QGP Physics − from Fixed Target to LHC

1. Introduction

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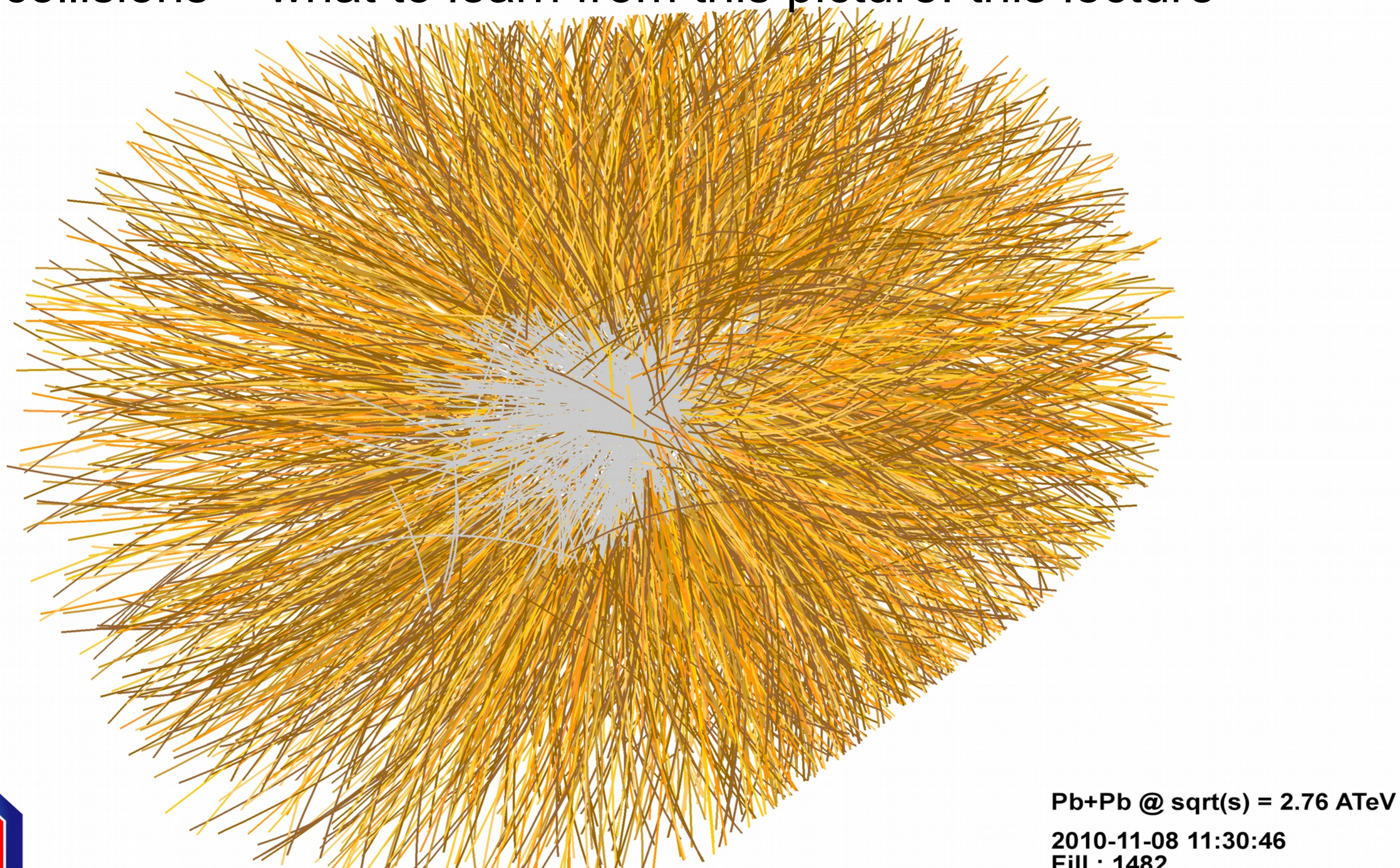
Physikalisches Institut, Universität Heidelberg
SS 2015

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

about 3000 tracks of charged particles

how to measure these: lecture on detectors in particle physics

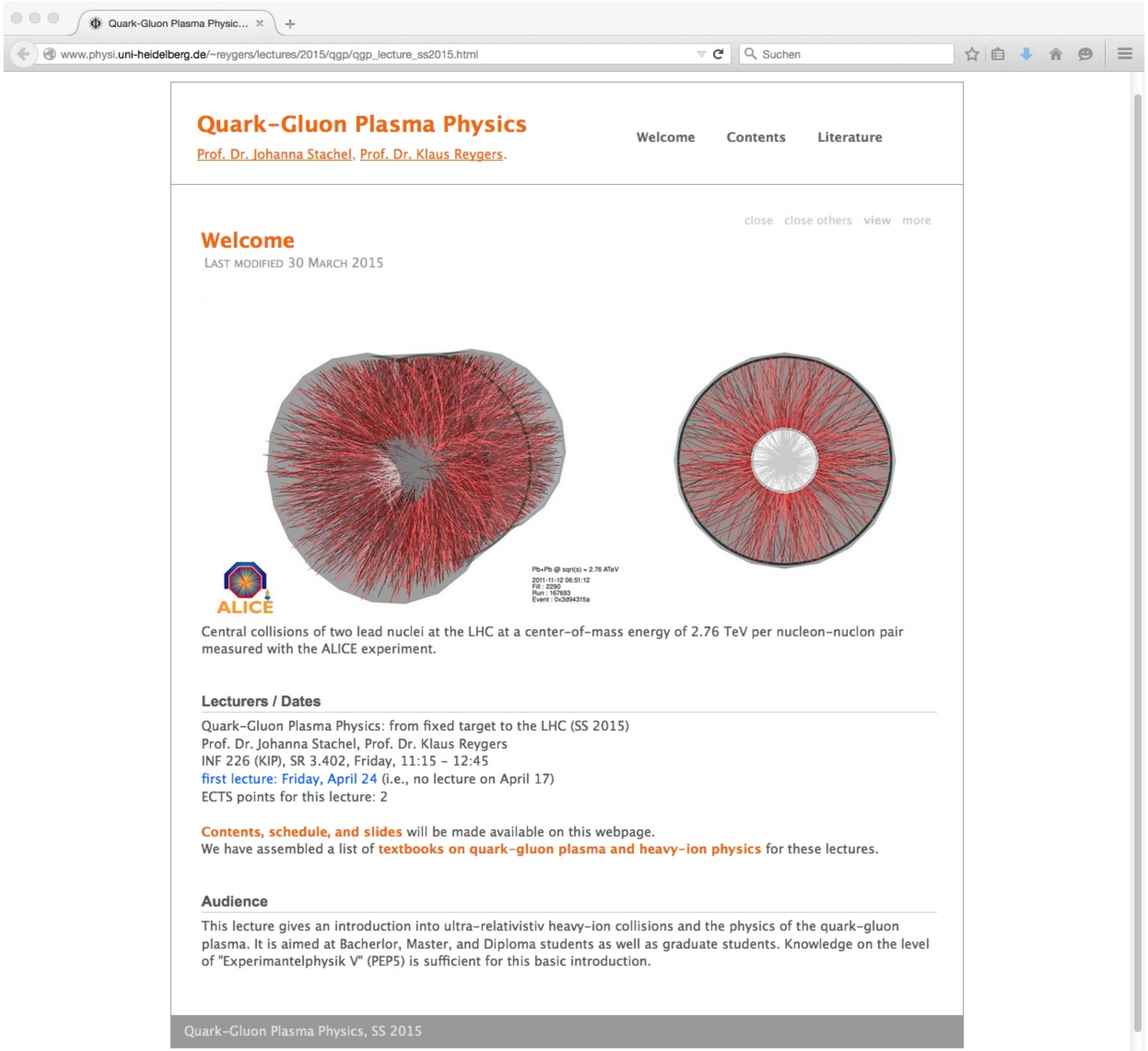
Physics of these collisions – what to learn from this picture: this lecture



Outline

1. Introduction
2. Kinematic Variables
3. Thermodynamics of the QGP
   - 3.1 QGP in the MIT Bag Model
   - 3.2 Lattice Results
4. Basics of NN and AA Collisions
5. Statistical Model and Strangeness
6. Space-time Evolution of the QGP
   - 6.1 Bjorken Picture, energy density
   - 6.2 Spectra and radial flow
   - 6.3 Hydrodynamics and azimuthal correlations
7. HBT
8. Hard Scattering, Jets and Jet Quenching
9. J/Psi and Quarkonia
10. Thermal Photons and Dileptons

Website



Quark-Gluon Plasma Physic...

www.physi.uni-heidelberg.de/~reygers/lectures/2015/qgp/qgp_lecture_ss2015.html

Quark-Gluon Plasma Physics

Prof. Dr. Johanna Stachel, Prof. Dr. Klaus Reygers.

Welcome Contents Literature

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Welcome

LAST MODIFIED 30 MARCH 2015

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

Quark-Gluon Plasma Physics: from fixed target to the LHC (SS 2015)
Prof. Dr. Johanna Stachel, Prof. Dr. Klaus Reygers
INF 226 (KIP), SR 3.402, Friday, 11:15 – 12:45
first lecture: Friday, April 24 (i.e., no lecture on April 17)
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.

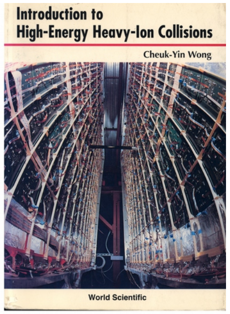
Audience

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" (PEP5) is sufficient for this basic introduction.

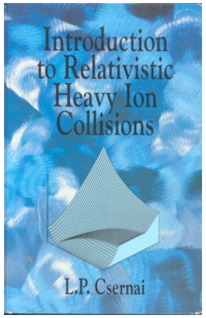
Quark-Gluon Plasma Physics, SS 2015

http://www.physi.uni-heidelberg.de/~reygers/lectures/2015/qgp/qgp_lecture_ss2015.html

Books (I)

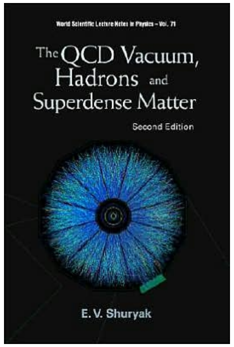


Wong, Introduction to High-Energy Heavy-Ion Collisions, World Scientific, 1994 (→ Link)



Csernai, Introduction to Relativistic Heavy-Ion Collisions, 1994

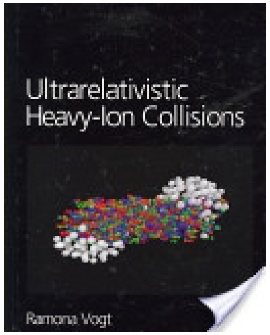
this book is now freely available as pdf (→ Link)



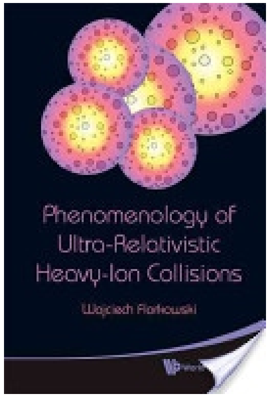
Shuryak, The QCD vacuum, hadrons, and superdense matter, World Scientific, 2004 (→ Link)

Books (II)

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

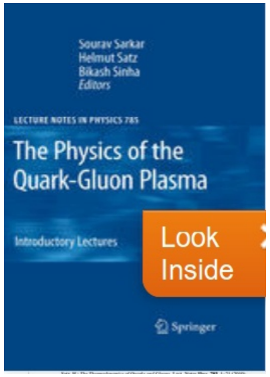


Vogt, Ultrarelativistic Heavy-Ion Collisions, Elsevier, 2007 (→ Link)



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

Books (III)



Sarkar, Satz, Sinha, The Physics of the Quark-Gluon Plasma, Lecture notes in physics, Volume 785, 2010

free download available (→ Link)

Reminder: fundamental components of matter

quarks

up   down

mass 5–7MeV

charm   strange

1500 MeV   150 MeV

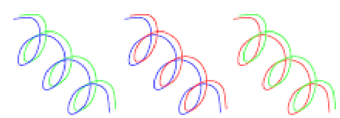
top   bottom

plus antiquarks

plus leptons

gluons

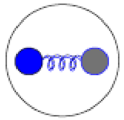
…mediate interaction between quarks



plus other gauge bosons

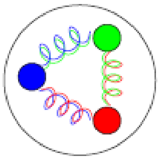
Quarks are bound by strong interaction into ***Hadrons***

Mesons



quark–antiquark

Baryons



3 valence quarks

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

due to breaking of chiral symmetry

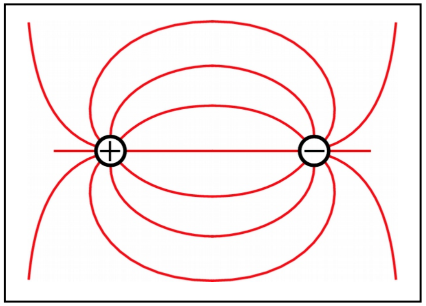
Strongly interacting matter described by QCD

quarks carry electric charge, color charge (1 of 3 possible), and several other quantum numbers
they interact stronly by exchange of colored gluons (8 different gluons from 3 colors and 3 anticolors)

because gluons are colored, QCD very different from QED (see lectures 'standard model' and 'quantum field theory')
QCD is non-Abelian field theory of Young Mills type (1973 Fritzsch, Gell-Mann, Wess)

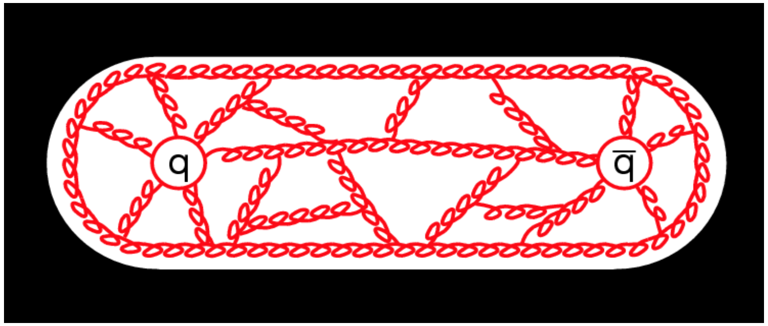
quarks are confined in hadrons, trying to pull them apart, the interaction becomes stronger

QED:



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

QCD:

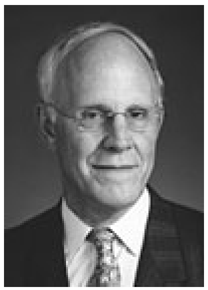


$$V(r) \approx -\frac{4\alpha_s(r)}{3r} + k\,r$$

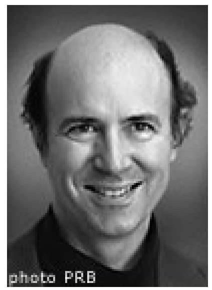
Strongly interacting matter described by QCD

at large momentum transfer or at small distances quarks are asymptotically free

H. David Politzer



David J. Gross



Frank Wilczek

formulated independently in 1973 by

D.J. Gross, F. Wilczek, Phys. Rev. Lett. **30** (1973) 1343

H.D. Politzer, Phys. Rev. Lett. **30** (1973) 1346

Physics Nobel Prize 2004

a_s drops with increasing q^2

or decreasing r

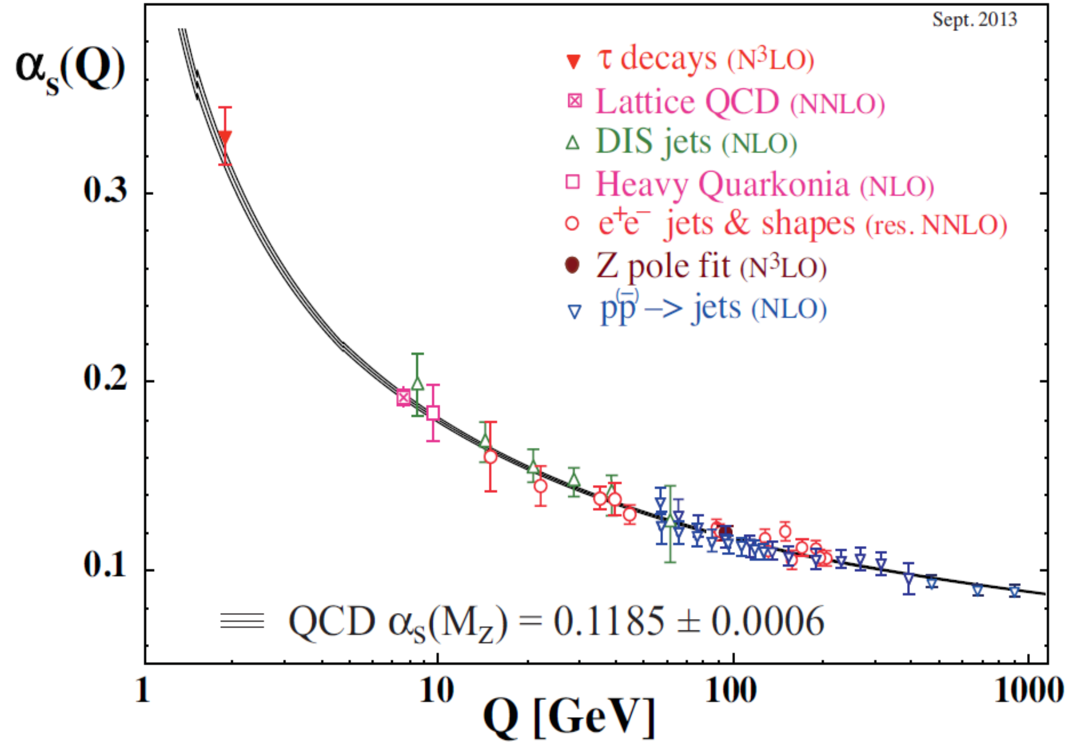
Running coupling constants

in QED vacuum polarization leads to increase of coupling constant a with decreasing r
running slow (1/128 at 58.5 GeV)

in QCD the opposite: colored gluons spread out color charge leading to anti-shielding decrease of coupling constant a_s with decreasing r or increasing momentum transfer q

REVIEW OF PARTICLE PHYSICS*

K.A. Olive et al. (Particle Data Group). Chin. Phys. C, 2014, **38**(9): 090001



Summary of measurement of a_s a function of energy scale Q

Phase diagram of strongly interacting matter

at low temperature and normal density
colored quarks and gluons are bound in colorless hadrons - confinement
chiral symmetry is spontaneously broken (generating e.g. 99% of proton mass)
1973 QCD (Gross, Politzer, Wilczek) asymptotic freedom at small distances and high momentum

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: in asymptotically free regime exists weakly interacting quark matter

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

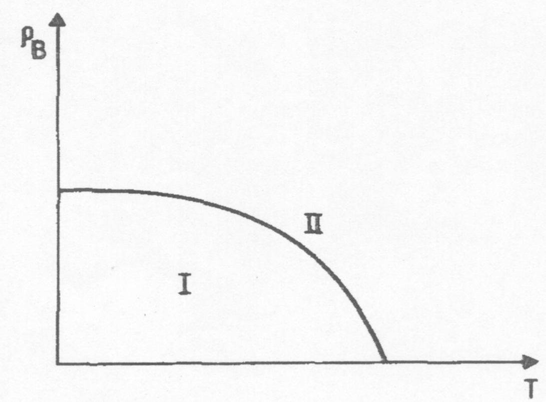
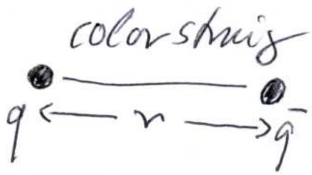


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

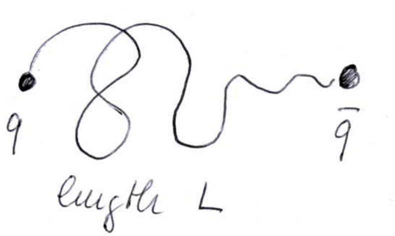
Estimate of critical temperature for deconfinement

first estimate by Polyakov 1978
at T=0, energy in a color string $E_{q\bar{q}} = \sigma r$
with string tension $\sigma \approx 1\mathrm{GeV/fm}$

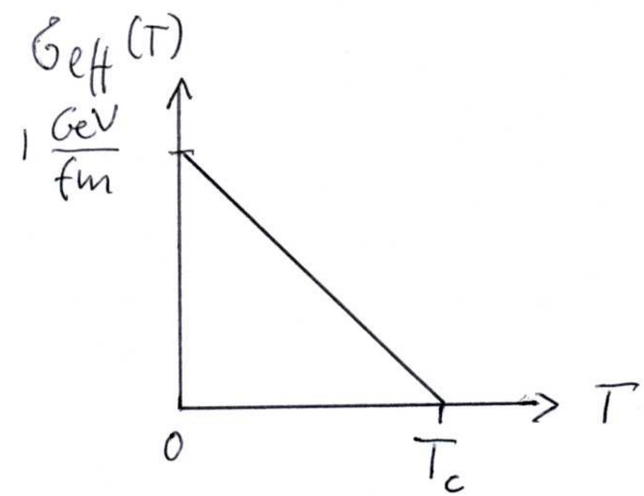


for T > 0, free energy of string

$$F_{q\bar{q}}(L) = E_{q\bar{q}}(L) - TS(L)$$
$$= \sigma L - T \ln N(L) = (\sigma - \frac{T}{a \ln 5})L = \sigma_{\mathrm{eff}} L$$



with the number of string configurations $N(L) = 5^{L/a}$
5 directions to go with typical stepsize a
and typical string thickness a = 0.3 fm
critical temperature reached when $\sigma_{\mathrm{eff}} = 0$



$$\rightarrow T_c = \frac{1\mathrm{GeV}\, 0.3\mathrm{fm}}{\mathrm{fm} \ln 5} = 185\mathrm{MeV}$$

the Hagedorn temperature

already in 1965, R. Hagedorn argued that there is a maximum temperature for hadronic matter based on the 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: $\rho_{\mathrm{m}} \propto (\mathrm{m}_0^2 + \mathrm{m}^2)^{(-5/4)} \exp(\mathrm{m}/\mathrm{b})$

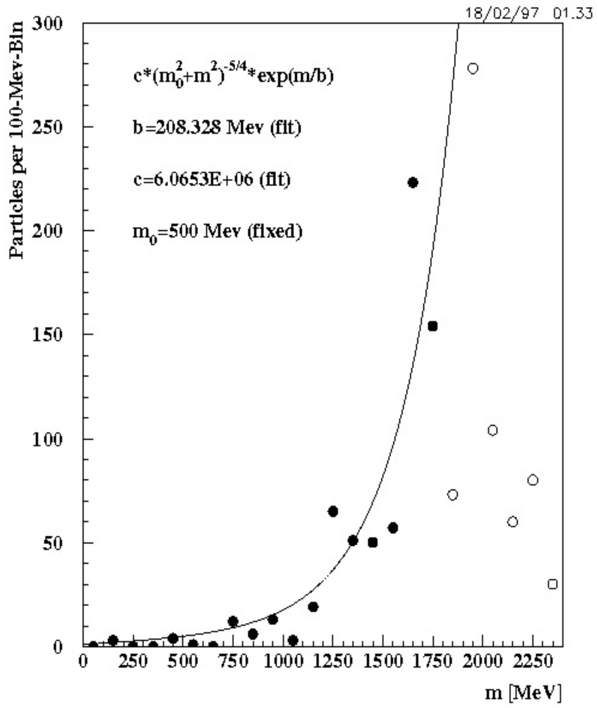
the energy density of a hadron gas becomes

$$\epsilon(\mathrm{T}) = \sum_{\mathrm{m}_\pi}^{\mathrm{M}} \epsilon(\mathrm{m_i}, \mathrm{T}) + \int_{\mathrm{M}}^{\infty} \epsilon(\mathrm{m}, \mathrm{T}) \rho(\mathrm{m}) \mathrm{dm}$$

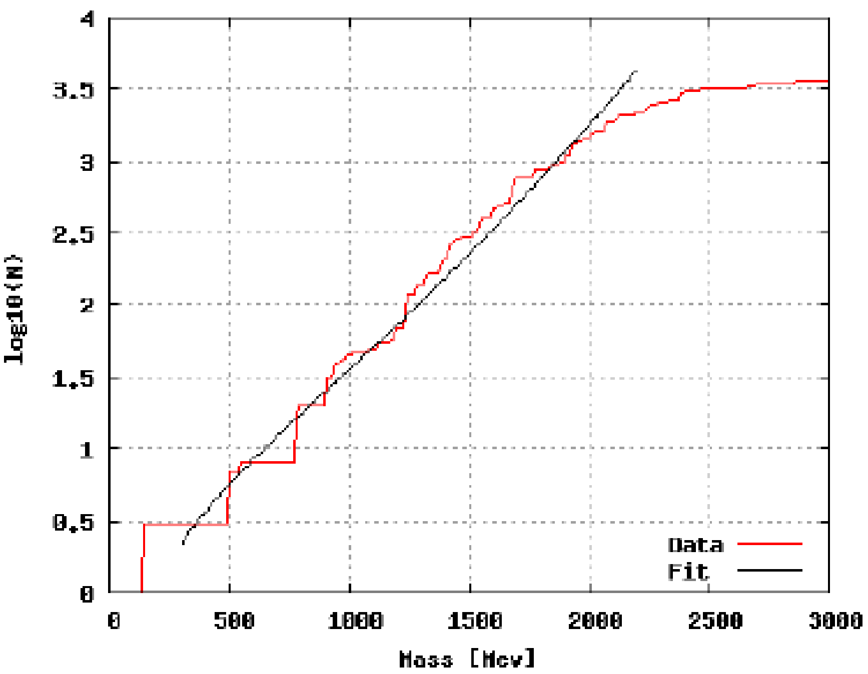
but for large masses m > M $\epsilon(m, \mathrm{T}) \propto \exp(-\mathrm{m}/\mathrm{T})$
implying that integral diverges for T > b

Best estimate of Hagedorn temperature is still evolving

Known hadronic spectrum in 1997



Fit to integrated density of states as of PDG2008



$$f_{FIT}(m) = log_{10}\left(\int_0^m \frac{c}{(x^2+m_0^2)^{5/4}} exp(x/T_H)\right)$$

All hadrons $T_H = 177.086$, $c = 18726.494$, range: $300 - 2200\ MeV$

Limiting temperature of hadron gas about 180 MeV – close to deconfinement estimate

the Quark-Gluon Plasma

Note: this is not in the asymptotically free region of QCD, a_s not small
at T=200 MeV, typical kinetic energy for nonrelativistic particle 3/2 kT = 300 MeV,
for relativistic particle 3 kT = 600 MeV

even in tails of Maxwell distribution a_s = 0.2-03

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 deconfinement transition

baryon density in normal nuclear matter
with r_0 = 1.15 fm

$$\rho_0 = \frac{\mathrm{A}}{4\pi/3\mathrm{R}^3} = \frac{1}{4\pi/3\mathrm{r}_0^3} \approx 0.16/\mathrm{fm}^3$$

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

$$\rightarrow \rho_\mathrm{c} = \frac{1}{4\pi/3\mathrm{r}_\mathrm{n}^3} \approx 0.47/\mathrm{fm}^3 = 3\rho_0$$

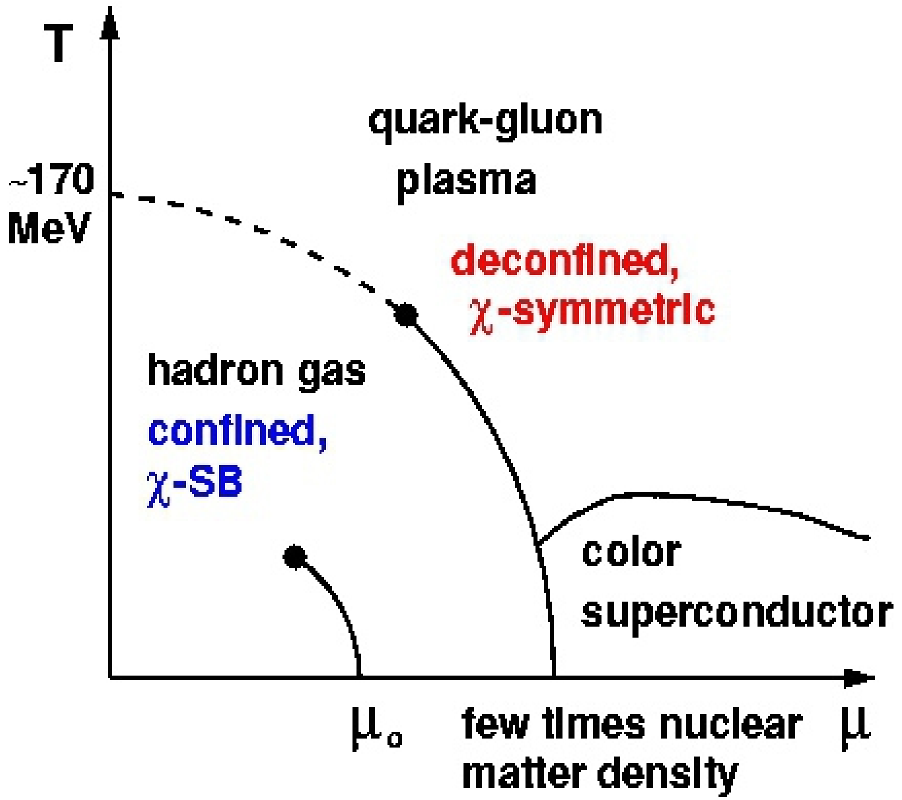
in fact, this is a bit too low
will see later, that in order for quark-gluon bubble to sustain the vacuum pressure from the outside minimally 4 r_0 is needed

Modern phase diagram of strongly interacting matter

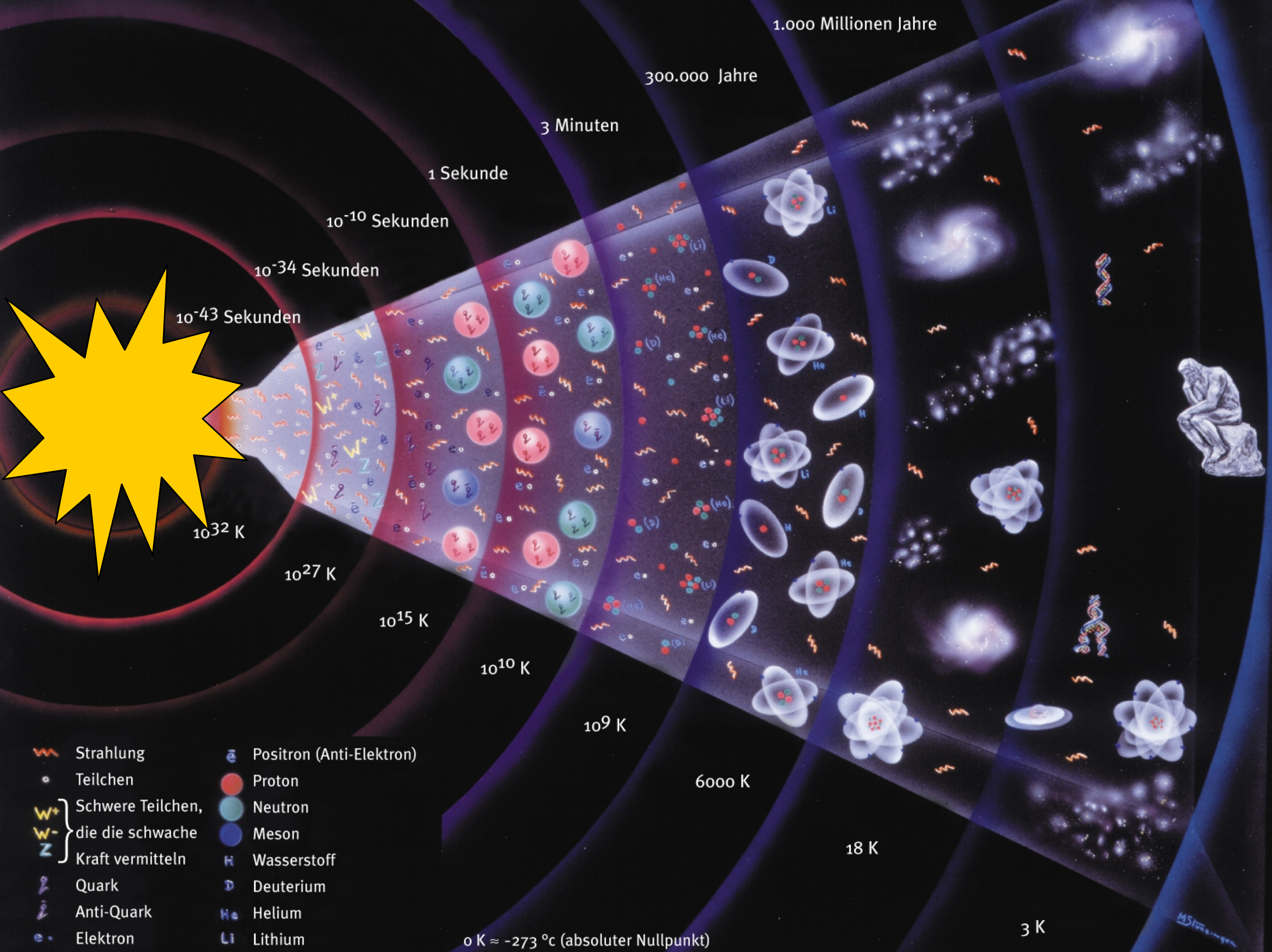
better knowledge of
  critical temperature at zero net baryon density
  nature of phase transition
(see chapter 4)

phase diagram at finite net baryon density (chemical potential):
  phase transition may change in nature
  possible critical end point
  expect rich phase structure

later we will see experimental data points in this phase diagram!
(see chapter 5)



Reise zum Urknall

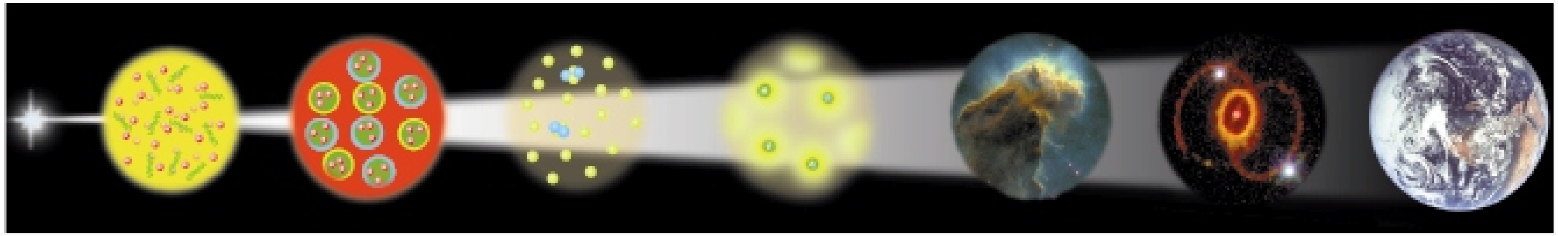


returning to the big bang

nature

Quark-Gluon Plasma | nucleons | nuclei | atoms | today

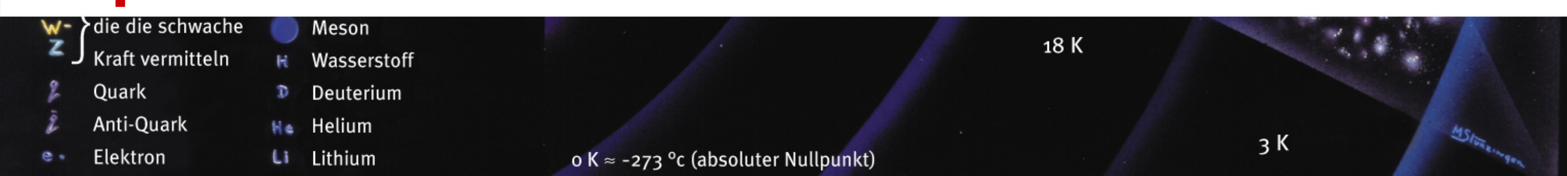
big bang



10^{-6} sec | 10^{-4} sec | 3 min

13.7 millio

experiment

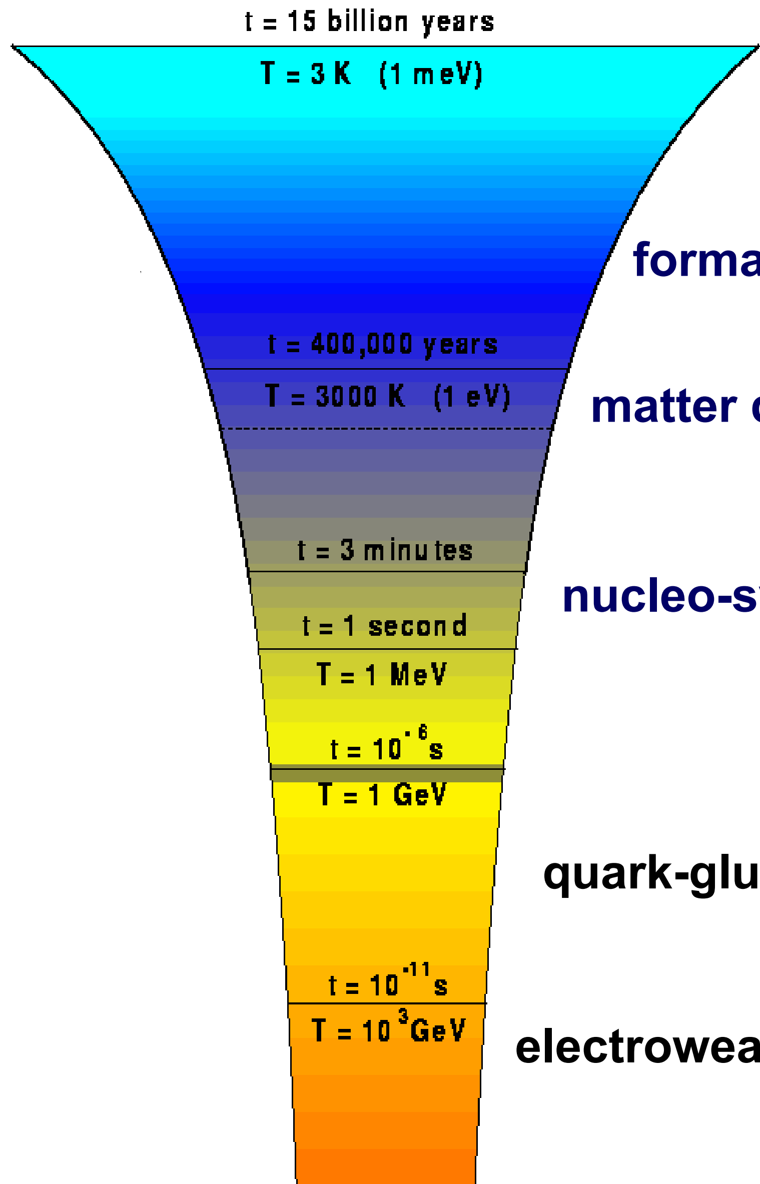


Tracing Back the Big Bang

Hubble expansion →

cosmic microwave radiation →

quark hadron phase transition →



today

formation of galaxies

matter dominated

nucleo-synthesis

quark-gluon matter

electroweak phase transition

How to make the Quark Gluon Plasma in Experiments

Collisions of heavy atomic nuclei

to bring in as much energy as possible,

to spread this energy over a large volume and many particles

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 in Brookhaven AGS and CERN SPS
1992/1994 beams of gold/lead “ and “
2000 gold – gold collisions in RHIC
2010 lead – lead collisions in LHC

increase in energy by factor >1000

What matters: the energy available in the c.m. system

energy in the c.m. system (brief reminder)

beam of nucleus A on stationary target nucleus of equal mass number A

$$\mathrm{E_{cm}} = \mathrm{Am_n}\sqrt{2+2\gamma}$$

due to baryon number conservation energy available to heat system and produce new particles

$$\mathrm{E^*_{cm}} = \mathrm{E_{cm}} - 2\mathrm{Am_n} = \mathrm{Am_n}(\sqrt{2+2\gamma} - 2)$$

beam of nucleus A colliding with equal energy and mass beam

$$\mathrm{E_{cm}} = \mathrm{Am_n} 2\gamma$$

and

$$\mathrm{E^*_{cm}} = \mathrm{Am_n}(2\gamma - 2)$$

but: at high energies nuclei become transparent, i.e. they do not stop each other completely in the c.m. system

from experiment we know: they loose about 85% of their energy, rest travels on

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}* = 570 TeV - 26000 prod. hadrons

AGS : 1986 - 2000

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

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

RHIC : 2000

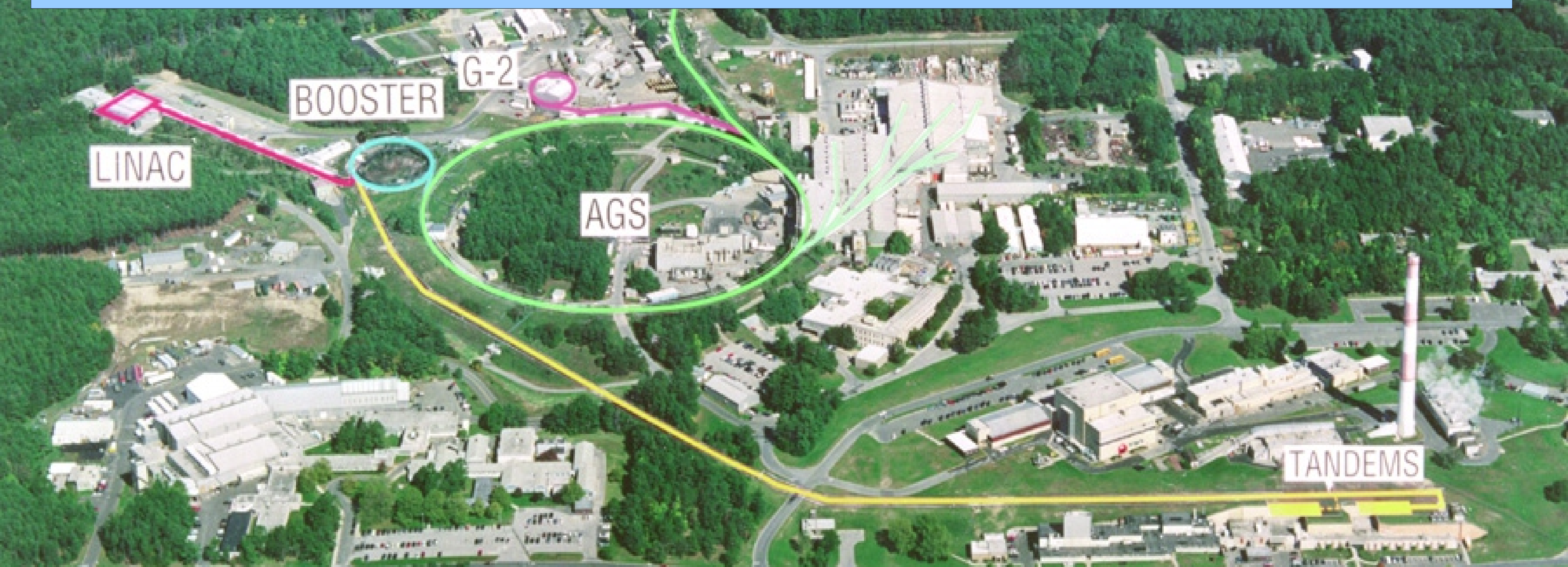
- Au ; up to **√s =** 200 GeV /nucl pair

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

Brookhaven AGS 1986 - 2000

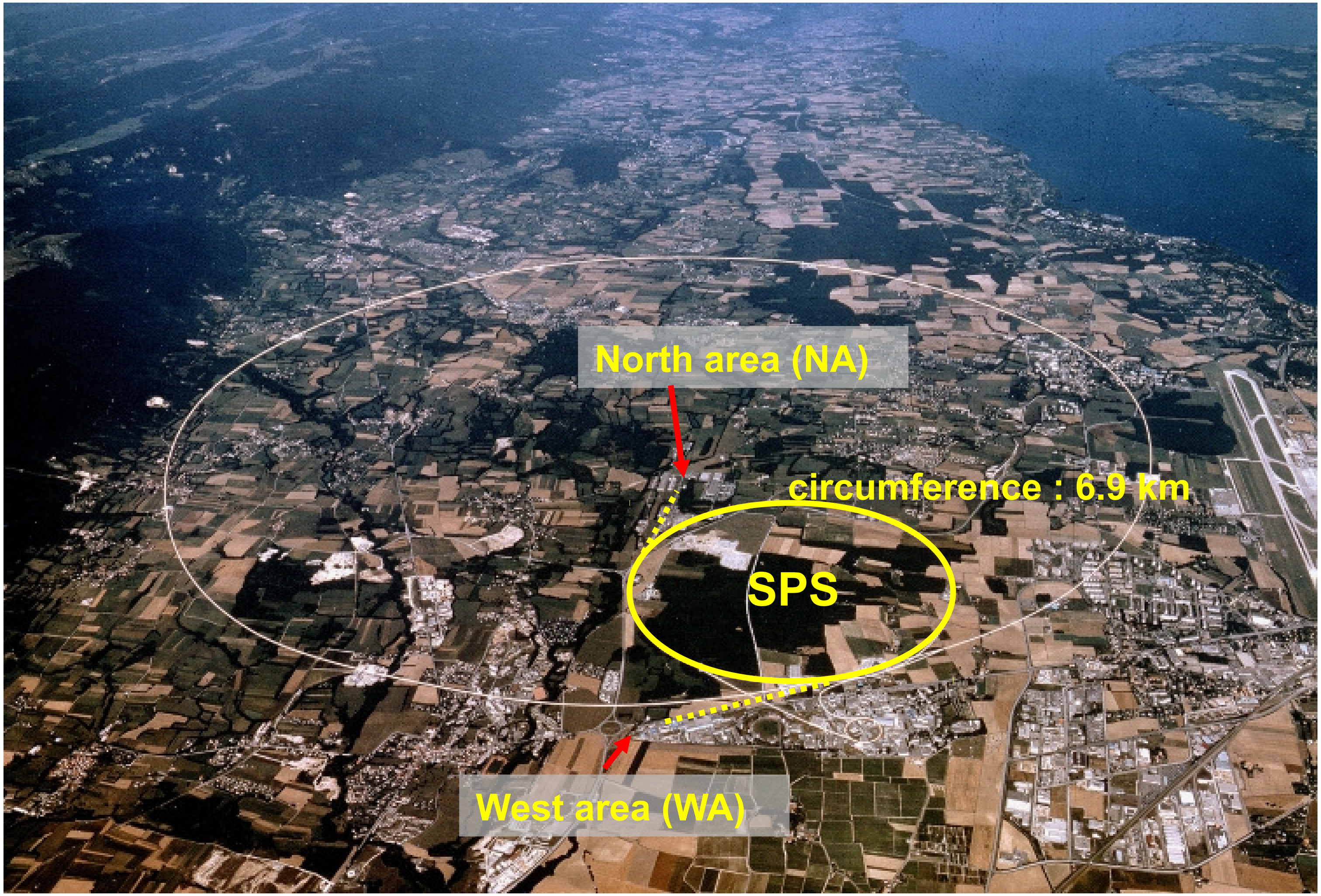
tandems inject beams via booster synchrotron into AGS
circumference 1 km, warm magnets
max momentum 29 A/Z GeV/c = 5.6 GeV per nucleon pair in Au

Experiments E802/866
E810
E814/E877
E864
E917



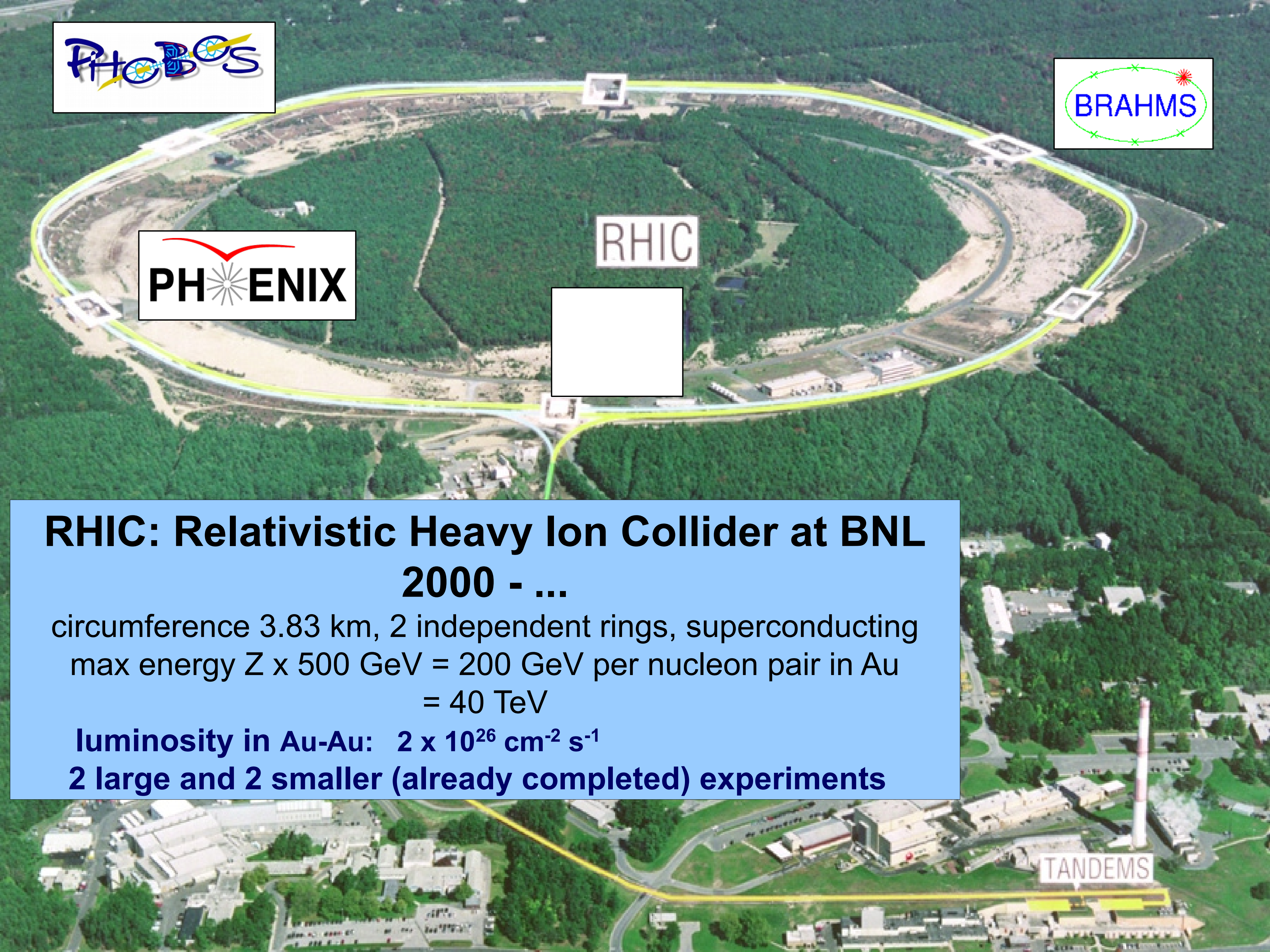
CERN SPS (1986 - 2003)

max momentum 450 A/Z per nucleon pair in lead



NA34/44
NA38/50/60
NA35/49/61
NA45(CERES)
NA52
NA57

WA80/98, WA97→NA57



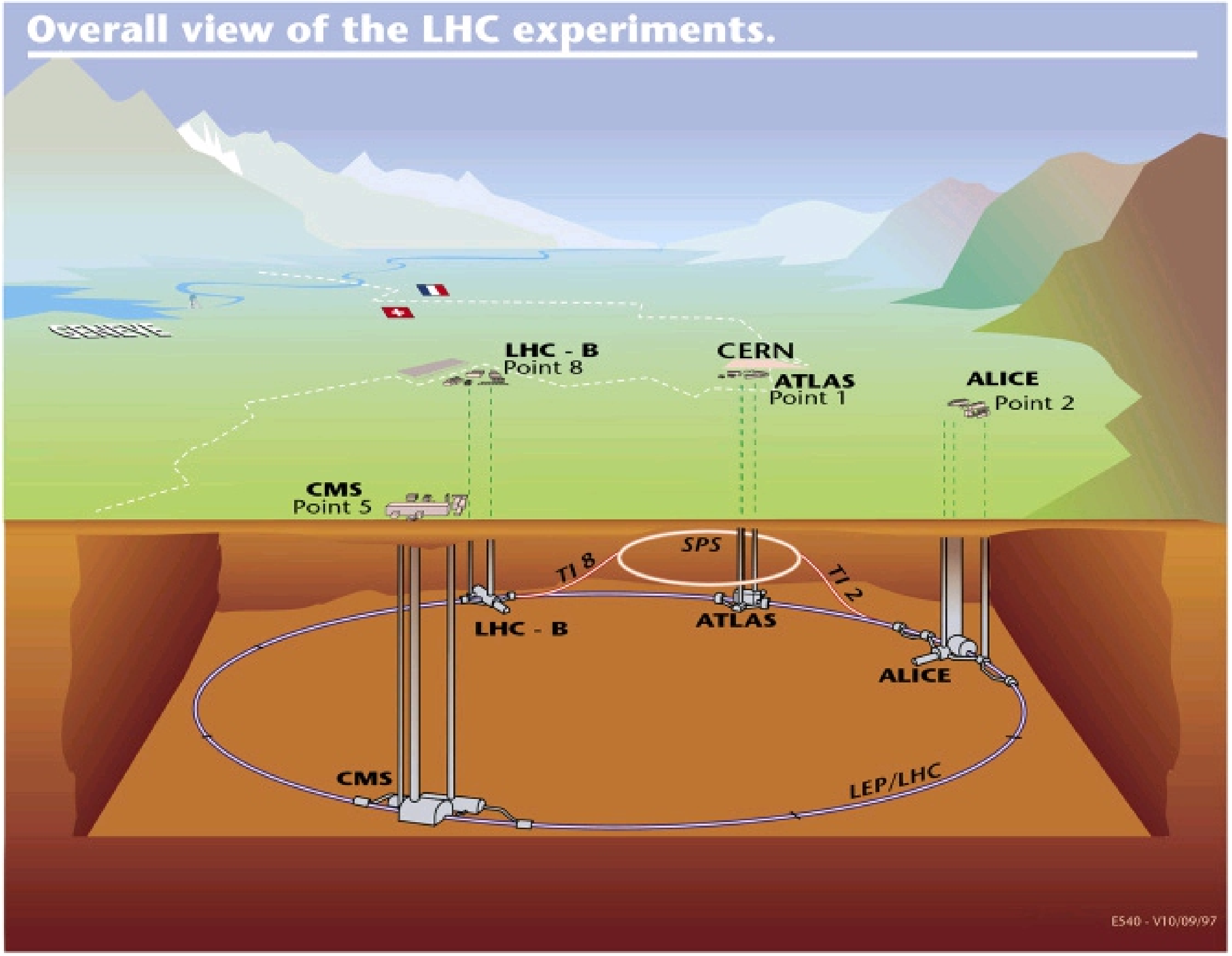
RHIC: Relativistic Heavy Ion Collider at BNL 2000 - ...

circumference 3.83 km, 2 independent rings, superconducting
max energy Z x 500 GeV = 200 GeV per nucleon pair in Au
= 40 TeV

luminosity in Au-Au: $2 \times 10^{26}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

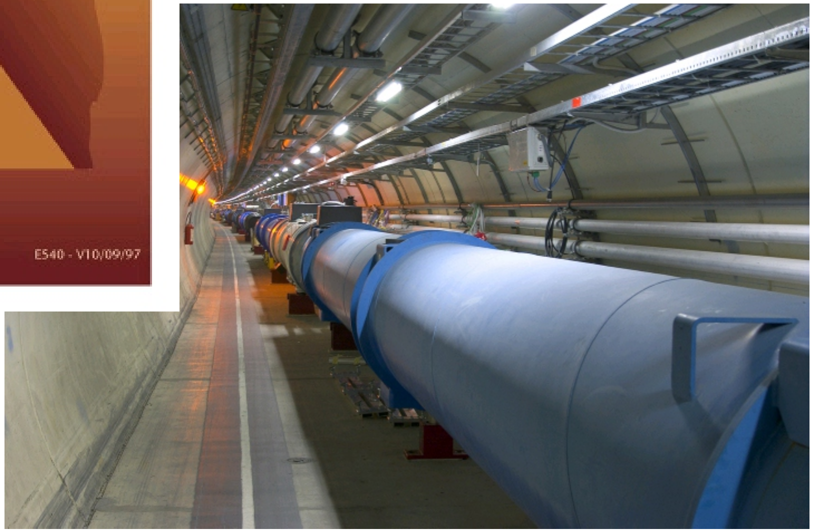
2 large and 2 smaller (already completed) experiments

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



p+p-collisions:
$\sqrt{s}$ = 14 TeV (sofar 8 TeV)
collision rate: 800 MHz

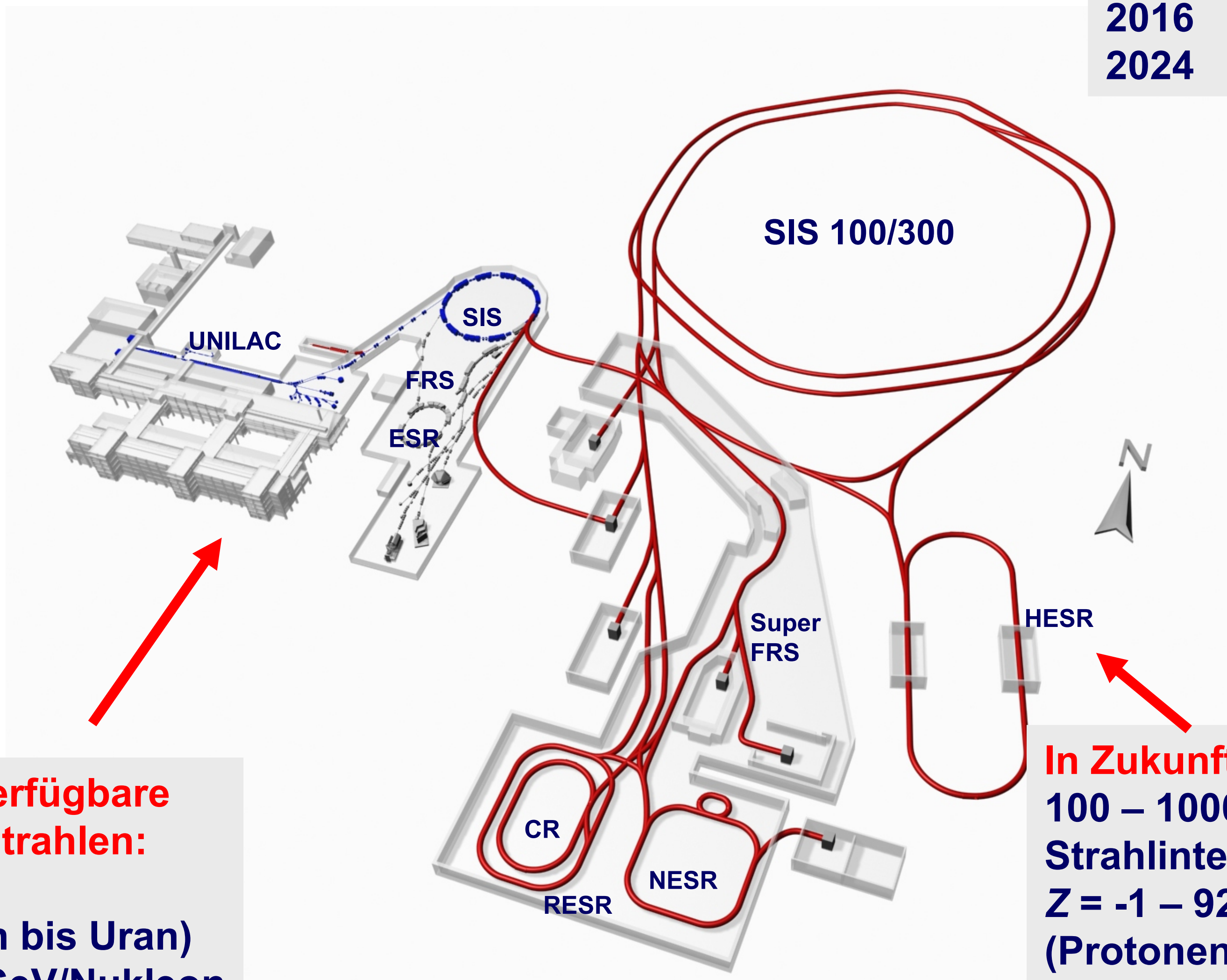
Pb+Pb collisions:
$\sqrt{s}$ =208 x 5.5 TeV max.
(sofar 2.76 TeV)
collision rate: 10 kHz



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

GSI-Zukunftsprojekt: FAIR

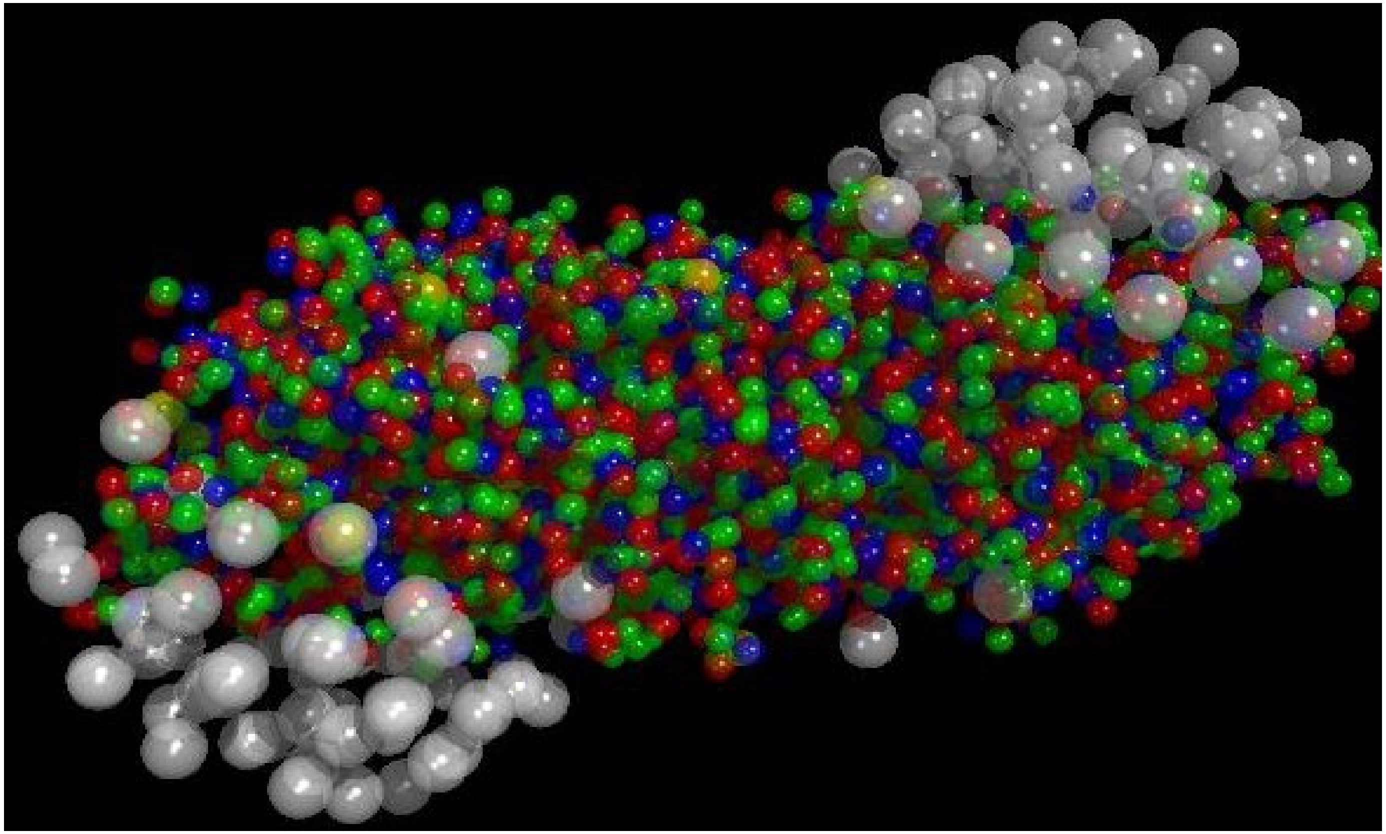
2016 Baubeginn
2024 Fertigstellung



Aktuell verfügbare Teilchenstrahlen:
$Z = 1 - 92$
(Protonen bis Uran)
bis zu 2 GeV/Nukleon

In Zukunft:
100 – 1000-fache Strahlintensitäten,
$Z = -1 - 92$
(Protonen bis Uran, Antiprotonen),
bis zu 12 (35) GeV/Nukleon

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

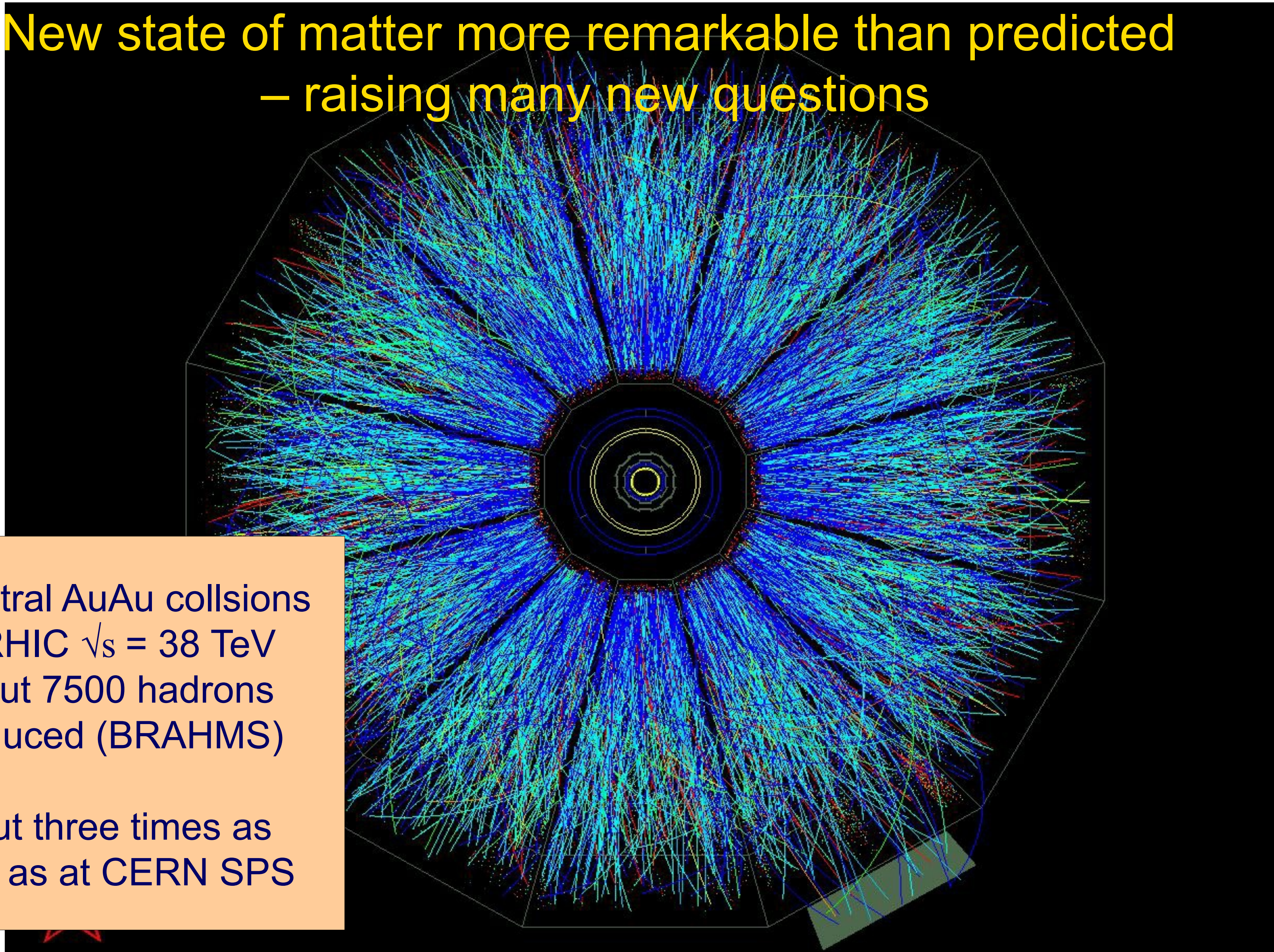


At a special seminar on 10 February, spokespersons from the experiments on CERN 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

BNL press release April 2005:

RHIC Scientists Serve Up “Perfect “ Liquid

New state of matter more remarkable than predicted – raising many new questions



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

about three times as many as at CERN SPS

Time evolution of fireball after collision

Minkowski diagram in time t and long. coord. z, proper time t = Öt^2 - z^2
collision at t=0, before nuclei approach each other with speed-of-light

1st stage: liberation of quarks and gluons
time scale order 0.1 fm/c

2nd stage: equlibration of quarks and gluons, at end QGP

3rd stage: expansion and cooling of QGP
$T \propto \tau^{-1/3}$

4th stage: hadronization when T_c is reached

5th stage: expansion of hadron gas

6th stage: freeze-out = momentum distributions are frozen in