QGP Physics − from Fixed Target to LHC

1. Introduction

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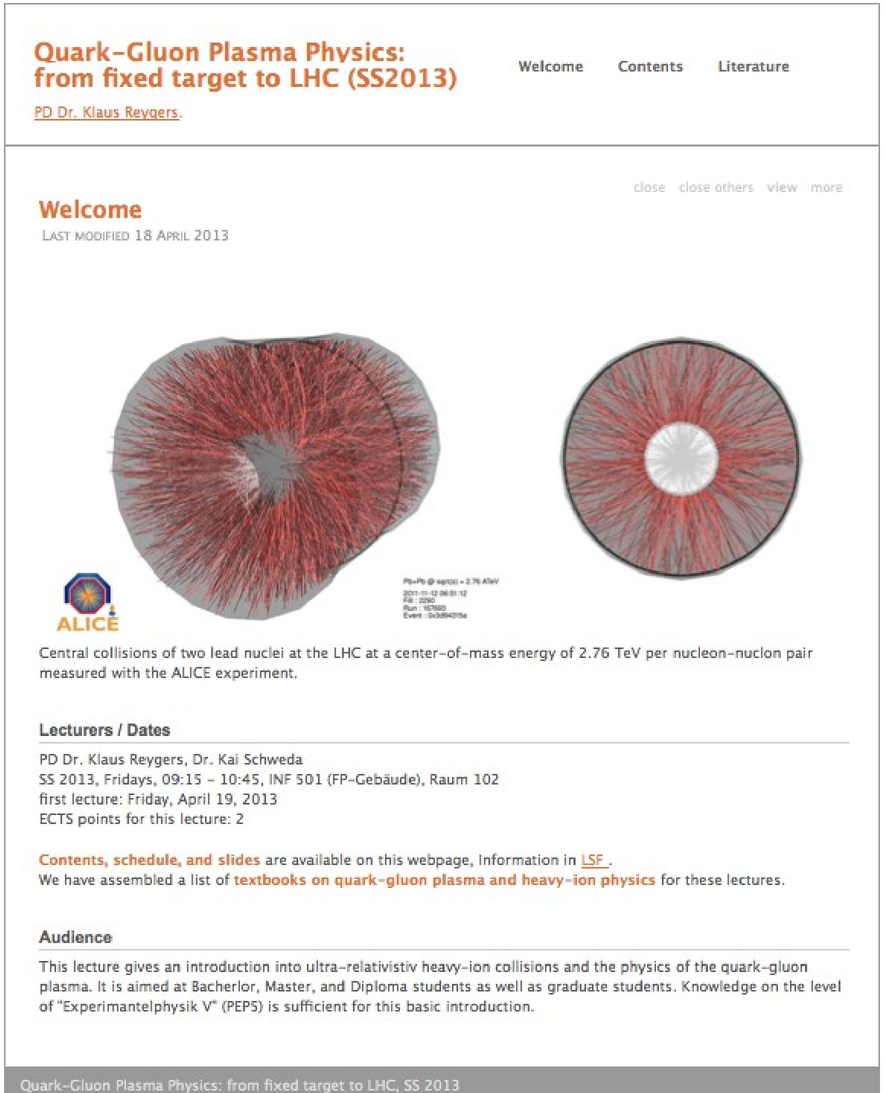
Physikalisches Institut
Universität Heidelberg
SS 2013

Website

http://www.physi.uni-heidelberg.de/~reygers/lectures/2013/qgp/qgp_lecture_ss2013.html



Quark-Gluon Plasma Physics: from fixed target to LHC (SS2013)

PD Dr. Klaus Reygers.

Welcome Contents Literature

close close others view more

Welcome

LAST MODIFIED 18 APRIL 2013

ALICE

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

PD Dr. Klaus Reygers, Dr. Kai Schweda
SS 2013, Fridays, 09:15 – 10:45, INF 501 (FP-Gebäude), Raum 102
first lecture: Friday, April 19, 2013
ECTS points for this lecture: 2

Contents, schedule, and slides are available on this webpage, Information in LSF .
We have assembled a list of textbooks on quark-gluon plasma and heavy-ion physics for these lectures.

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 "Experimantelphysik V" (PEPS) is sufficient for this basic introduction.

Quark-Gluon Plasma Physics: from fixed target to LHC, SS 2013

contents + slides

schedule

useful links

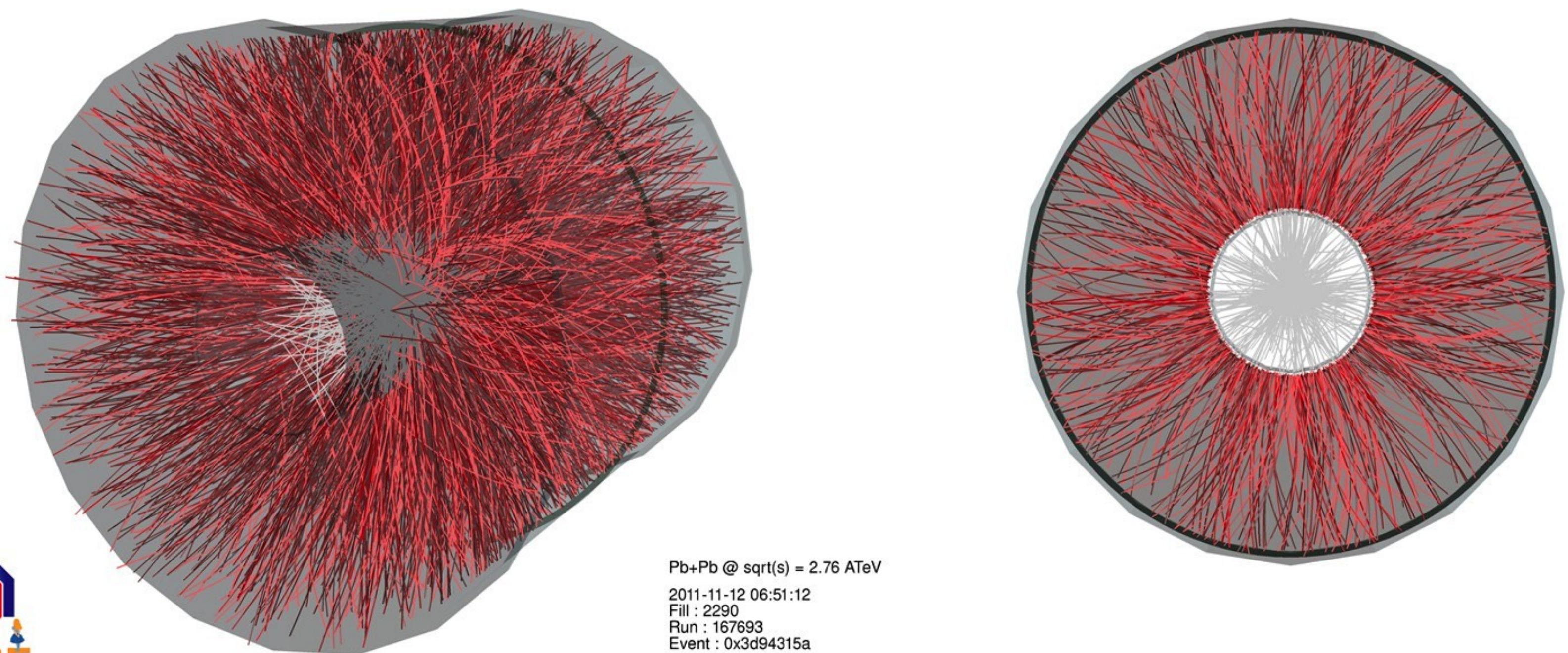
2 ECTS points

We will make a couple of homework problems available and reserve one of the lectures for the students to present their solutions on the blackboard.

To set the stage: Picture of one central collision of two Pb nuclei at the LHC observed by ALICE

About 3000 tracks of charged particles per collision

Physics of these collisions – this lecture: what to learn from these pictures



ALICE

Ultra-relativistic heavy-ion physics

Basic, childlike questions addressed in ultra-relativistic heavy-ion physics

What happens to matter if you make it:

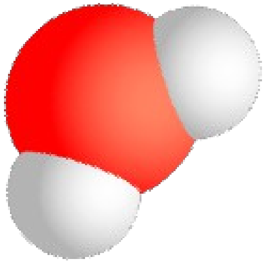
- hotter and hotter?
- denser and denser?

With increasing temperature *T*:

solid → liquid → gas → plasma → QGP

The Objective of Ultra-Relativistic Heavy-Ion Physics: Study of Emergent Properties of QCD

- It is a hard problem to determine the properties of water and its phases (ice, water, steam) from the known properties of a water molecule

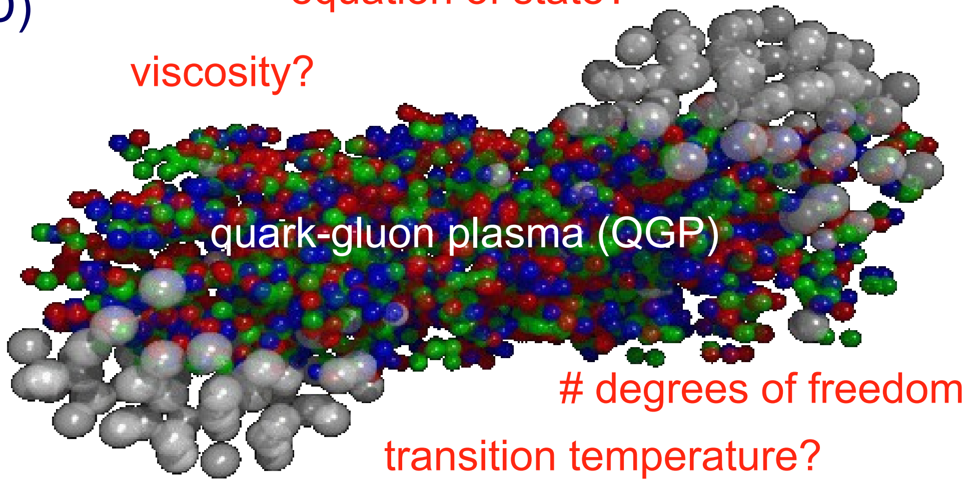


source: de.wikipedia.org

- Ultra-relativistic heavy-ion physics: Study of emergent properties of QCD (condensed-matter aspects of QCD)

„More is different"

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

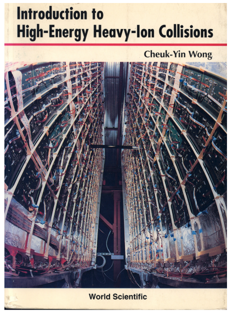


source: urqmd.org

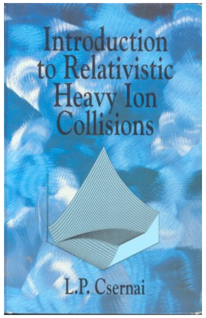
Outline

1. Introduction
2. Kinematic Variables
3. Basics of NN and AA Collisions
4. Thermodynamics of the QGP
    4.1 QGP in the MIT Bag Model
    4.2 Lattice Results
5. Statistical Model and Strangeness
6. Space-time Evolution of the QGP
    6.1 Bjorken Picture, energy density
    6.2 Hydrodynamic evolution, spectra, radial flow, elliptic flow
    6.3 HBT
7. Hard Scattering, Jets and Jet Quenching
8. Open Heavy Flavor and Quarkonia
9. Thermal Photons and Dileptons

Books (I)

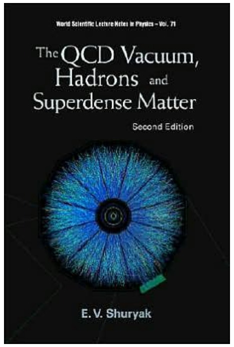


Wong, Introduction to High-Energy Heavy-Ion Collisions, World Scientific, 1994 (→ Link)



Csernai, Introduction to Relativistic Heavy-Ion Collisions, 1994

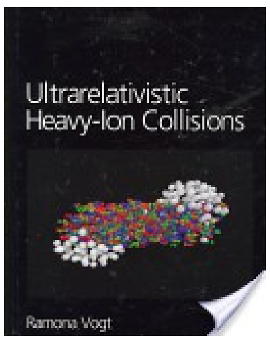
This book is now freely available as pdf (→ Link)



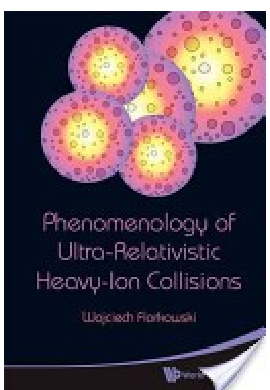
E. Shuryak, The QCD vacuum, hadrons, and superdense matter, World Scientific, 2004 (→ Link)

Books (II)

Yagi, Hatsuda, Miake, Quark-Gluon Plasma, Cambridge University Press, 2005 (→ Link)

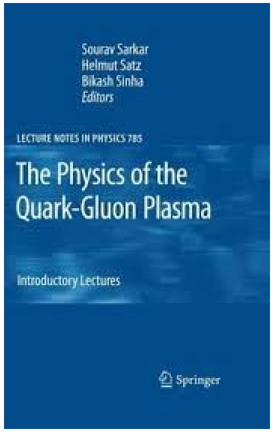


Vogt, Ultrarelativistic Heavy.ion Collisions, Elsevier, 2007 (→ Link)



Florkowski, Phenomenology of Ultra-Relativistic Heavy-Ion Collisions, World Scientific, 2010 (→ Link)

Books (III)



Lecture notes in physics, Volume 785, 2010,
DOI: 10.1007/978-3-642-02286-9:
The physics of the quark-gluon plasma (→ Link)

Reminder: Fundamental components of matter

quarks

up | down

mass 5–7MeV

charm | strange

1500 MeV | 150 MeV

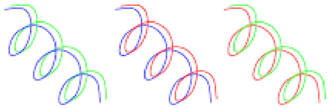
top | bottom

plus antiquarks

plus leptons

gluons

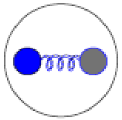
...mediate interaction between quarks



plus other gauge bosons

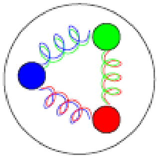
Quarks are bound by strong interaction into ***Hadrons***

Mesons



quark–antiquark

Baryons

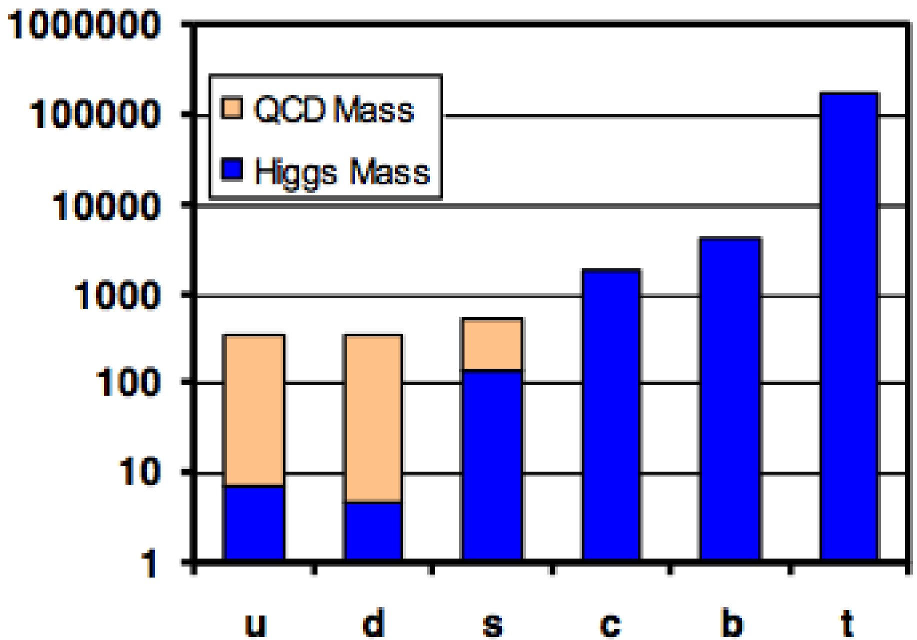


3 valence quarks

mass scale set by constituent quark masses (u,d=300 MeV)

due to breaking of chiral symmetry

Quark masses



- Current quark mass
  - Generated by spontaneous symmetry breaking (“Higgs mass”)
  - Contributes ~ 2% to our mass
- Constituent quark mass
  - Related to chiral symmetry breaking
  - valence quark “dressed” with a sea of gluons and virtual quark-antiquark pairs
  - QCD: responsible for ~ 98% of our mass

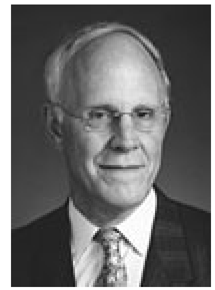
QCD calculations on a lattice show that the deconfinement transition coincides with restoration of chiral symmetry, i.e., masses of light quarks revert to basic “Higgs” mass

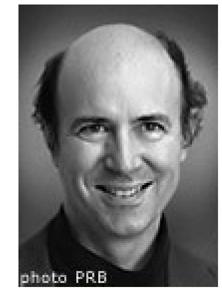
An analogy for the constituent quark mass: Electrons in a conductor

- In an insulator, the mass of the electrons in the material is just the physical electron mass
- In a conductor, however, the conducting electrons acquire an effective “in-medium” mass different from the physical mass
- The “in-medium” mass reflects the mean background field resulting from the periodic field of the charged ions, the other conduction electrons, and lattice vibrations

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 ($\alpha_s(q^2) \rightarrow 0$ for $q^2 \rightarrow \infty$),
  perturbative methods applicable for $r < 1/10$ fm

- Limit of low particle densities and weak coupling experimentally well tested (→ QCD perturbation theory)

- Nucleus-Nucleus collisions: QCD at high temperatures and density („QCD thermodynamics“)

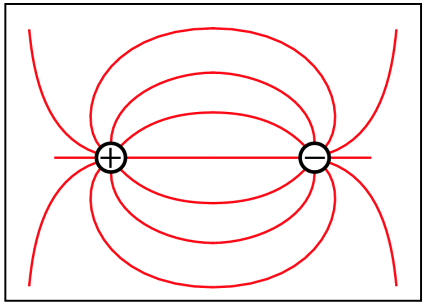
QED vs. QCD (I)

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).

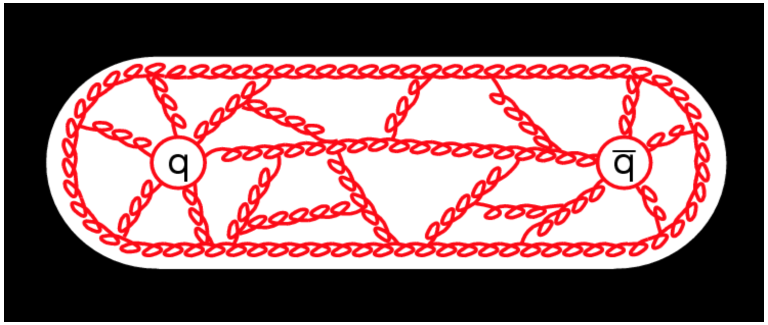
Because gluons are colored, QCD is very different from QED. QCD is a non-Abelian field theory of Young Mills type (1973 Fritzsch, Gell-Mann, Wess).

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

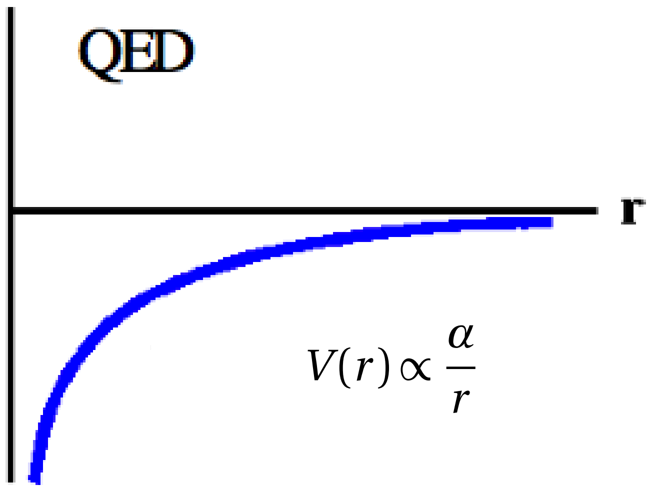
QED:



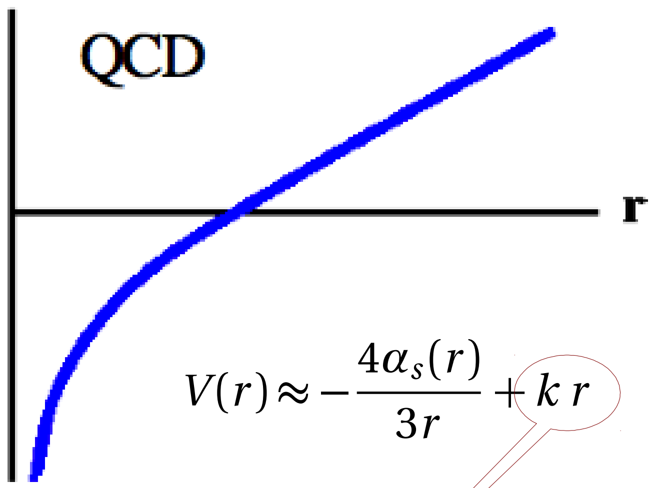
QCD:



QED vs. QCD (II)



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



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

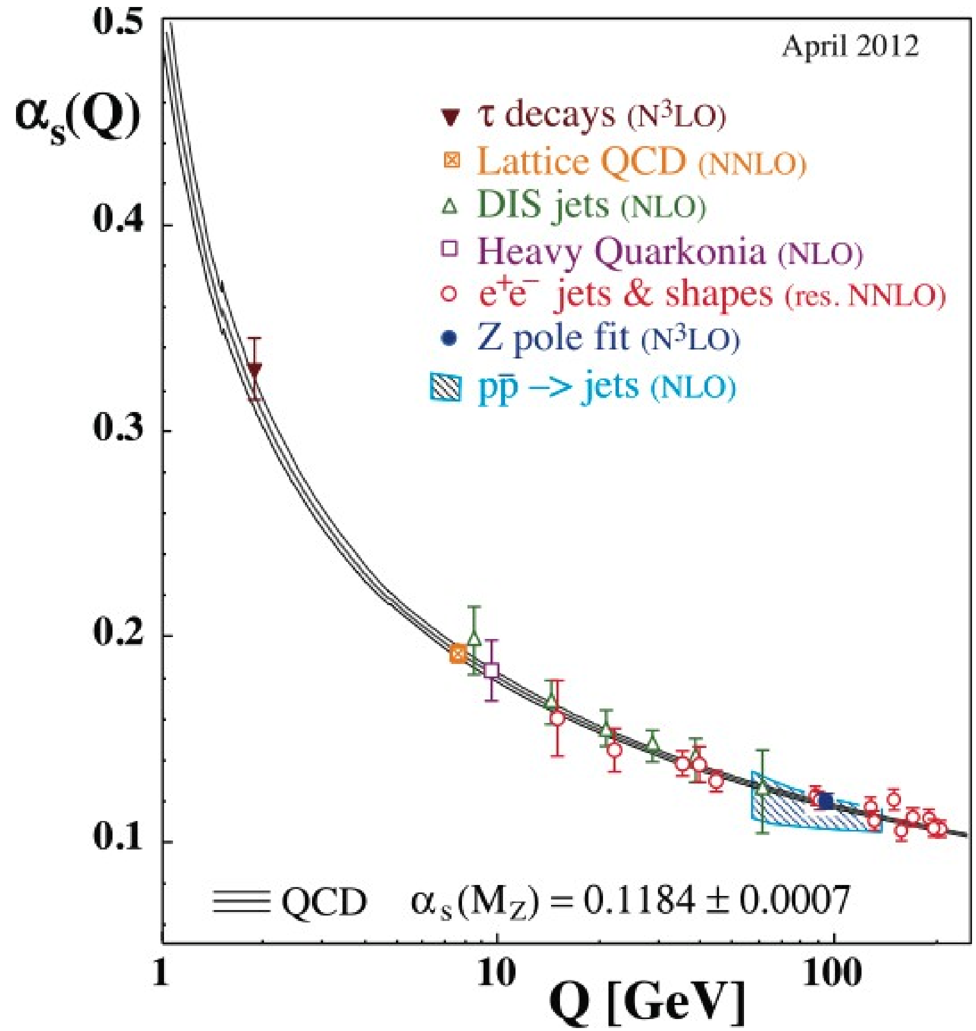
Linear term (often associated with confinement) expected to disappear in the QGP

Running coupling constant

Particle Data Group (PDG)
http://pdg.lbl.gov/2012/reviews/rpp2012-rev-qcd.pdf

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



The phase diagram of strongly interacting matter

At low temperature and normal density:
Color charges are confined, chiral symmetry is spontaneously broken (generating 98% of proton mass e.g.)

At high temperature and/or high density:
Quarks and gluons freed from confinement
→ new state of strongly interacting matter

J.C. Collins, M.J. Perry,
Phys. Rev. Lett. **34** (1975) 1353
N. Cabibbo, G. Parisi, Phys. Lett. **B59** (1975) 67

Initial idea: weakly interacting quark matter exists in asymptotically free regime

Actually already 1974 speculations by T.D.Lee and G.C.Wick that disturbing the vacuum could lead to abnormal dense states of nuclear matter

Volume 59B, number 1 PHYSIC

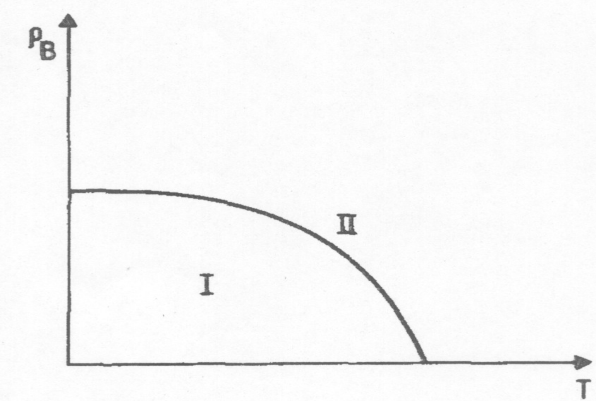


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

The Hagedorn temperature

Already in 1965, R. Hagedorn argues that there is a maximum temperature for hadronic matter based on the exponentially increasing density of hadronic states with increasing energy (Suppl. Nuovo Cim. 3 (1965) 147)

The statistical bootstrap model: strongly interacting particle form resonances (3,4,5, …, *n*) and those may combine to form new resonances only low lying ones experimentally known

Assume for density of states as function of mass: $\rho_m \propto (m_0^2 + m^2)^{(-5/4)} \exp(m/b)$

The energy density of a hadron gas becomes

$$\epsilon(T) = \sum_{m_\pi}^{M} \epsilon(m_i, T) + \int_M^\infty \epsilon(m, T) \rho(m) \mathrm{d}m$$

But for large masses *m* > *M* $\epsilon(m, T) \propto m^{5/2} T \exp(-m/T)$

implying that the integral diverges for *T* > *b.*

The Quark-Gluon Plasma

Note: this is not in the asymptotically free region of QCD, as not small α_s at T = 200 MeV, typical kinetic energy (from equipartition theorem)

for a nonrelativistic particle ($E = p^2/2m$): 3/2 kT = 300 MeV

for relativistic particle ($E \approx p$): 3 kT = 600 MeV

even in tails of Maxwell distribution α_s = 0.2 - 0.3

first perturbative corrections to ideal gas already early
Baym/Chin 1976, Shuryak 1978

by 1980 new phase was called Quark-Gluon Plasma (QGP):

excitations are quark and gluon quasiparticles plus collective 'plasmon' modes similar to usual QED plasma of ions and electrons

Critical density for the deconfinement transition

Baryon density in normal nuclear matter with r_0 = 1.15 fm

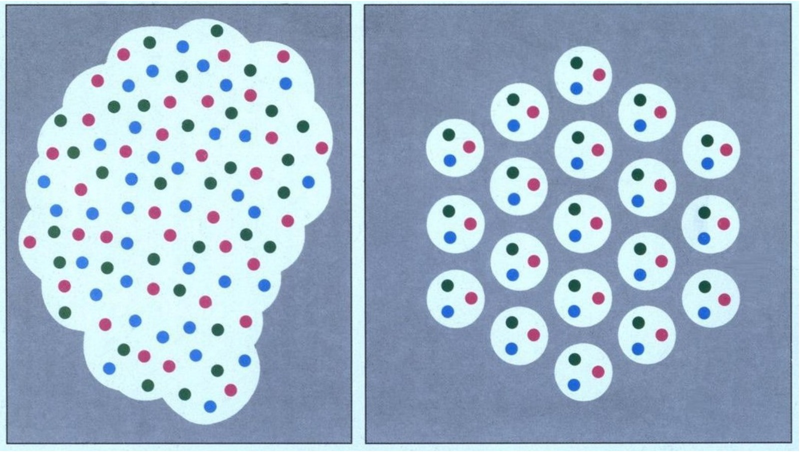
$$\rho_0 = \frac{A}{4\pi/3R^3} = \frac{1}{4\pi/3r_0^3} \approx 0.16\,\mathrm{fm}^{-3}$$

When nuclei are compressed, eventually nucleons start to overlap
remember: charge radius of the nucleon r_n = 0.8 fm

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

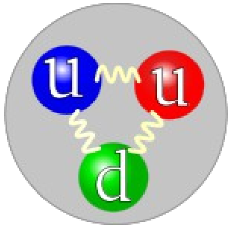
In fact, this is a bit too low.

Will see later, that in order for a quark-gluon bubble to sustain the vacuum pressure from the outside minimally 4 ρ_0 is needed.



Compressing nuclear matter created a QGP at low temperatures
Figure: CERN

Critical temperature for the deconfinement phase transition (very naive estimate)



Consider energy density within the proton:

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

Let's suppose for the moment that this is approx. the relevant scale for the transition to a QGP. Now consider an ideal gas of massless quarks and gluons with the same number of quarks and antiquarks and calculate the temperature at which it has this energy density:

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

Serious calculations on the lattice show that the transition from a gas of hadrons to the QGP at vanishing chemical potential takes place at

$$T_c = 150 - 160\,\text{MeV} \approx 1.8 \times 10^{12}\,\text{K}$$

Critical temperature:
The conceptual limit of the pion gas

Pomeranchuk argued that a pion gas makes sense as long as there is some minimum volume available per pion:

$$\Rightarrow \quad n_c = \frac{1}{V_0} = \frac{3}{4\pi r_0^3}$$

$$r_0 \simeq 1/m_\pi$$

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

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

$$= \frac{VTm^2}{2\pi^2} K_2(m/T)$$

modified Bessel function of second kind

Pion density from partition function:

$$n(T) = \left(\frac{\partial \ln Z_0(T,V)}{\partial V}\right)_T = \frac{Tm^2}{2\pi^2} K_2(m/T)$$

Find temperature at which density reaches critical pion density:

$$n(T_c) = n_c \qquad \rightarrow \qquad T_c \approx 190\,\text{MeV}$$

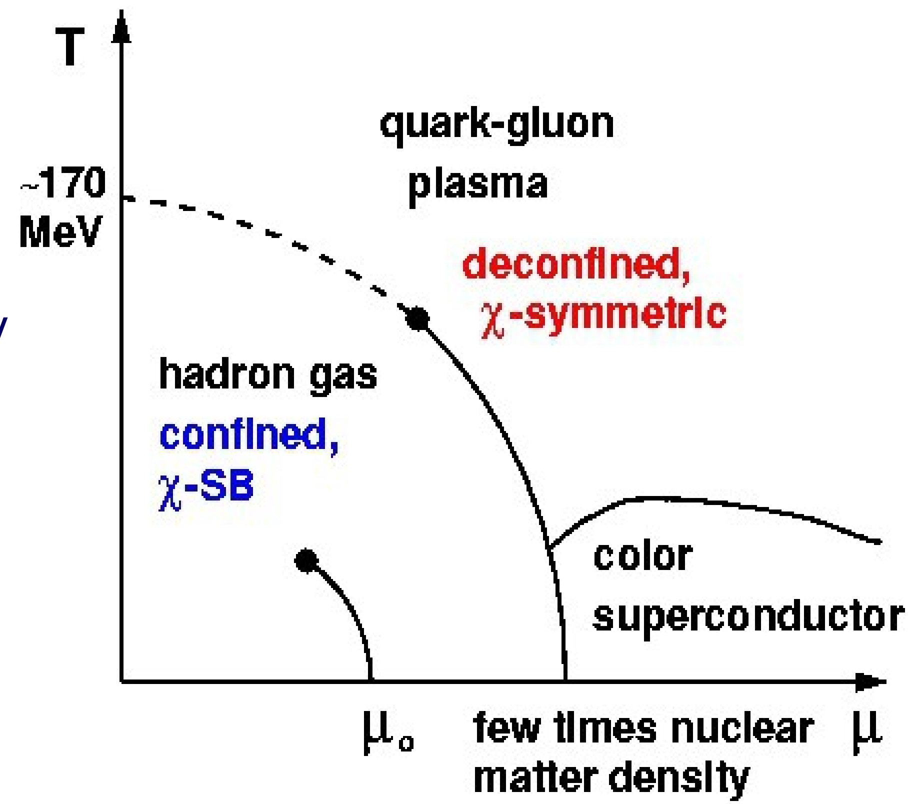
Modern phase diagram of strongly interacting matter

Better knowledge of

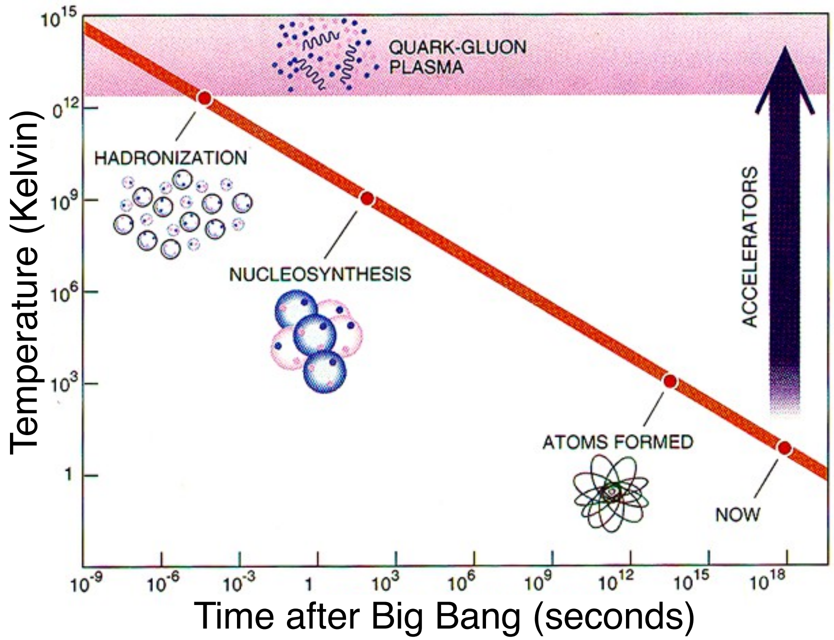
- critical temperature at zero net baryon density (from lattice QCD)
- nature of phase transition (see chapter 4)

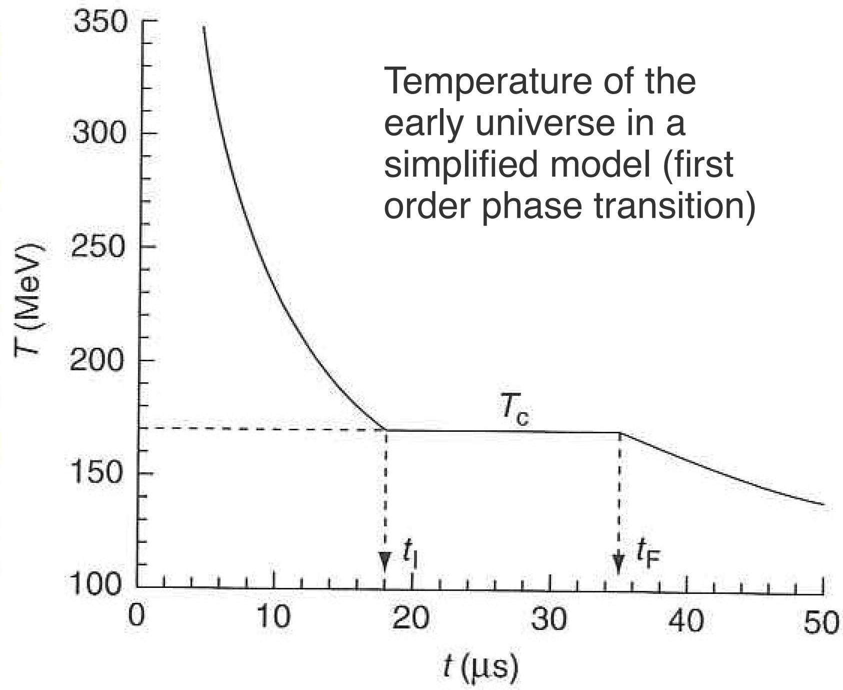
Phase diagram at finite net baryon density (chemical potential):

- phase transition may change in nature
- possible critical end point
- expect rich phase structure



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





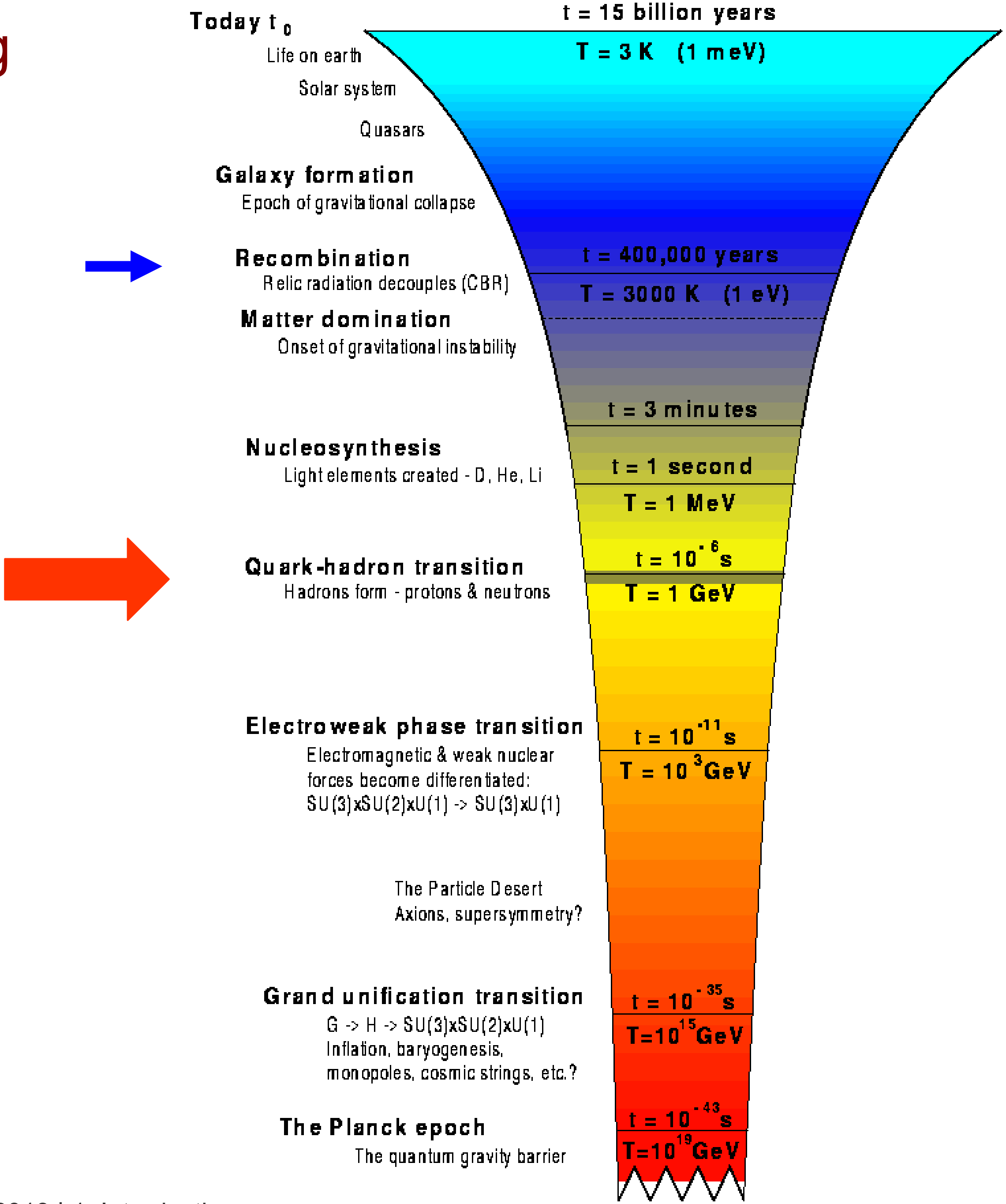
Temperature of the early universe in a simplified model (first order phase transition)

- 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

Tracing the Big Bang

cosmic microwave radiation

quark hadron phase transition



A little bit of history

- 1974 Bear mountain workshop 'BeV/nucleon collisions of heavy ions'
  - T.D.Lee “we should investigate … phenomena by distributing high energy or high nucleon density over a relatively large volume”
  - focussed largely on astrophysical implications
- gradual build up of momentum, various conferences, quantitative estimate of energy needed
- 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
- first step realized: 1-2 GeV/*c* per nucleon beams from SuperHILAC into Bevalac at Berkeley in 1984
- 1986 beams of oxygen/silicon/sulfur at Brookhaven AGS and CERN SPS
- 1992/1994 beams of gold/lead Brookhaven AGS and CERN SPS
- 2000 gold – gold collisions at RHIC
- 2010 lead – lead collisions in LHC

SPS : 1986 - 2003

S and Pb ; up to √s =20 GeV/nucl pair

E_{cm}* = 3200 GeV - 2500 prod. hadrons

LHC : starting 2009

Pb ; up to √s = 5.5 TeV/nucl pair

E_{cm}* = 1150 TeV - 25000? prod. hadrons

AGS : 1986 - 2000

- Si and Au ; up to √**s** =5 GeV /nucl pair

E_{cm}* = 600 GeV - 1000 prod. hadrons

RHIC : 2000

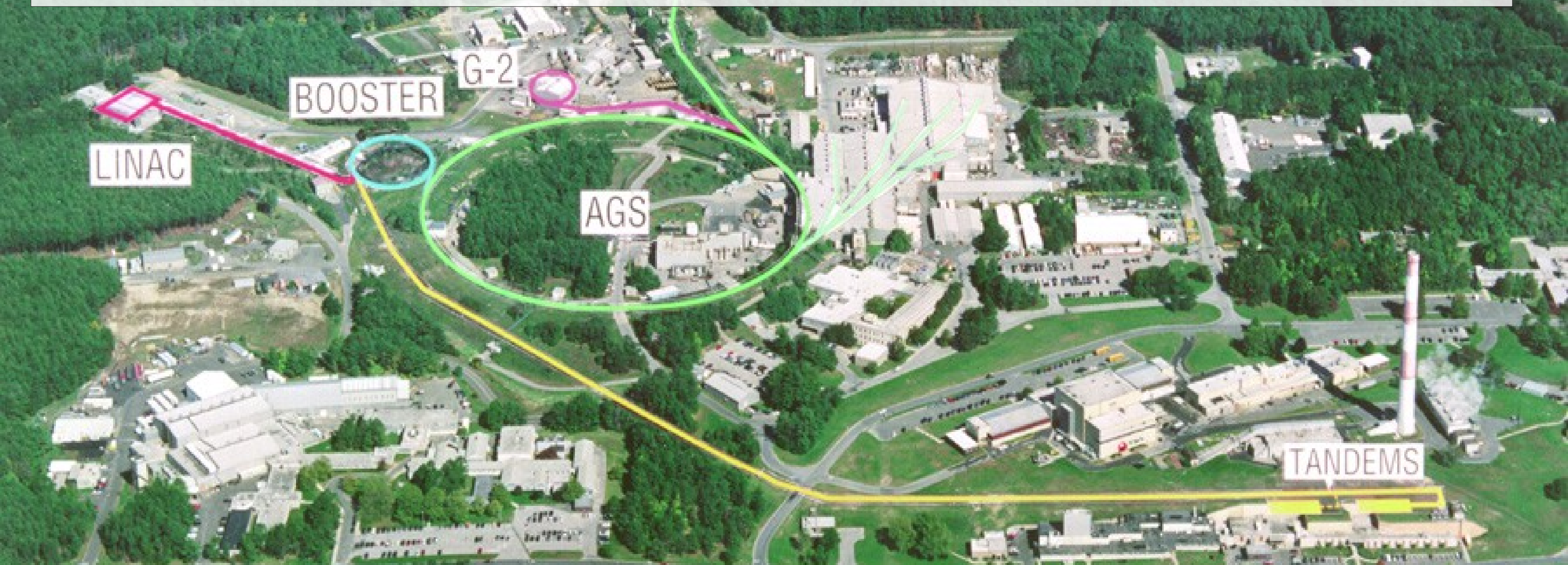
Au ; up to **√s =** 200 GeV /nucl pair

E_{cm}* = 40 TeV - 7500 prod. hadrons

Brookhaven AGS 1986 – 2000

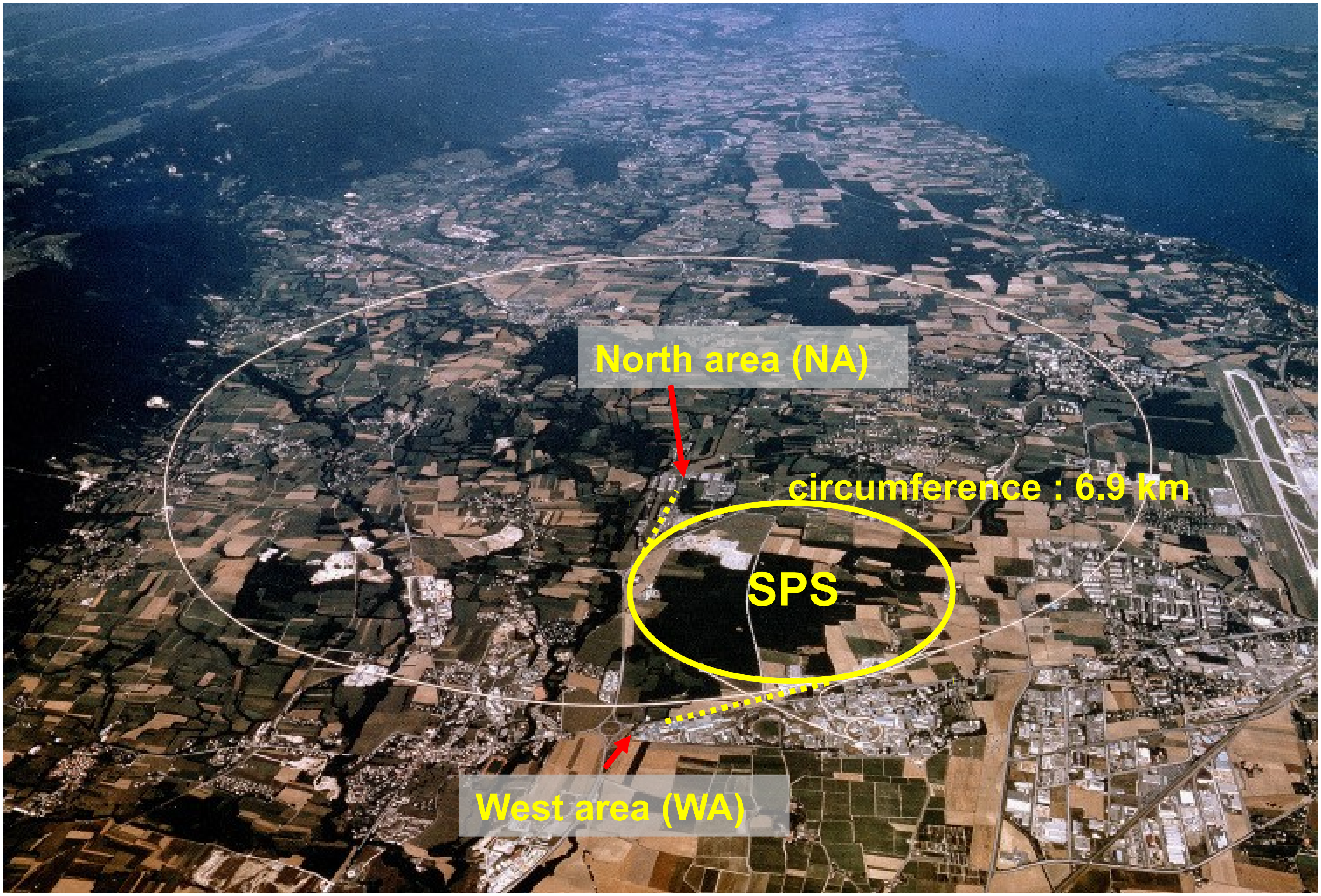
tandems inject beams via booster synchrotron into AGS,
circumference 1 km, warm magnets,
max. momentum 29 *Z*/*A* GeV/*c* = 5.6 GeV per nucleon pair in Au

Experiments E802/866
E810
E814/E877
E864
E917



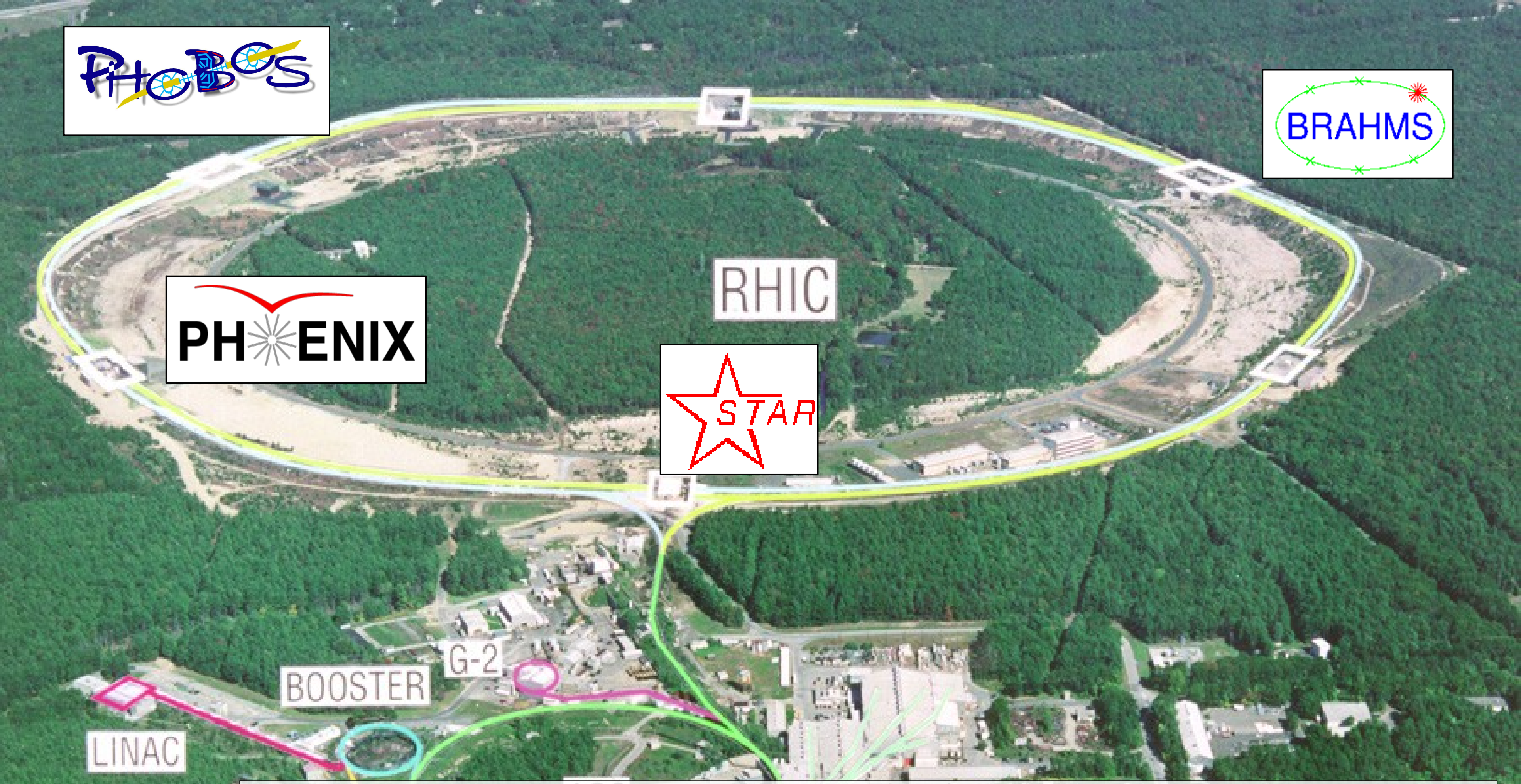
CERN SPS fixed-target programme (1986 - 2003)

Max. momentum 450 *Z*/*A* GeV/*c*, max. momentum 158 GeV per nucleon for lead ions



NA34/44
NA38/50/62
NA35/49/61
NA45(CERES)
NA52
NA57

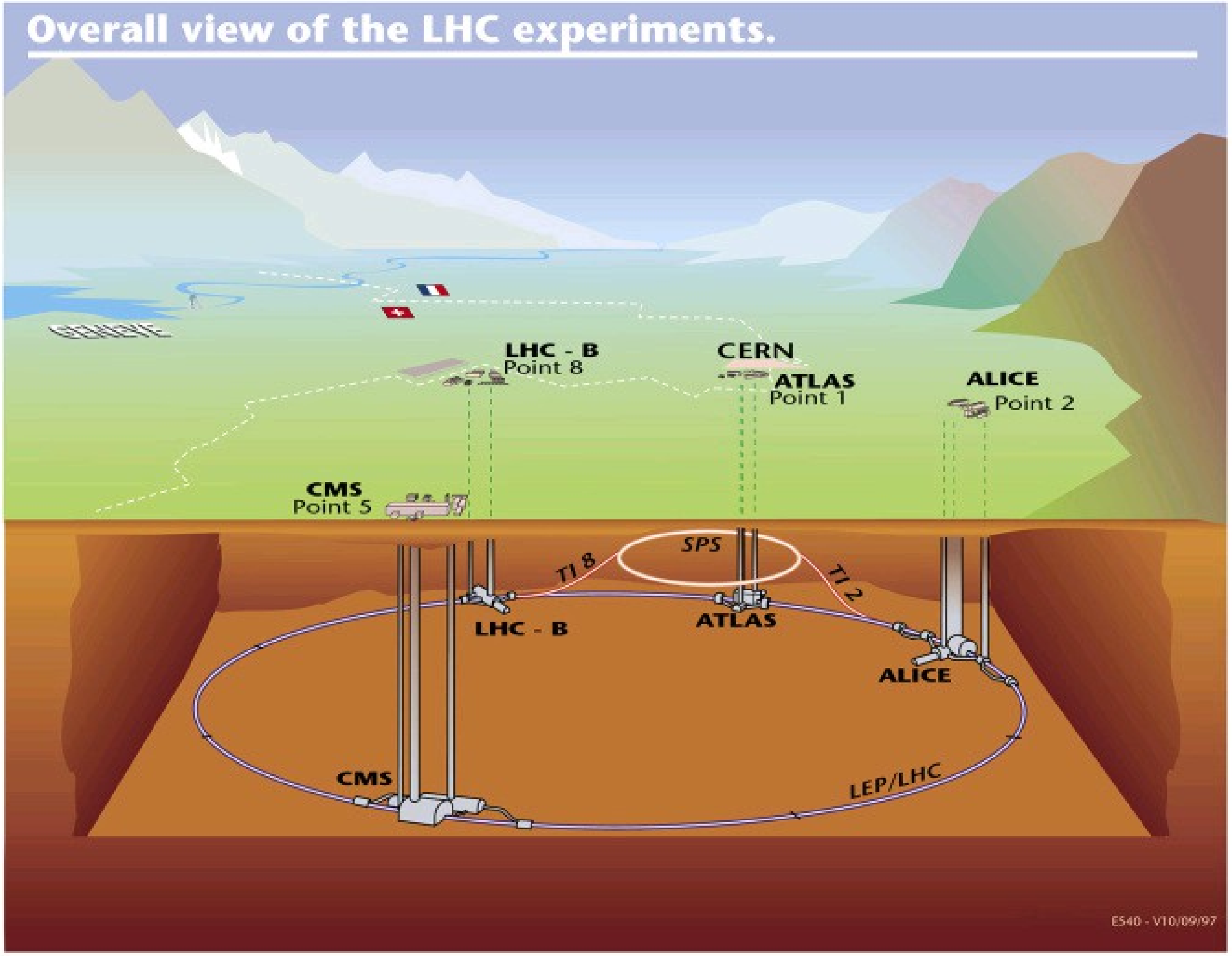
WA80/98, WA97→NA57



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

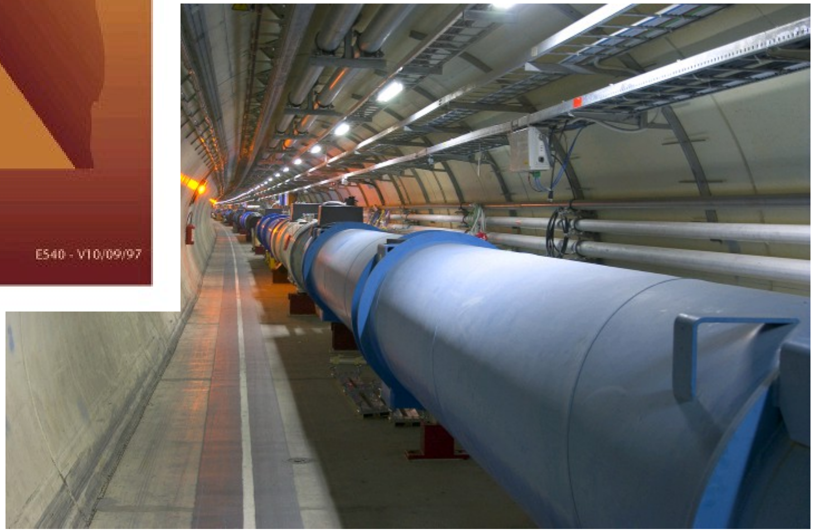
CERN: Large Hadron Collider (LHC) – 2009 - ...



p+p-collisions:
$\sqrt{s}$ = 14 TeV
collision rate: 800 MHz

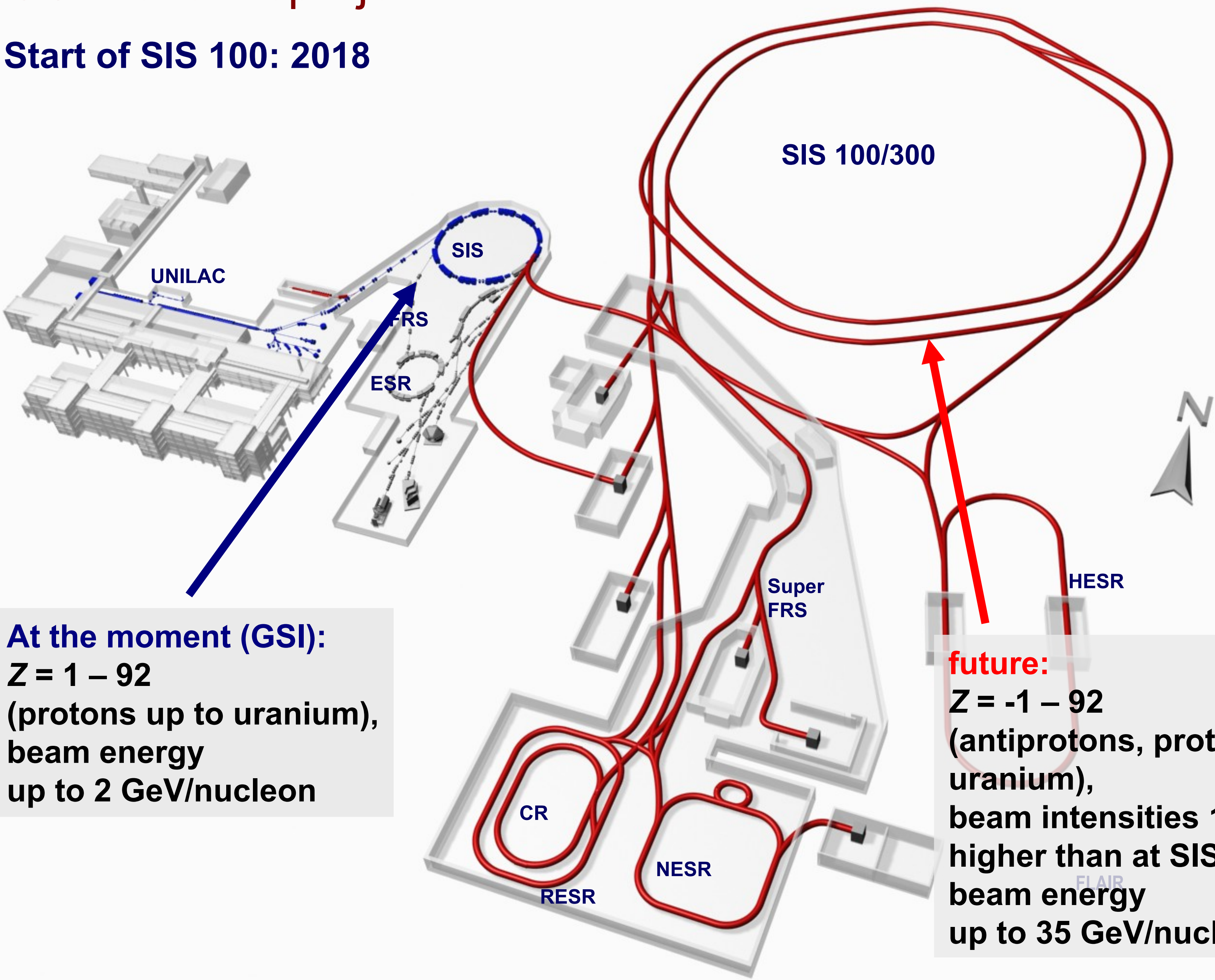
Pb+Pb collisions:
$\sqrt{s}$ =208 x 5,5 TeV max.
collision rate: 10 kHz

circumference: 27 km
B-field: 8 T, supercond.
50-100 m below ground



GSI-Zukunftsprojekt: FAIR

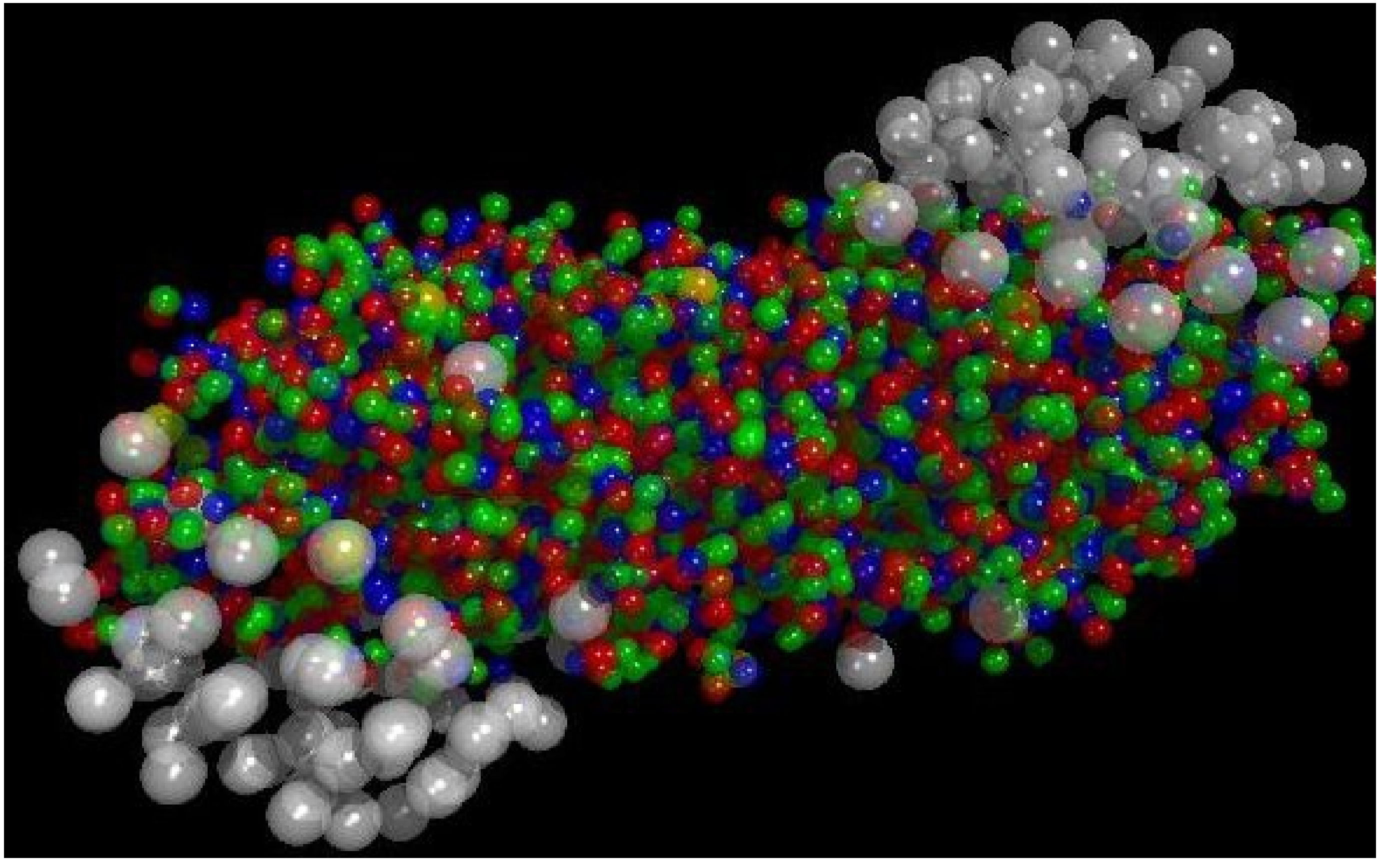
Start of SIS 100: 2018



At the moment (GSI):
Z = 1 – 92
(protons up to uranium),
beam energy
up to 2 GeV/nucleon

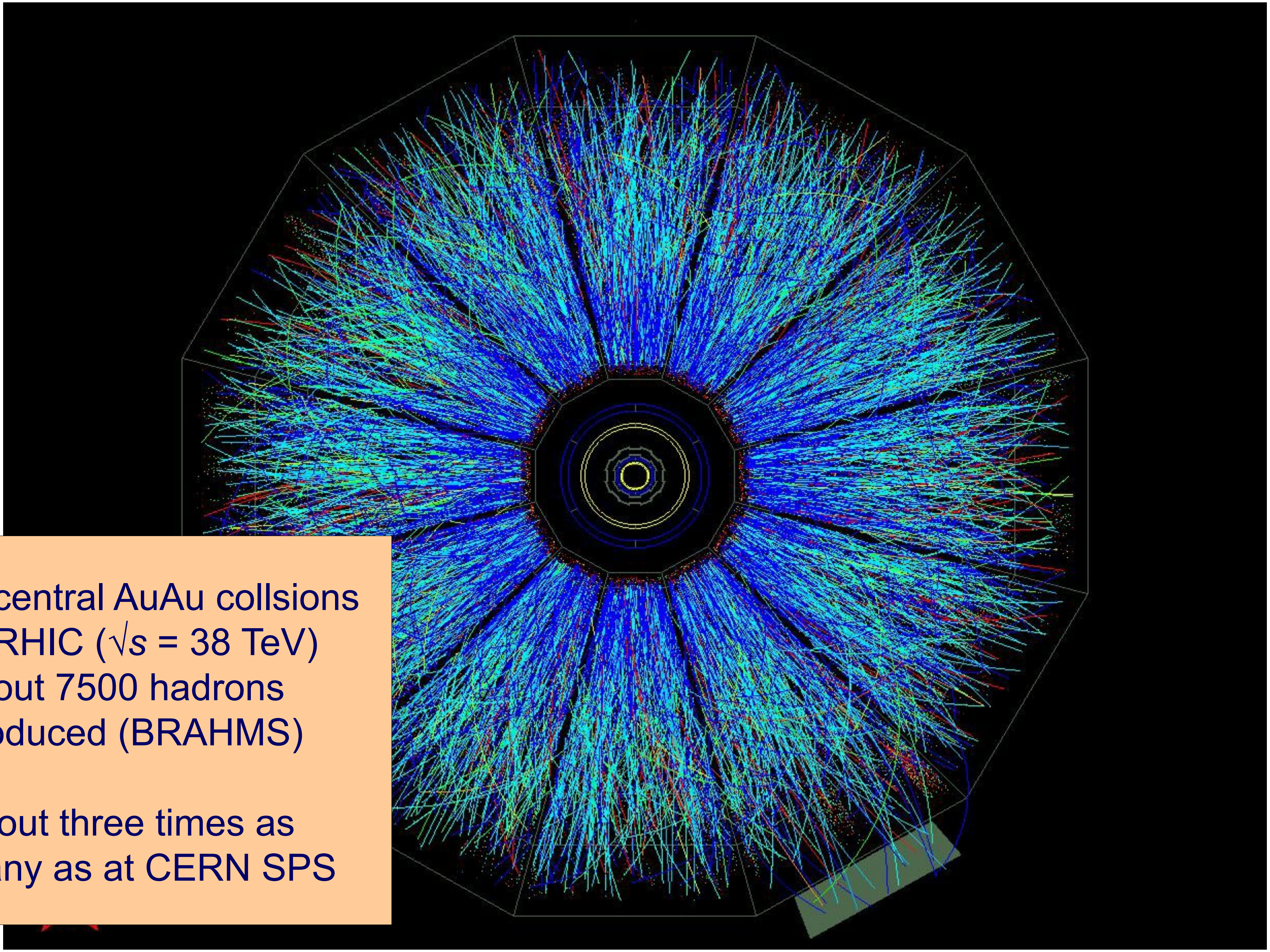
future:
Z = -1 – 92
(antiprotons, protons, …, uranium),
beam intensities 10 – 1000 higher than at SIS 18,
beam energy
up to 35 GeV/nucleon

CERN Press Release in February 2000: New State of Matter created at CERN



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.

BNL press release April 2005: RHIC Scientists Serve Up “Perfect“ Liquid



In central AuAu collsions at RHIC ($\sqrt{s}$ = 38 TeV) about 7500 hadrons produced (BRAHMS)

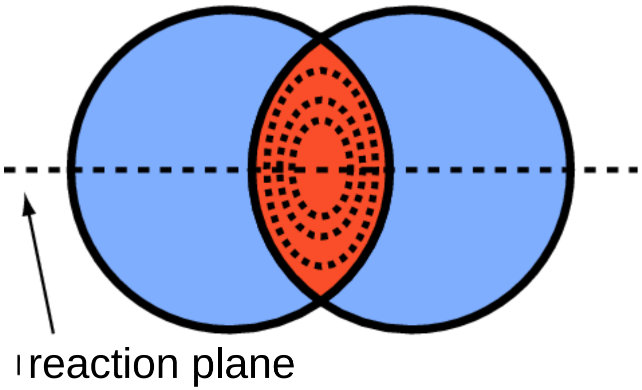
About three times as many as at CERN SPS

Important Results of the RHIC Heavy-Ion Programme

- 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
    $\Rightarrow$ Small viscosity: "perfect liquid"
  - Evidence for early thermalization ($\tau < \sim 1$ fm/c)
- All hadron species in chemical equillibrium
  ($T \approx 160$ MeV, $\mu_B \approx 20$ MeV)

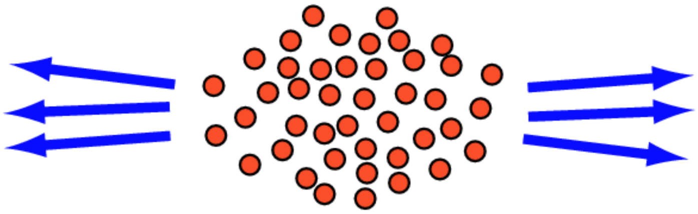
Elliptic flow:

Anisotropy in position space

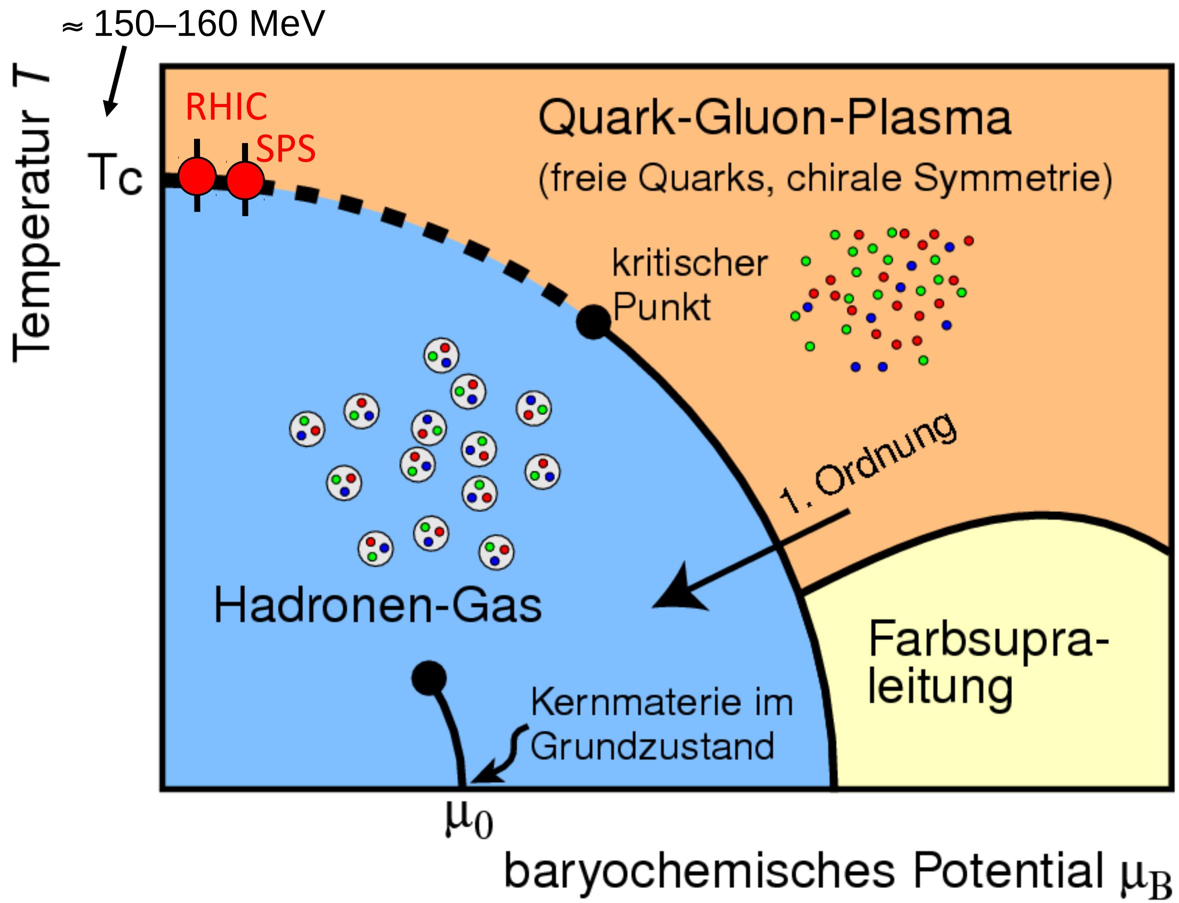


$\Downarrow$

Anisotropy in momentum space



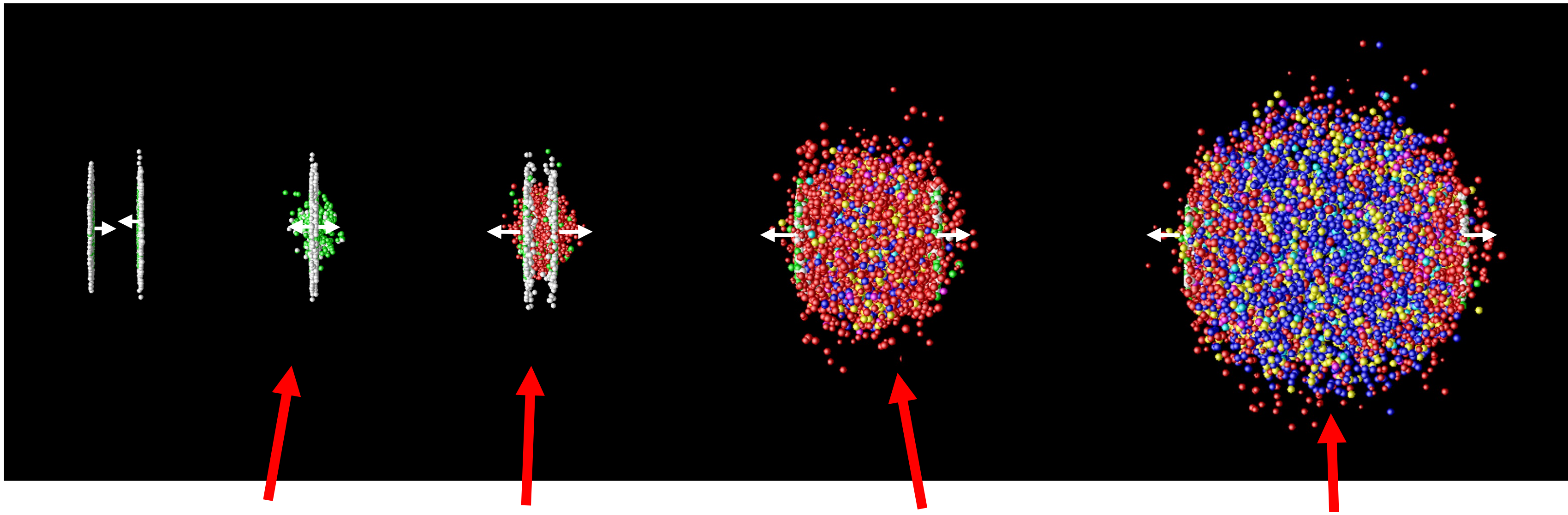
Nucleus-Nucleus Collisions: Freeze-out Parameters at SPS and RHIC



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

Stages of Ultra-Relativistic Nucleus-Nucleus Collisions

time →



Early hard parton-parton scatterings ($Q^2 >> \Lambda^2_{QCD}$)

Thermalized medium (QGP!?) ($T_0 > T_c$, $T_c \approx$ 150–160 MeV)

Transition QGP → hadron gas

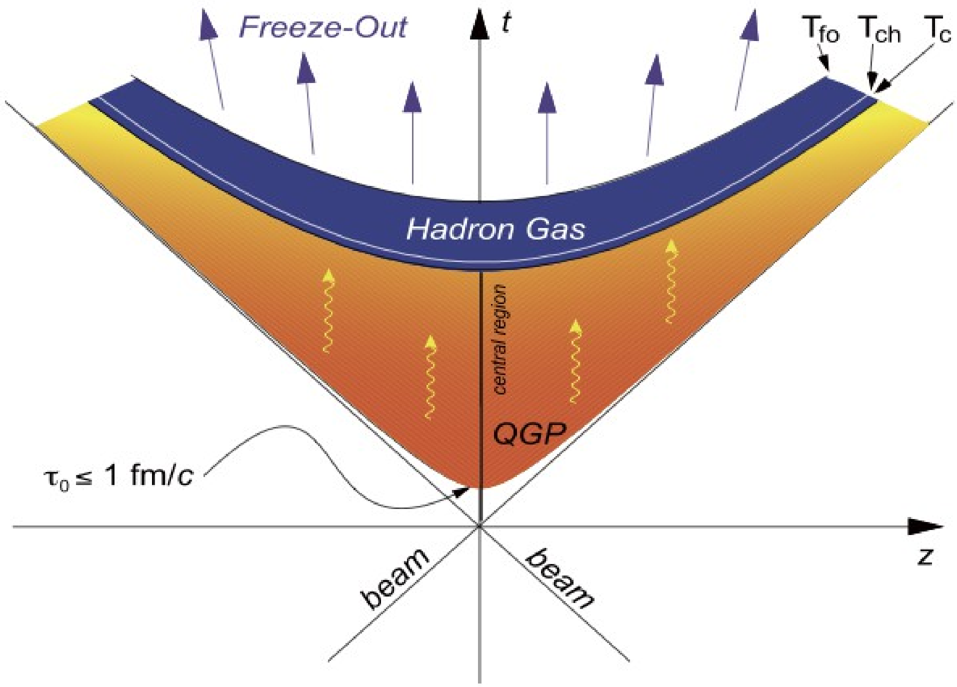
Freeze-out

Note:

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

- Time scales (RHIC, $\sqrt{s_{NN}}$ = 200 GeV):
  - Thermalization: τ_0 < ~ 1 fm/*c*
  - QGP lifetime (center of a central Au+Au coll.): ~ 5 fm/c
- Advantage at the LHC: longer QGP lifetime, abundant production of hard probes to be used as tools to study the QGP

Space-time evolution



- Gluons liberated from the nuclear wave function during collision
- Rapid thermalization: QGP created at ~ 1 fm/c
- Longitudinal and transverse expansion describable by almost ideal relativistic hydrodynamics ($\eta/s \approx 0$)*
- Transition QGP → hadrons
- 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: $\eta/s|_{min} = 1/4\pi$
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Points to Take Home

- 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: $\mu_B \approx 0$
- Experiments at FAIR (in a couple of years):
  $\mu_B > 0$ search for critical point