of Ultra-Relativistic Heavy Ion Collisions, World Scientific, 2010
- Sarkar, Satz, Sinha, The Physics of the Quark-Gluon Plasma
  - download for members of Heidelberg university (→ link)

Units in this lecture

- Energy: GeV
- Momentum: GeV/c
- Length: fm ("Fermi"), 1 fm = 10^{-15} m

$$\hbar c = 0.197 \,\mathrm{GeV\,fm}$$

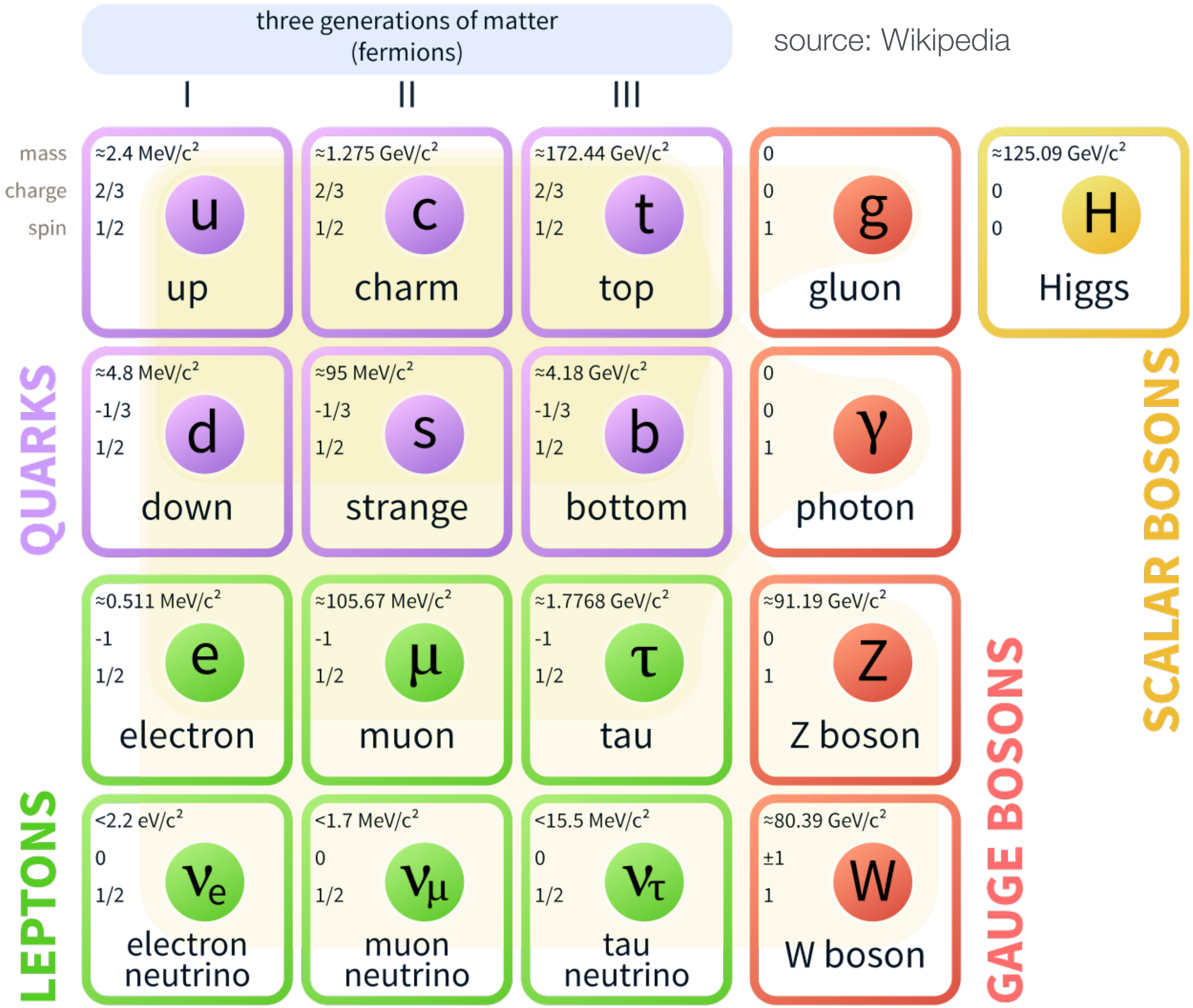
- time: fm/c, 1 fm/c = $0.33 \cdot 10^{-23}$ s

- temperature: $k_B = 8.617 \cdot 10^{-5}$ eV/K
  - room temperature: $k_B T$ = 1/40 eV (T = 300 K)
  - QGP phase transition: $k_B T$ = 155 MeV ($T = 1.8 \cdot 10^{12}$ K)

- Natural units: $\hbar = c = k_\mathrm{B} = 1$

$$E^2 = m^2 c^4 + p^2 c^2 \quad \rightsquigarrow \quad E^2 = m^2 + p^2, \qquad T_c = 155\,\mathrm{MeV}$$

Reminder: Fundamental components of matter

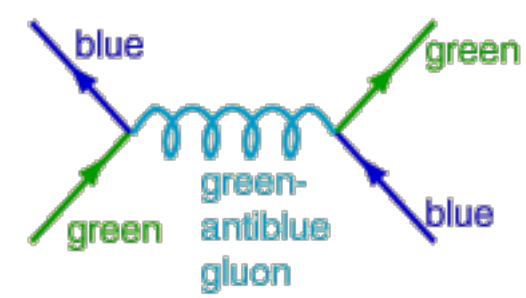


source: Wikipedia

+ antiparticles

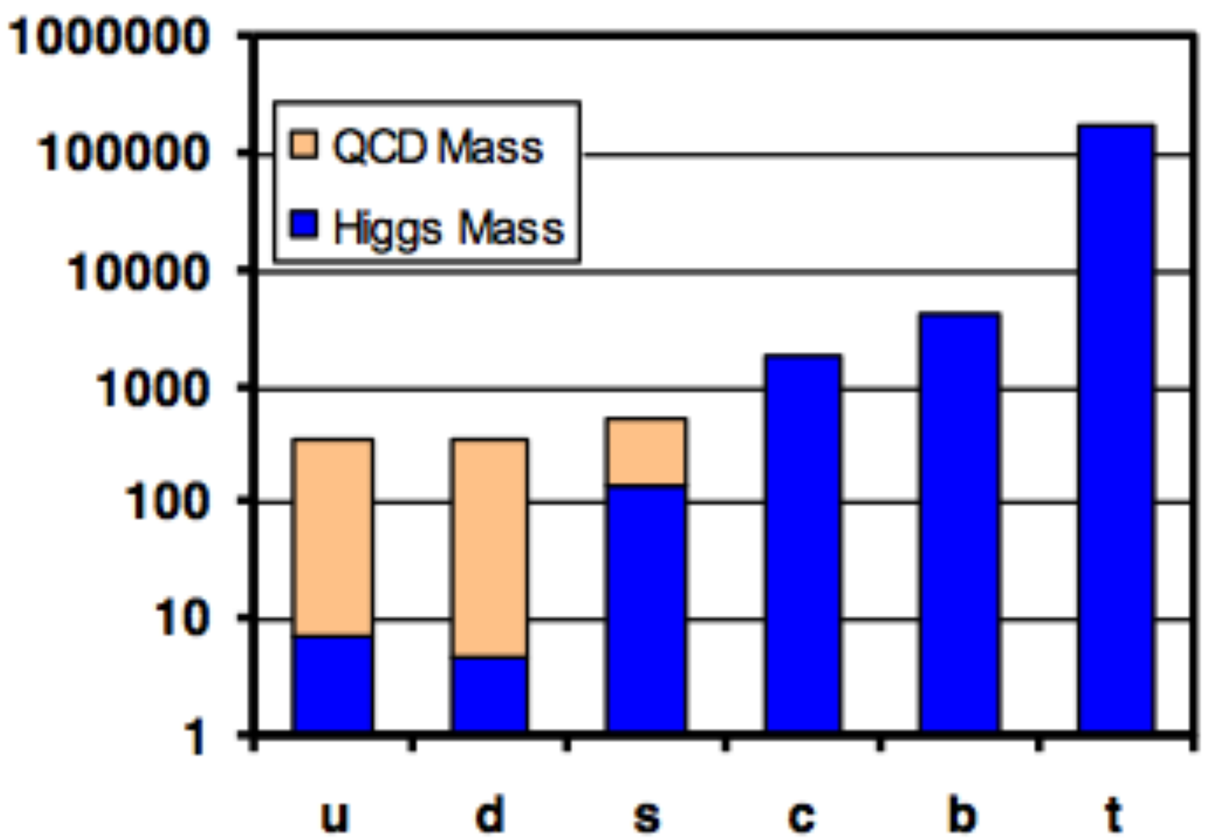
Quarks come in three different colors: ● ● ●

Gluons: mediate interaction between quarks



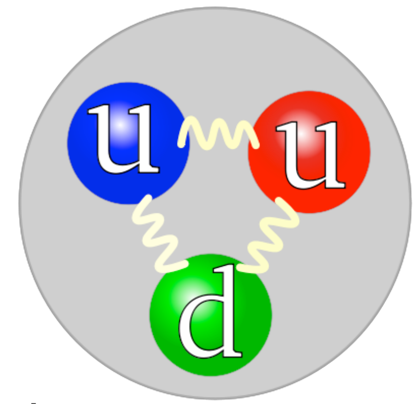
Feynman diagram for an interaction between quarks generated by a gluon.

Quarks are bound in (color-neutral) hadrons by the strong interaction

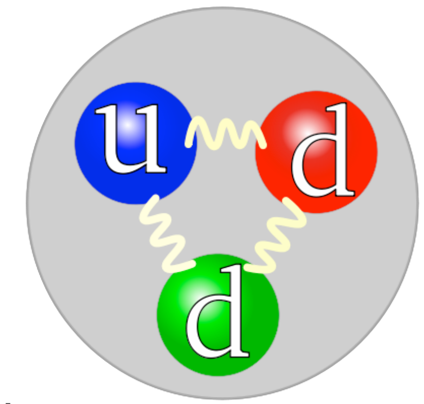


$2\, m_{\mathrm{u}} + m_{\mathrm{d}} = 9.6\ \mathrm{MeV}/c^2$

$m_{\mathrm{proton}} = 938.27\ \mathrm{MeV}/c^2$!!!

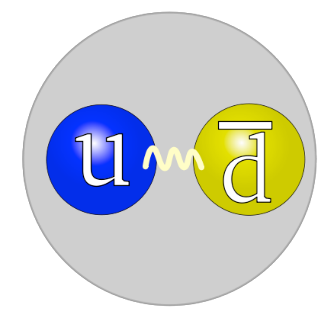


proton



neutron

source: http://de.wikipedia.org

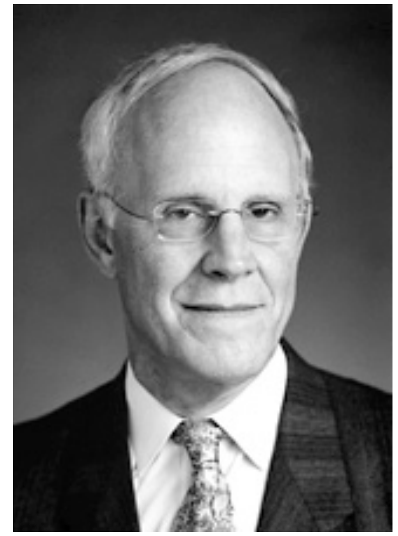


positive pion

- Hadron mass scale set by constituent quarks masses ($m_{\mathrm{u,d,const}} \approx 300\ \mathrm{MeV}/c^2$)
- QCD responsible for 99% of the mass of your body!
- Related to breaking of chiral symmetry

The Strong Interaction

Nobel prize in physics (2004)



David J. Gross

H. David Politzer

Frank Wilczek

D.J. Gross, F. Wilczek, Phys. Rev. Lett. 30 (1973) 1343
H.D. Politzer, Phys. Rev. Lett. 30 (1973) 1346

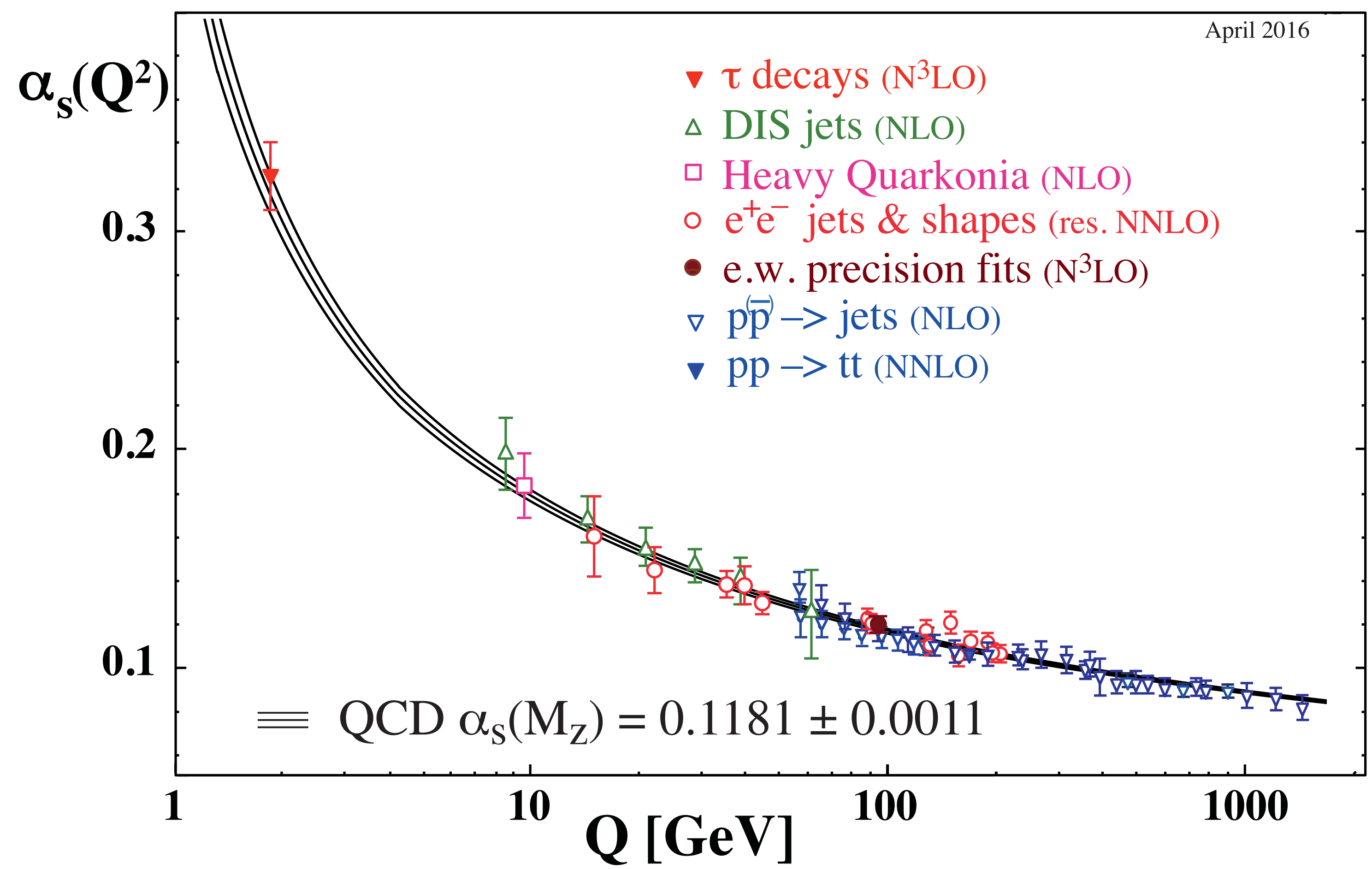
- Confinement:
  Isolated quarks and gluons cannot be observed, only color-neutral hadrons
- Asymptotic freedom:
  Coupling α_s between color charges gets weaker for high momentum transfers, i.e., for small distances ($\alpha_s(q^2) \to 0$ for $q^2 \to \infty$), perturbative methods applicable for distances $r < 1/10$ fm
- Limit of low particle densities and weak coupling experimentally well tested (→ QCD perturbation theory)
- High-energy Nucleus-Nucleus collisions:
  QCD at high temperatures and density („QCD thermodynamics")

Running QCD coupling constant

In QED vacuum polarization leads to increase of coupling constant α with decreasing *r*, running slow (1/128 at the *Z* mass, $\sqrt{Q^2}$ = 91 GeV)

In QCD the opposite: colored gluons spread out color charge leading to anti-shielding, decrease of coupling constant α_s with decreasing *r* or increasing momentum transfer *Q*

Particle Data Group: http://pdg.lbl.gov/



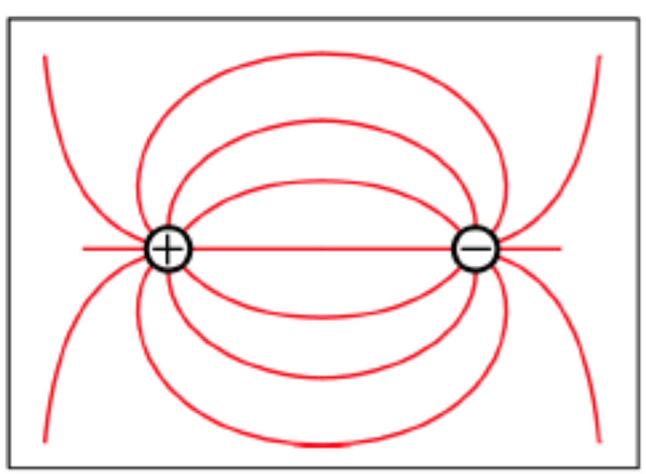
QED vs. QCD (1)

Quarks carry electric charge and color charge (1 of 3 possible). They interact strongly by exchange of colored gluons (8 different gluons from 3 colors and 3 anticolors).

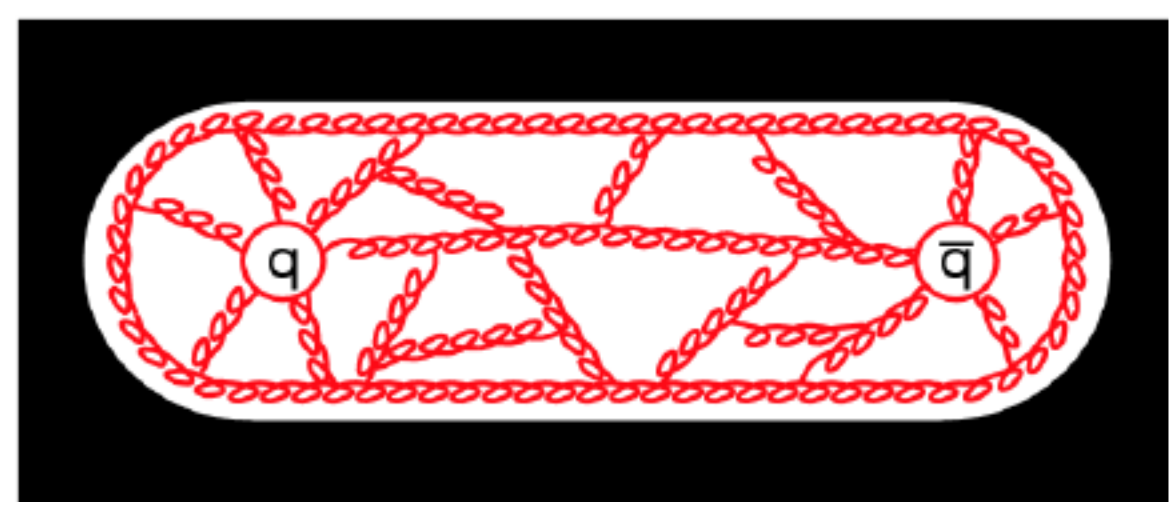
Because gluons are colored, QCD is very different from QED. QCD is a non-Abelian field theory of Yang-Mills type (1973 Fritzsch, Gell-Mann, Wess).

Quarks are confined in hadrons, trying to pull them apart finally leads to the production of new hadrons

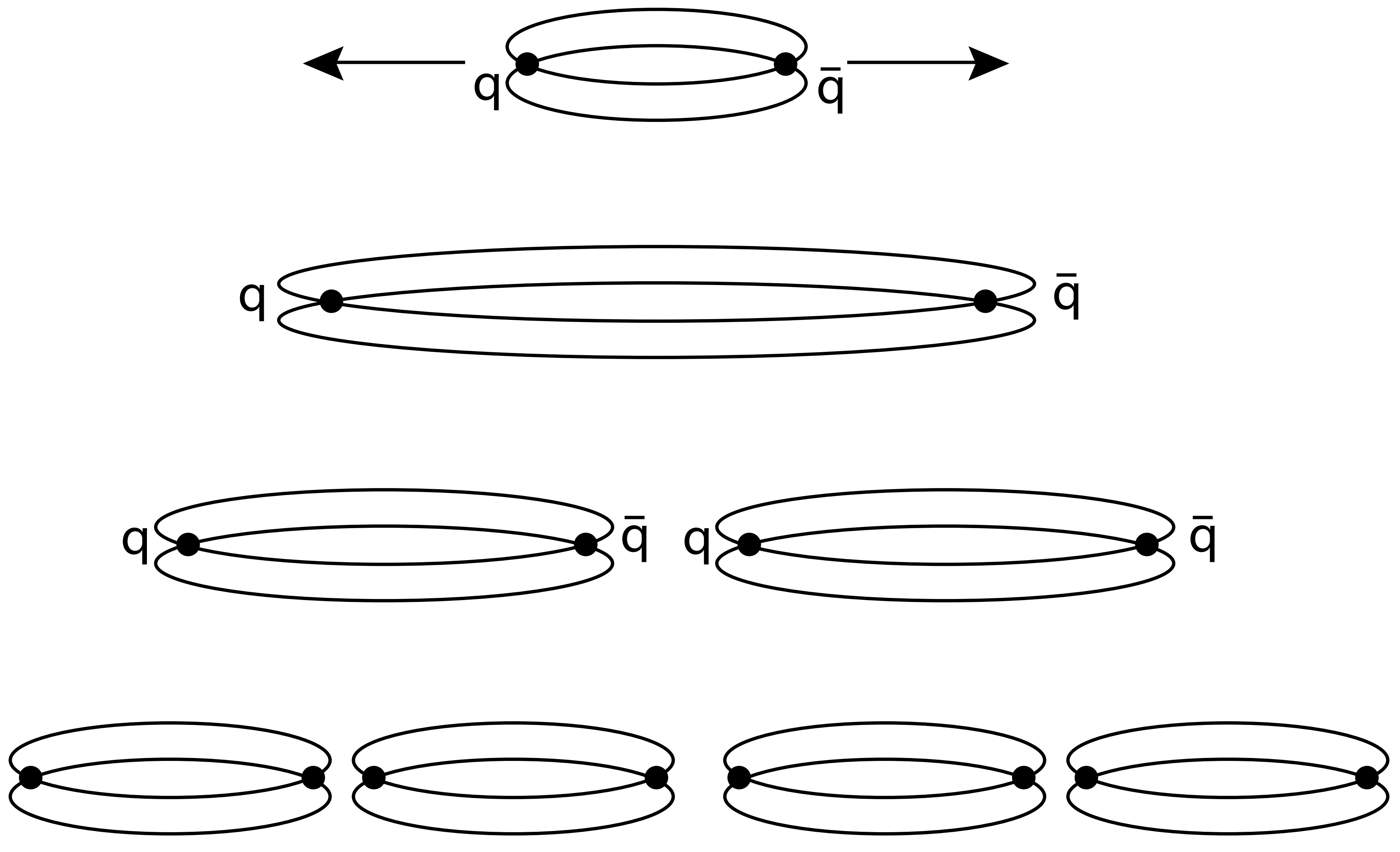
QED:



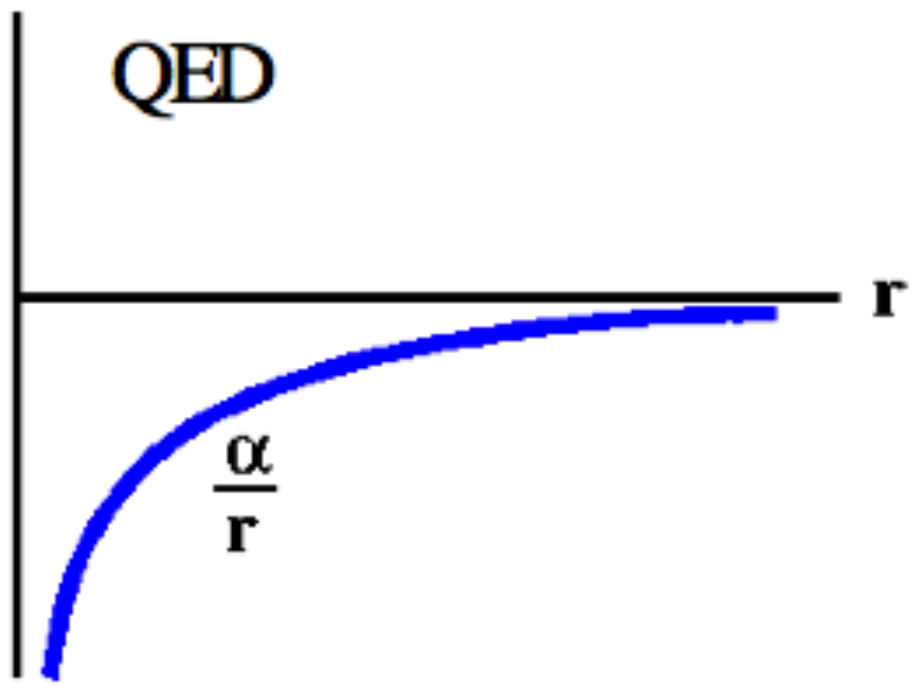
QCD:



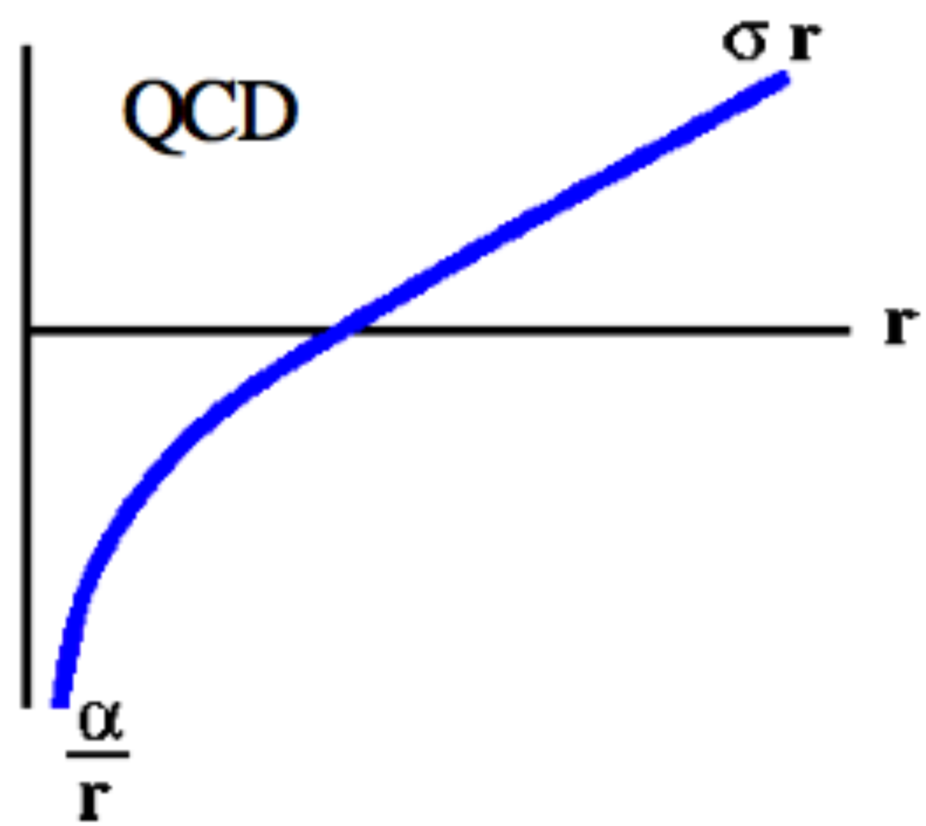
Production of hadrons when quark-antiquark pair is pulled apart



QED vs. QCD (2)



$$V(r) \propto \frac{\alpha}{r}$$



$$V(r) = -\frac{4\alpha_s(r)}{3r} + k\,r$$

Linear term associated with confinement, expected to disappear in the QGP

Limits of the hadron gas

Dokl. Akad. Nauk SSSR 78, 889 (1951)

- Pomeranchuk considered the conceptual limit of the ideal pion gas
- He argued that a pion gas makes sense as long as there is some minimum volume available per pion:

$$n_c = \frac{1}{V_0} = \frac{3}{4\pi r_0^3} \qquad r_0 \simeq 1/m_\pi \approx 1.4\,\mathrm{fm}$$

- Partition function for an ideal gas of identical, point-like pions

$$\begin{aligned} \ln Z_0(T,V) &= \frac{V}{(2\pi)^3} \int d^3p \exp\left(-\sqrt{p^2+m^2}/T\right) \\ &= \frac{VTm^2}{2\pi^2} K_2(m/T) \end{aligned}$$

modified Bessel function of 2nd kind

- Pion density: $$n(T) = \left(\frac{\partial \ln Z_0(T,V)}{\partial V}\right)_T = \frac{Tm^2}{2\pi^2} K_2(m/T)$$
- Critical density: $$n(T_c) = n_c \qquad \rightarrow \qquad T_c = 1.4 m_\pi \approx 190\,\mathrm{MeV}$$

The Hagedorn limiting temperature (1)

- Observation ca. 1960:
  Number density of hadronic states ρ(m) seemed to grow without limit
- 1965: Hagedorn described this with his statistical bootstrap model
  - "fireballs consist of fireballs, which consist of fireballs, and so on …"
  - Suppl. Nuovo Cim. 3 (1965) 147
- Such self-similar models lead to an exponentially growing mass spectrum of hadronic states

$$\rho(m) = m^{-a} e^{bm}$$

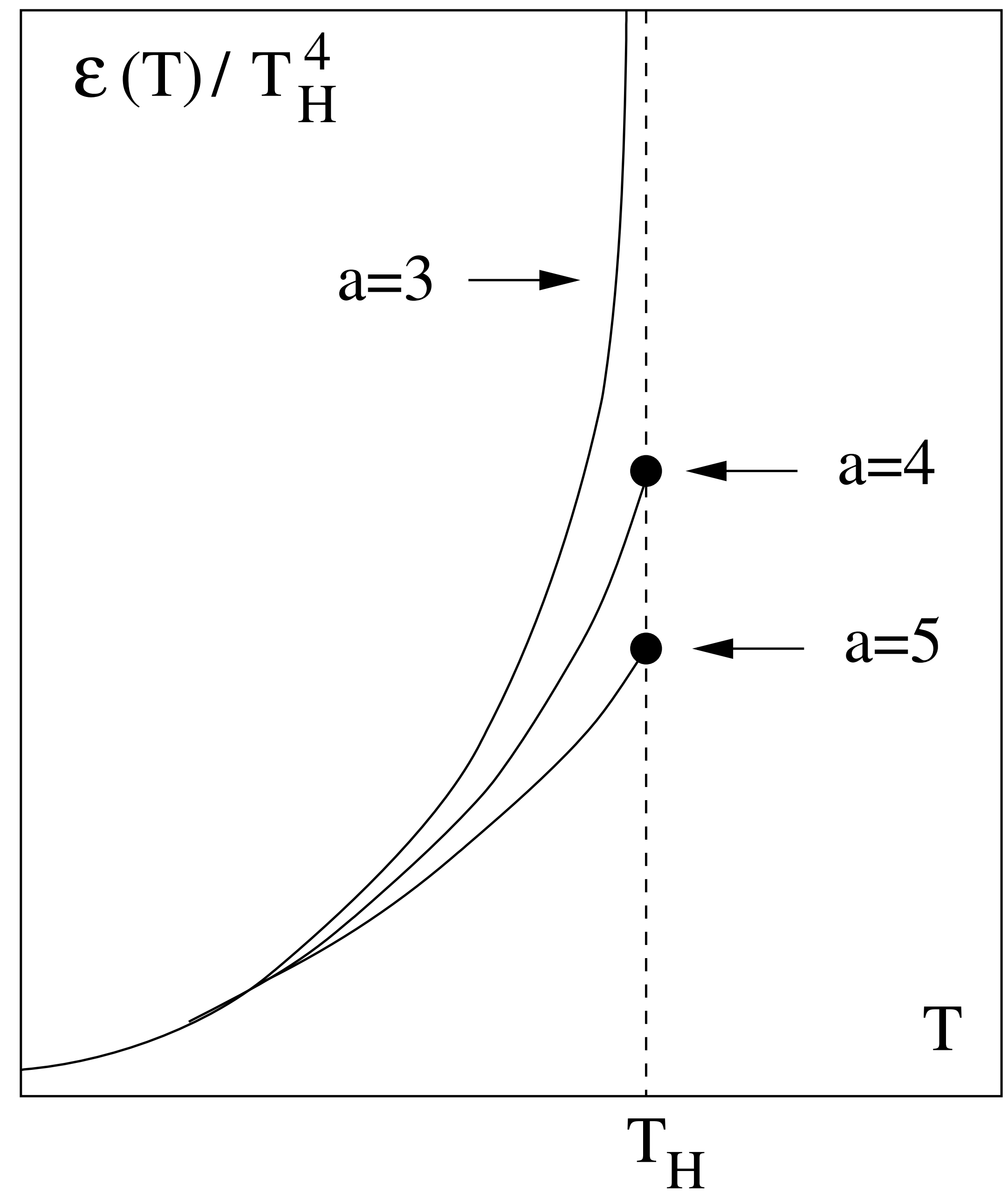
  where $1/b$ = 0.15 - 0.20 GeV.
- Resulting energy density of the hadron resonance gas:

$$\varepsilon(m) \sim V T^{7/2} \int_{m_0}^{\infty} \mathrm{d}m \, m^{\frac{5}{2}-a} e^{m(b-\frac{1}{T})}$$

The Hagedorn limiting temperature (2)

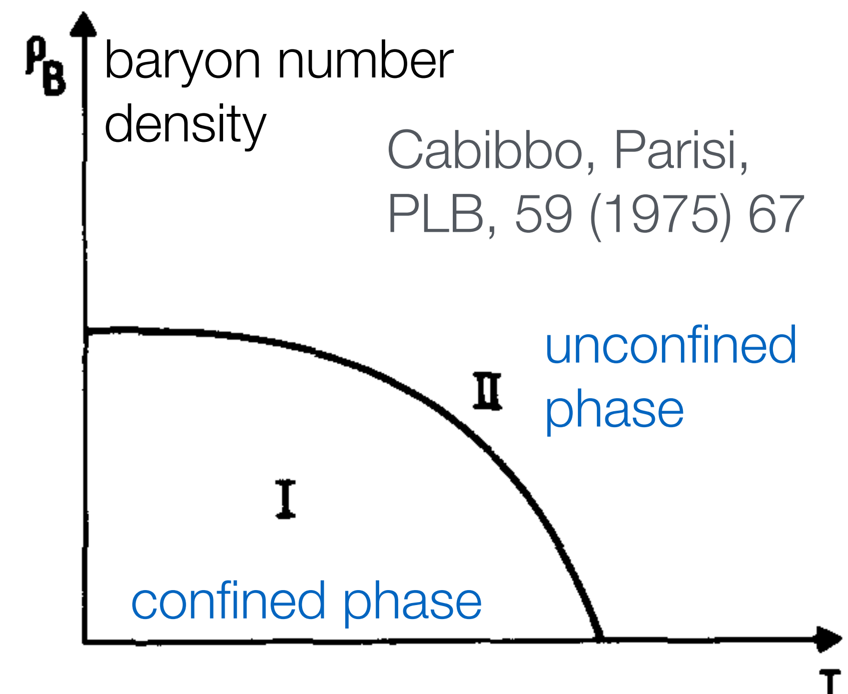
- Hagedorn used a = 3 and concluded that T_H = 0.15 GeV would be the ultimate temperature of all matter
- Physical reason:
  - Energy put into the system excites high-mass resonances
  - This prevents a further increase of the temperature
- However, this conclusion depends on the value of a
  - For a > 7/2 the energy density remains finite
  - In this case temperatures $T > T_H$ could perfectly well exist

H. Satz, Extreme States of Matter in Strong Interaction Physics, Springer, 2012



QGP — the idea

- 1973 — Birth of QCD
  - All ideas in place:
    Yang-Mills theory; SU(3) color symmetry; asymptotic freedom; confinement in color-neutral objects
- 1975 — Idea of quark deconfinement at high temperature and/or density
  - Collins, Perry, PRL 34 (1975) 1353
    - "Our basic picture then is that matter at densities higher than nuclear matter consists of a quark soup."
    - Idea based on weak coupling (asymptotic freedom)
  - Cabibbo, Parisi, PLB, 59 (1975) 67
    - Exponential hadron spectrum not necessarily connected with a limiting temperature
    - Rather: Different phase in which quarks are not confined
- It was soon realized that this new state could be created and studied in heavy-ion collisions



Order-of-magnitude physics of the QGP: Critical temperature at vanishing net baryon number

- Consider an ideal gas of u, d quarks and antiquarks, and gluons
- Calculate temperature at which energy density equals that within a proton
- Energy density in a proton

$$\varepsilon_{\text{proton}} = \frac{m}{V} = \frac{0.94\,\text{GeV}}{4/3\pi(0.8\,\text{fm})^3} \approx 0.44\,\text{GeV}/\text{fm}^3$$

- Energy density of an ideal gas of massless u and d quarks

$$\varepsilon_{\text{id.gas}} = 37\frac{\pi^2}{30}T^4 = 0.44\,\text{GeV}/\text{fm}^3 \rightarrow T \approx 130\,\text{MeV} \qquad (k_B = 1)$$
$$= 1.5 \times 10^{12}\,\text{K}$$

Note, however, that the α_s around T = 200 MeV is not small (ideal gas assumption not justified)

Order-of-magnitude physics of the QGP: Critical density at vanishing temperature

- Baryon density of nuclear matter ($R = r_0 A^{1/3}, r_0 \approx 1.15$ fm):

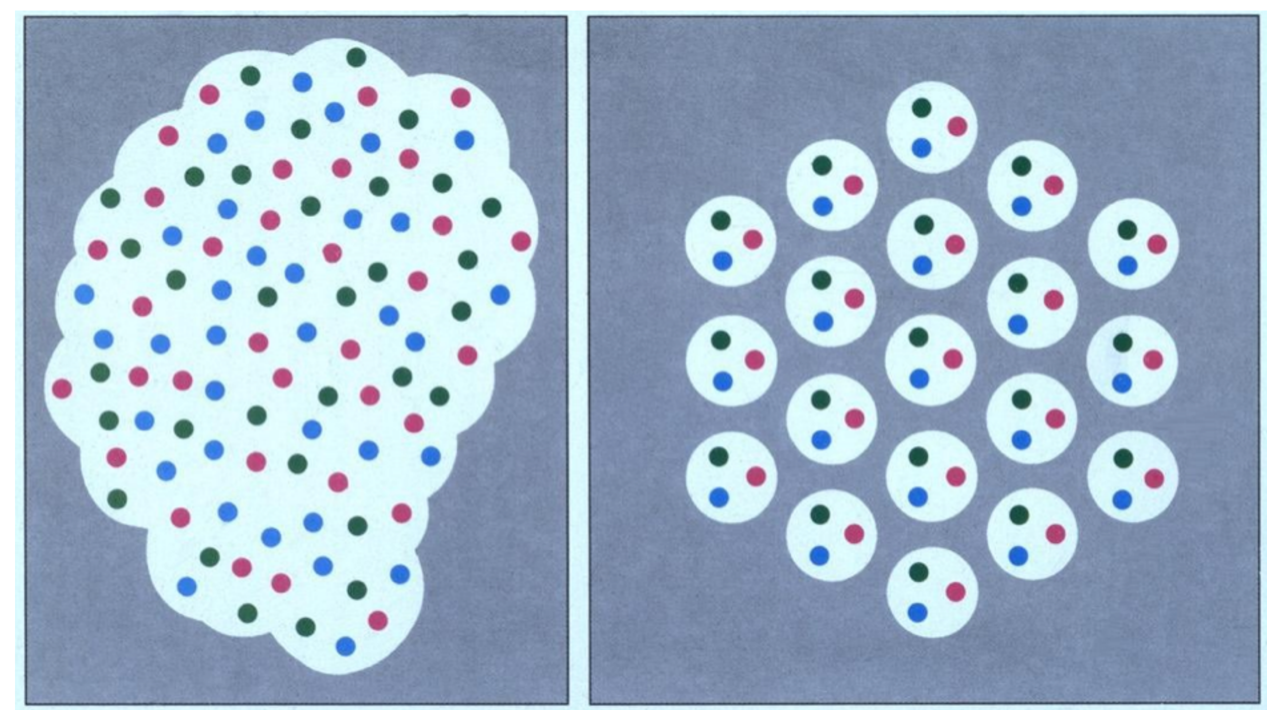
$$\rho_0 = \frac{A}{4\pi/3R^3} = \frac{1}{4\pi/3r_0^3} \approx 0.16\,\mathrm{fm}^{-3}$$

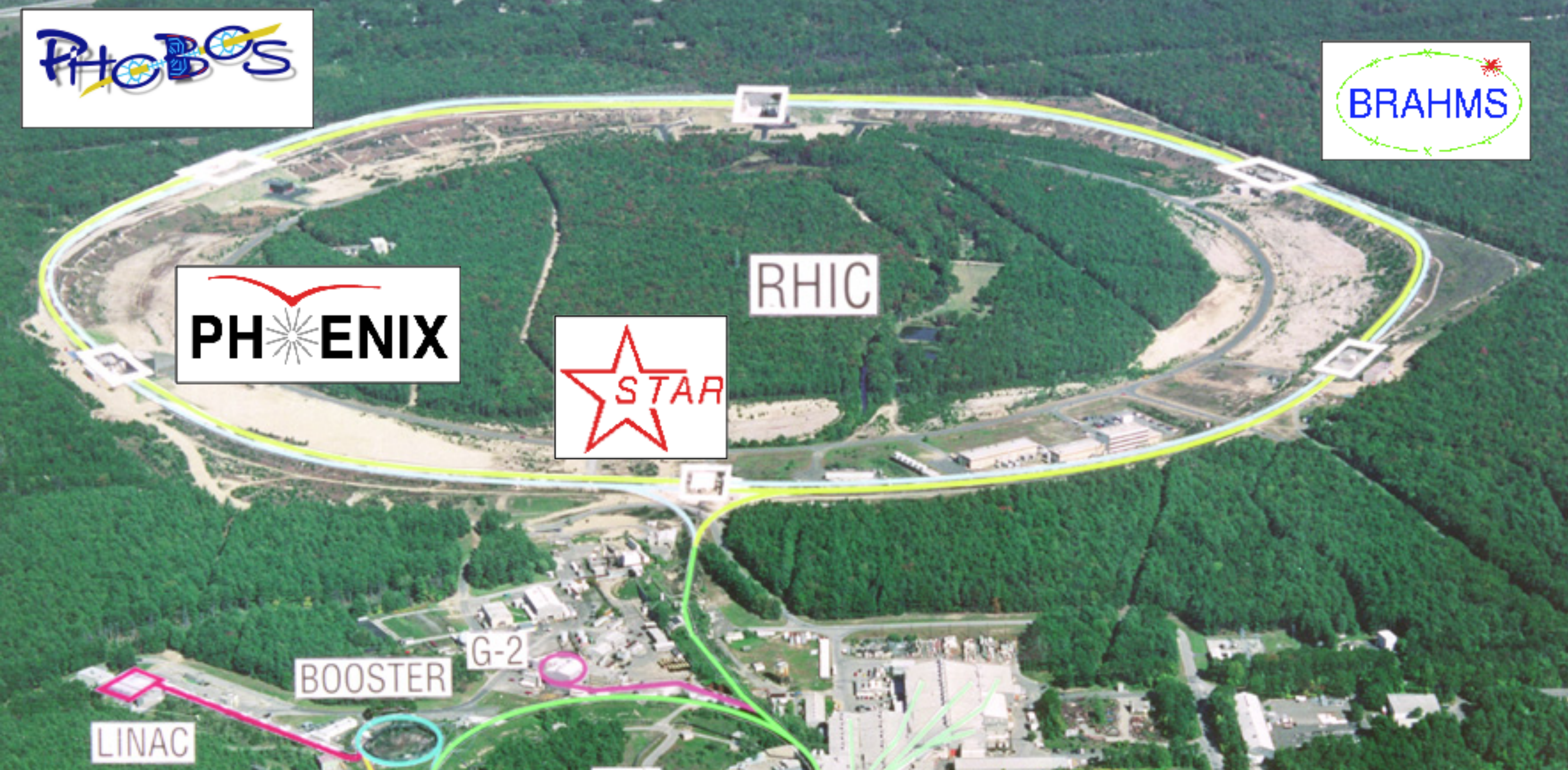
- Nucleons start to overlap at a critical density ρ_C if nuclear matter is compressed ($r_N \approx 0.8$ fm):

$$\rho_c = \frac{1}{4\pi/3r_n^3} \approx 0.47/\mathrm{fm}^3 = 3\rho_0$$

- A refined calculation in fact gives a somewhat higher critical density

Figure: CERN





RHIC: Relativistic Heavy Ion Collider at BNL 2000 - ...

circumference 3.83 km, 2 independent rings, superconducting,
max. energy *Z/A* x 500 GeV = 200 GeV per nucleon pair for Au,
luminosity in Au-Au: 2×10^{26} cm^{-2} s^{-1}
2 large and 2 smaller experiment

LHC lead beam 2010/11:
1.38 TeV/nucleon Pb beams → $\sqrt{s_{NN}}$ = 2.76 TeV

A little bit of history

- 1974 Bear mountain workshop 'BeV/nucleon collisions of heavy ions' [link]
  - Focus on exotic matter states and astrophysical implications
- 1983 long range plan for nuclear physics in US:
  Realization that the just abandoned pp collider project at Brookhaven could be turned into a nuclear collider inexpensively
- 1984: 1-2 GeV/*c* per nucleon beam from SuperHILAC into Bevalac at Berkeley
- 1986
  - beams of silicon at Brookhaven AGS ($\sqrt{s_{NN}} \approx 5$ GeV)
  - beams of oxygen/sulfur at CERN SPS ($\sqrt{s_{NN}} \approx 20$ GeV)
- 1992/1994
  - beams of gold at Brookhaven AGS ($\sqrt{s_{NN}} \approx 5$ GeV)
  - beams of lead at CERN SPS ($\sqrt{s_{NN}} \approx 17$ GeV)
- 2000: gold-gold collisions at RHIC ($\sqrt{s_{NN}} \approx 200$ GeV)
- 2010: lead-lead collisions at the LHC ($\sqrt{s_{NN}} \approx 2760$ GeV)
- 2015: lead-lead collisions at the LHC ($\sqrt{s_{NN}} \approx 5020$ GeV)

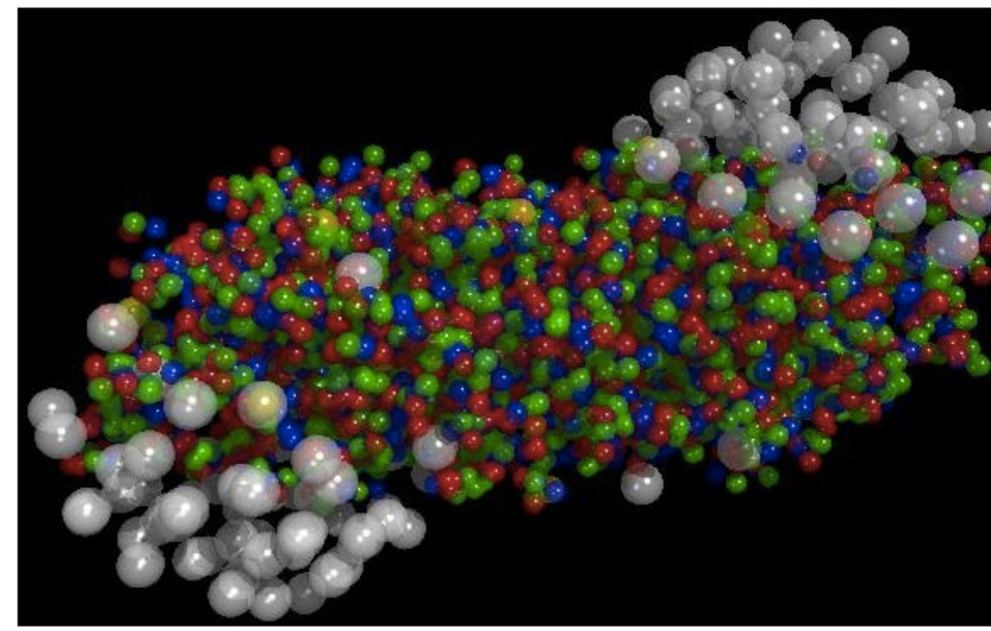
CERN press release in February 2000:

http://press.web.cern.ch/press-releases/2000/02/new-state-matter-created-cern

- Press release text
  - At a special seminar on 10 February, spokespersons from the experiments on CERN's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.
- Summary in nucl-th/0002042
  - “The new state of matter found in heavy ion collisions at the SPS features many of the characteristics of the theoretically predicted quark-gluon plasma”

New State of Matter created at CERN

10 Feb 2000



- Featured on front page of the NY times
- Mixed reactions among US physicists …

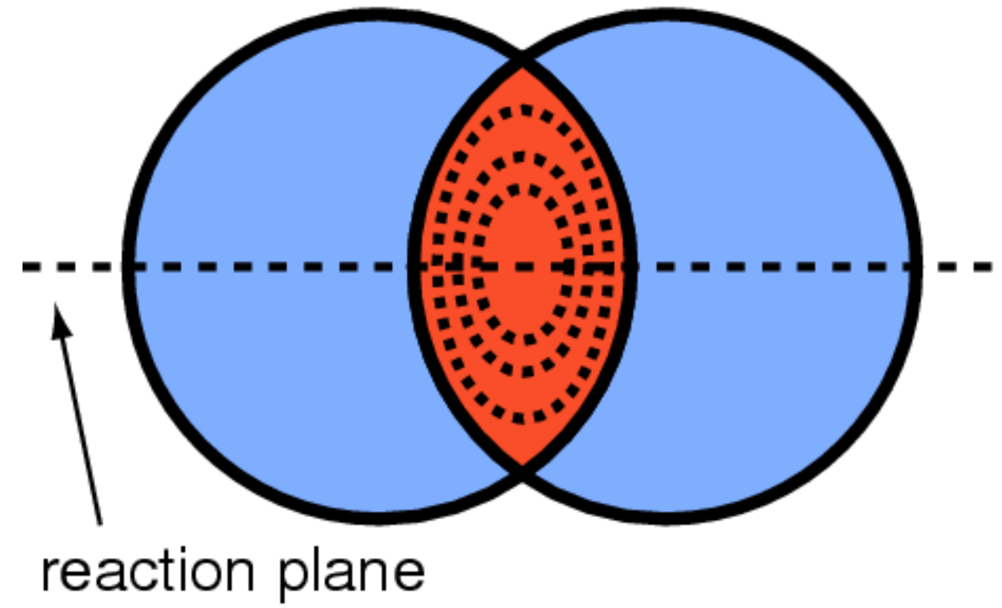
BNL press release April 2005: RHIC Scientists Serve Up "Perfect" Liquid [link]

- Considered to be the announcement of the QGP discovery
- Accompanied by the four papers on the first three years of RHIC running
  - BRAHMS
    - "Quark gluon plasma and color glass condensate at RHIC? The Perspective from the BRAHMS experiment"
  - PHENIX
    - "Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration"
  - PHOBOS
    - "The PHOBOS perspective on discoveries at RHIC"
  - STAR
    - "Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions"
- QGP near T_c is not a weakly interacting gas, but a strongly correlated liquid (sQGP)
- But: Not easy to find clear statements on QGP discovery in these papers

Important results from the RHIC heavy-ion programme

- Azimuthal anisotropy of particle production at low p_T (< 2 GeV/c)
  - Interpreted as a result of the collective expansion of the QGP
  - Ideal hydrodynamics close to data
  - Small viscosity over entropy density: strongly coupled QGP, "perfect liquid"
  - Evidence for early QGP thermalization ($\tau \lesssim$ 1-2 fm/c)
- Hadron suppression at high p_T
  - Medium is to large extent opaque for jets ("jet quenching")
- Yields of hadron species in chemical equilibrium with freeze-out temperature T_{ch} close to T_c
  - $T_{ch} \approx$ 160 MeV, $\mu_B \approx$ 20 MeV

Elliptic Flow:
Anisotropy in position space



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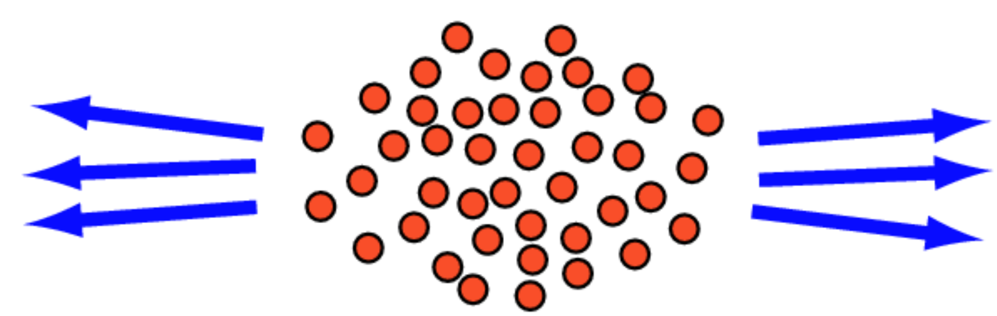
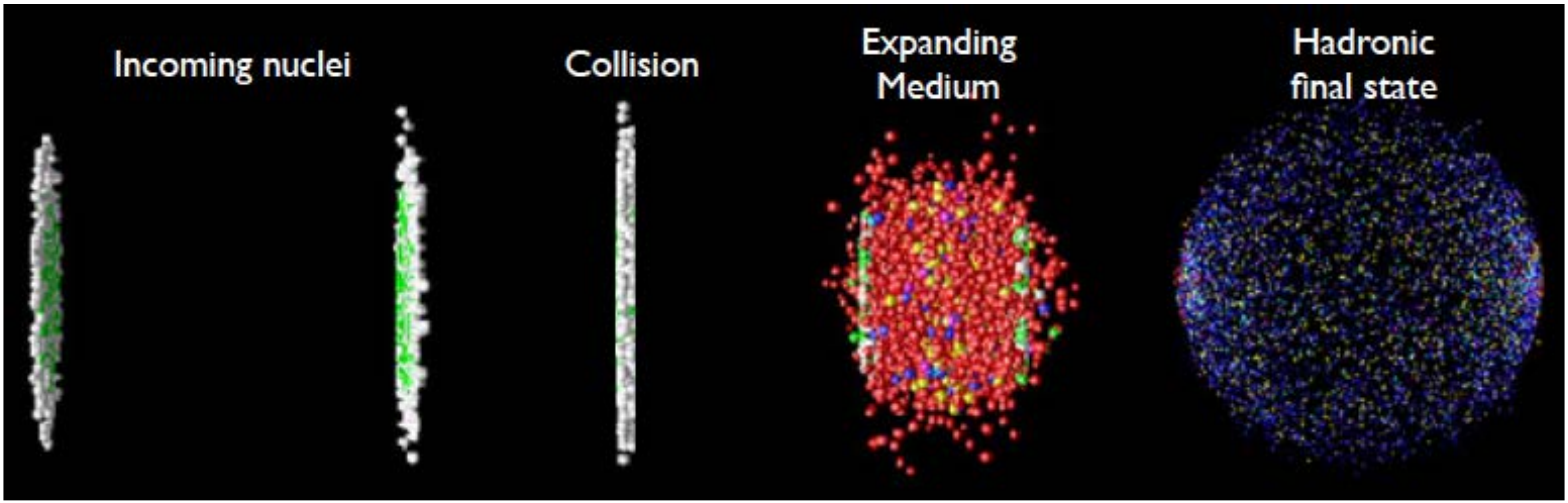
Anisotropy in momentum space



Heavy-ions at the LHC

- Qualitatively similar results in A-A collisions
  - Jet quenching
  - Elliptic flow
  - Particle yields in or close to chemical equilibrium values
- A surprise:
  Observation of elliptic flow and other effects first seen in heavy-ion collisions also in (high-multiplicity) pp and p-Pb collisions
  - QGP in small systems?
  - But no jet quenching seen in small systems
  - Ongoing discussion

Space-time evolution (1):

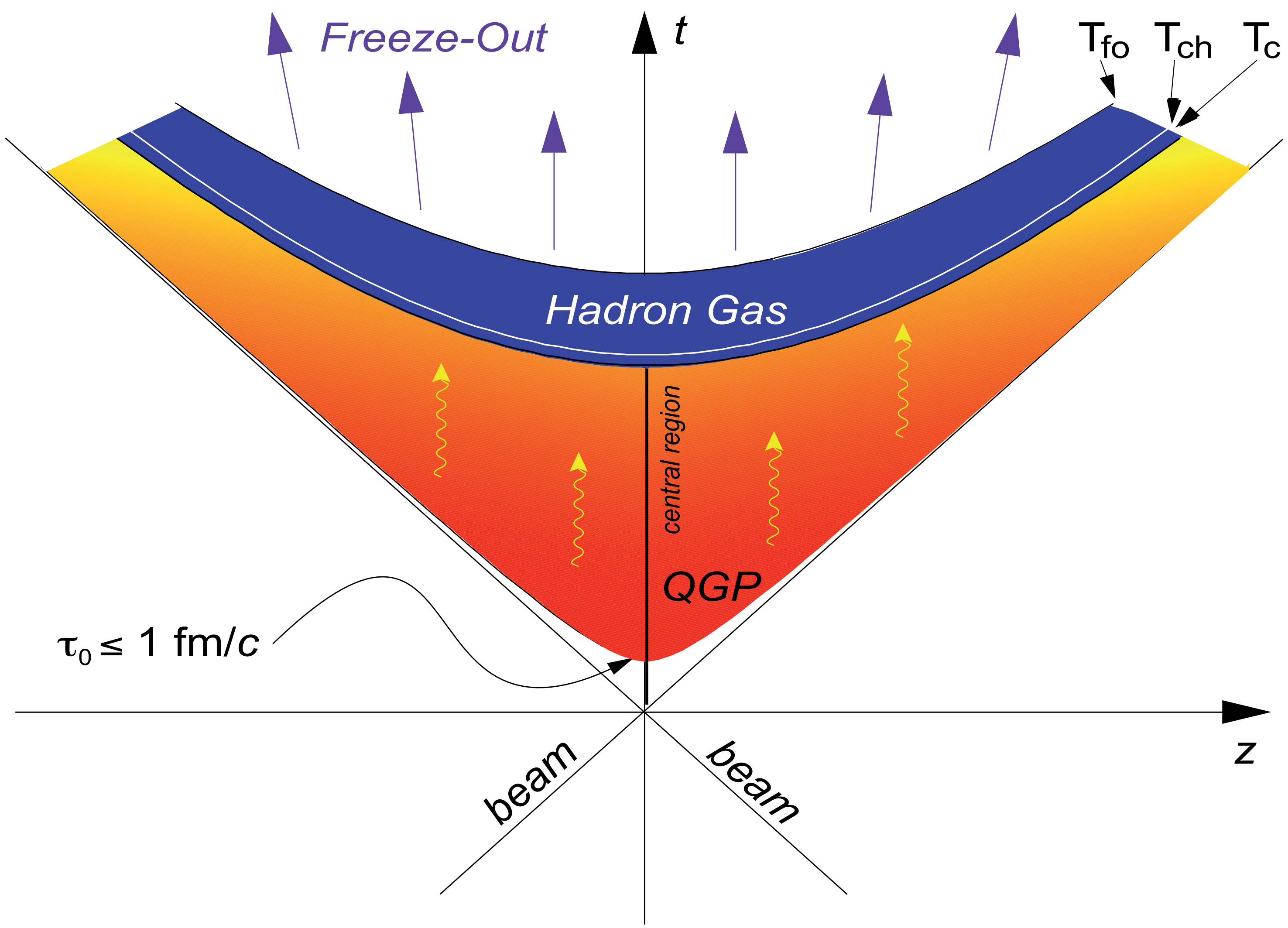


Initial parton wave function described in the Color Glass Condensate model

Central region initially dominated by low-*x* partons (i.e. gluons), then, at some point, quark-antiquarks pairs appear

Expansion, cooling, transition to hadrons

Space-time Evolution (2)



arxiv:0807.1610

- Strong color-electric glue fields between nuclei
- Rapid thermalization: QGP created at ~ 1-2 fm/c
- Expected initial temperatures of 600 MeV or higher
- Cooling due to longitudinal and transverse expansion describable by almost ideal relativistic hydrodynamics ($\eta/s \approx 0$)*
- Transition QGP → hadrons after about 10 fm/c
- Chemical freeze-out at $T_{ch} \approx T_c$ (T_c = 150 - 160 MeV)
- Kinetic freeze-out at T_{fo} ~ 100 MeV

* conjectured lower bound from string theory: $\eta/s|_{min} = 1/4\pi$ (Phys.Rev.Lett. 94 (2005) 111601)

Summary

- Ultra-relativistic Heavy-Ion Collisions:Study of QCD in the non-perturbative regime of extreme temperatures and densities
- Goal: Characterization of the Quark-Gluon Plasma
- Transition QGP → hadrons about 10^{-5} s after the Big Bang
- QCD phase diagram: QGP reached
    - at high temperature
      (about 150 - 160 MeV [~ $1.8 \cdot 10^{12}$ K])
    - and/or add high baryochemical potential μ_B (maybe realized in neutron stars)
- RHIC/LHC and early universe: $\mu_B \approx 0$
- Experiments at FAIR (in a couple of years):
    - QCD phase diagram at $\mu_B > 0$
    - search for critical point, first order phase transition, …
    - uncharted territory: surprises possible