

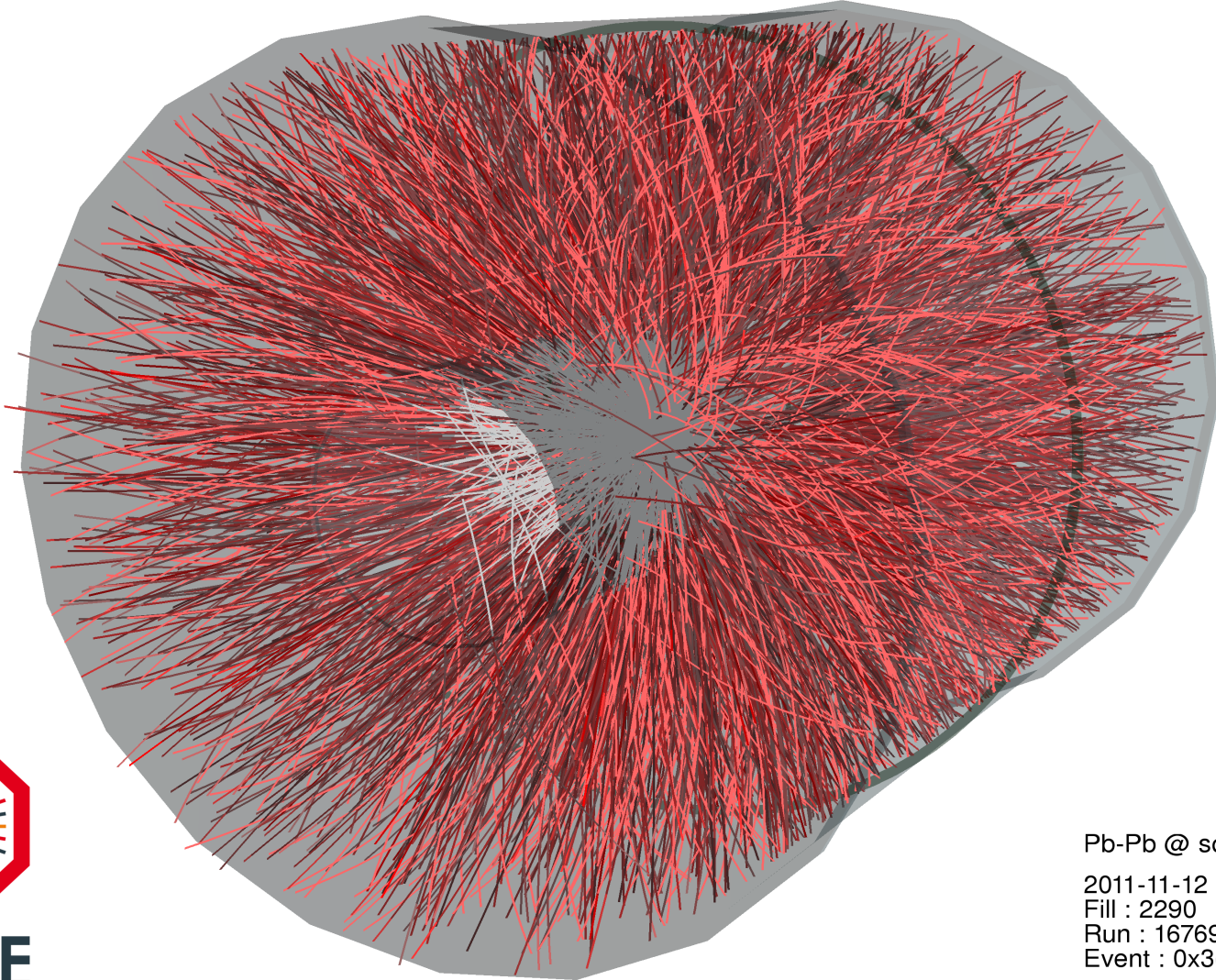


# **Quark-Gluon Plasma Physics**

## **1. Introduction**

**Prof. Dr. Klaus Reygers, Prof. Dr. Johanna Stachel  
Heidelberg University  
SS 2019**

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



**ALICE**

A JOURNEY OF DISCOVERY

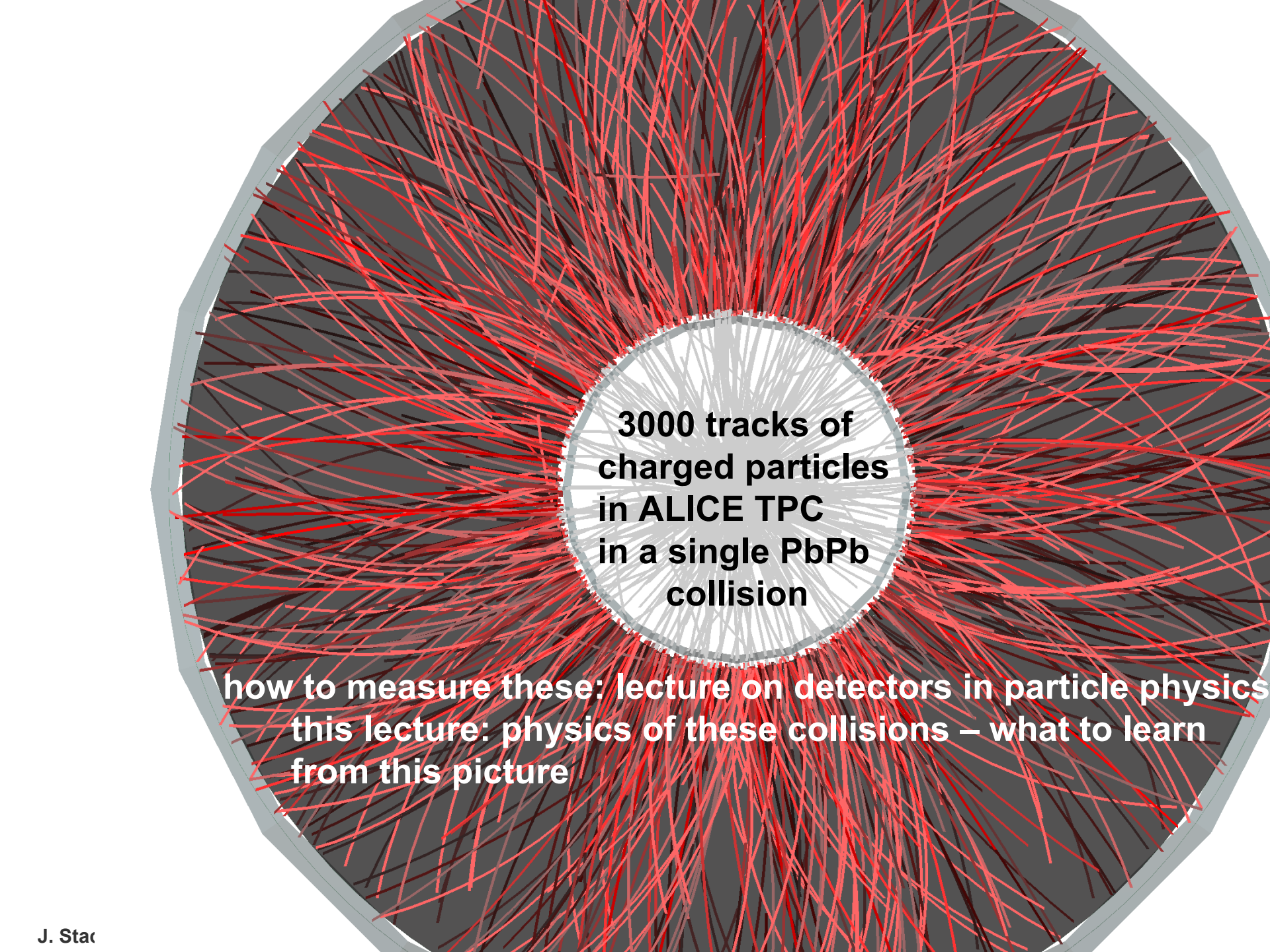
Pb-Pb @  $\sqrt{s} = 2.76$  ATeV

2011-11-12 06:51:12

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Event : 0x3d94315a

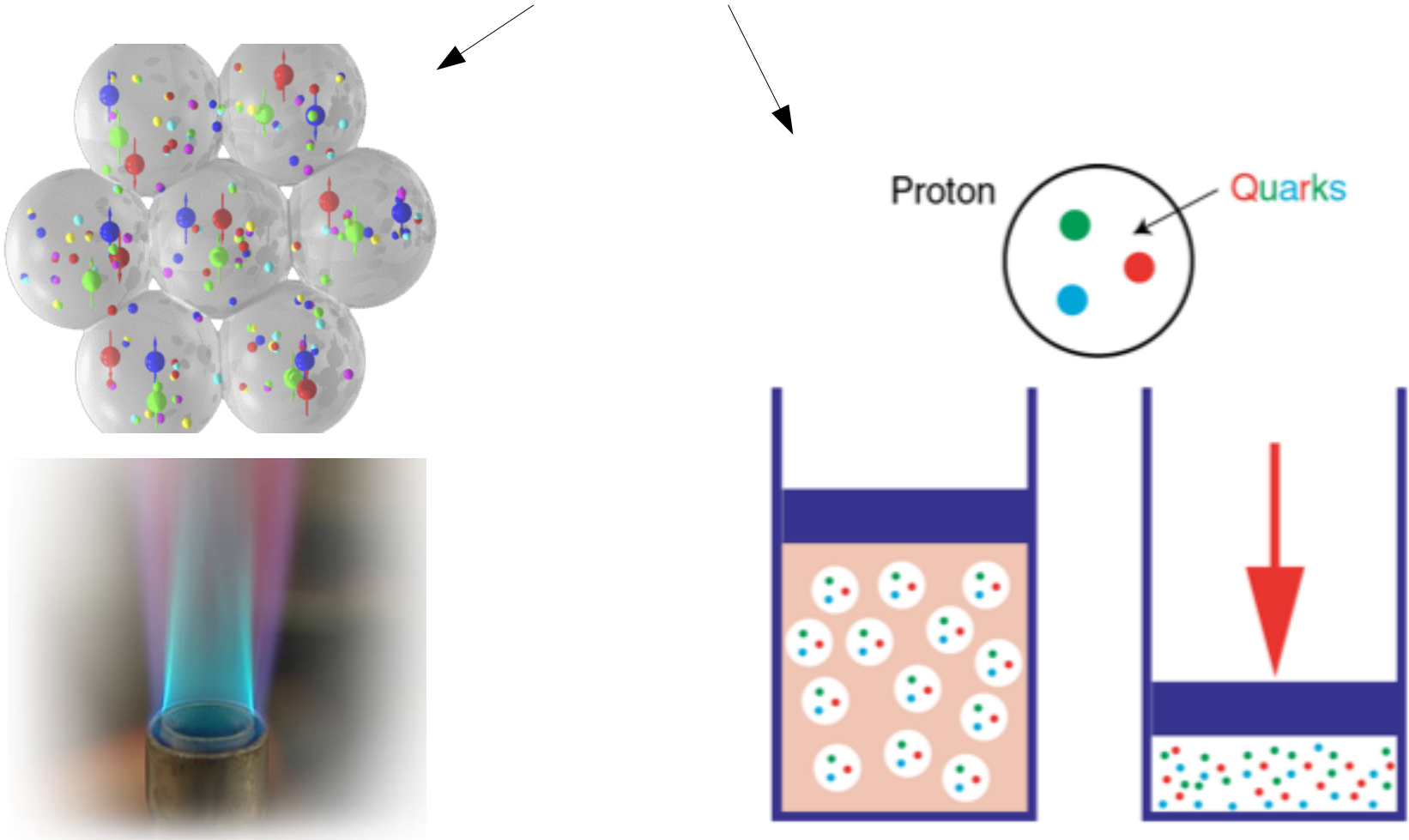


**3000 tracks of  
charged particles  
in ALICE TPC  
in a single PbPb  
collision**

**how to measure these: lecture on detectors in particle physics  
this lecture: physics of these collisions – what to learn  
from this picture**

# What is a Quark-Gluon Plasma?

A macroscopic state of thousands of quarks and gluons produced by either extreme heating or compression of matter

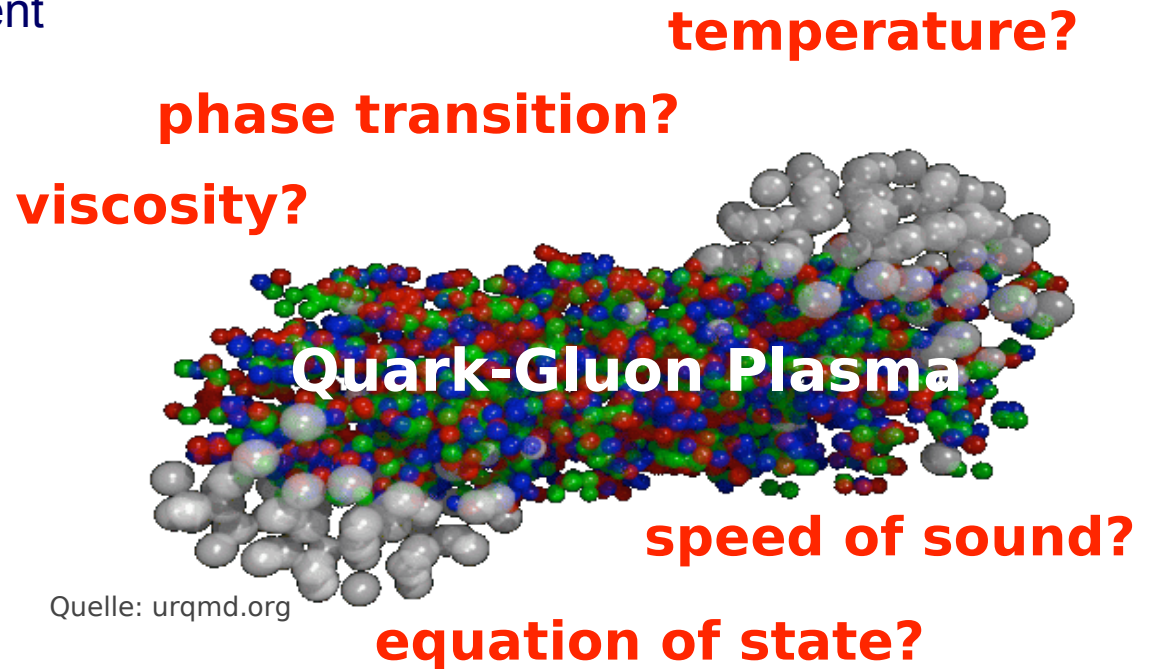


# a Quark-Gluon Plasma is Matter

We want to study material properties of this state

Particle physics: reductionism

Heavy ion physics: emergent properties of QCD



„More is different“

Philip W. Anderson, Science 177 (1972) 393

# Organizational matters

## Quark-Gluon Plasma Physics

[Prof. Dr. Johanna Stachel](#), [Prof. Dr. Klaus Reygers](#).

Welcome

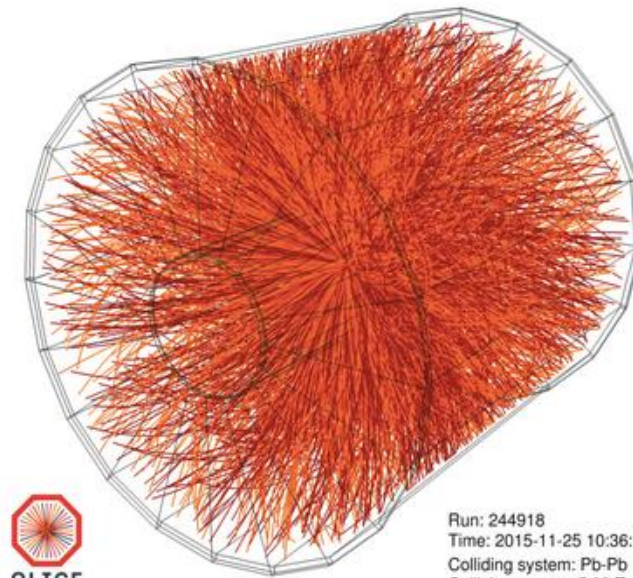
Contents

Literature

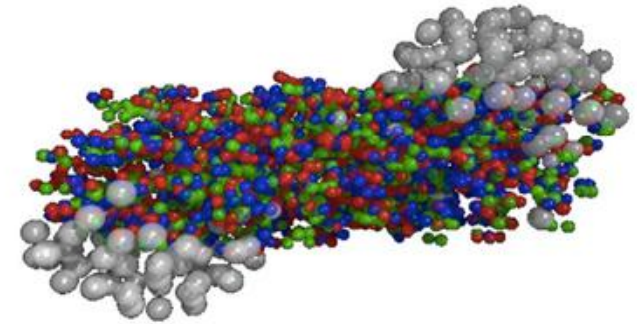
[close](#) [close others](#) [edit](#) [more](#)

### Welcome

LAST MODIFIED 5 APRIL 2019



Run: 244918  
Time: 2015-11-25 10:36:18  
Colliding system: Pb-Pb  
Collision energy: 5.02 TeV



QCD in extreme conditions: Central collisions of two lead nuclei at the LHC.

In this experimental lecture you will learn about the physics of QCD matter under extreme conditions as studies in ultra-relativistic collisions of nuclei.

[http://www.physi.uni-heidelberg.de/~reygers/lectures/2019/qgp/qgp\\_lecture\\_ss2019.html](http://www.physi.uni-heidelberg.de/~reygers/lectures/2019/qgp/qgp_lecture_ss2019.html)

# 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. Correlations
8. Hard Scattering, Jets and Jet Quenching
9. J/Psi and Quarkonia
10. Thermal Photons and Dileptons



# Audience

## ■ Bachelor/Master students

- deepen knowledge about nuclear and particle physics
- relativistic kinematics, statistical mechanics, basics of QCD, hydrodynamics
- obtain overview of ultra-relativistic heavy-ion physics
- obtain/apply programming skills as part of solving problems (root, Mathematica, jupyter notebook, ...)

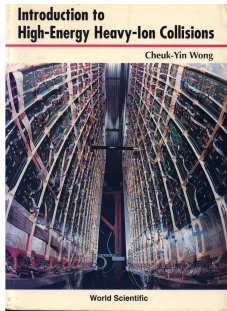
## ■ Doctoral students

- update on developments in areas besides own research topic

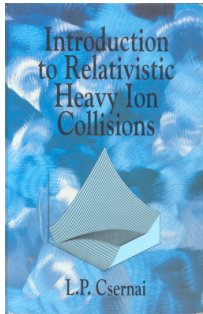
# Requirement for successful participation

- no written exam
- each week about one homework problem, to be solved e.g. using jupyter notebook. Solutions presented at beginning of next lecture by students and discussed by everybody
- Some questions on previous lecture given at beginning of lecture, discussion in small groups and then jointly. Including additional questions on previous lecture by students.
- Successful participation: show solution of one homework problem and participate in discussions

# Books (I)

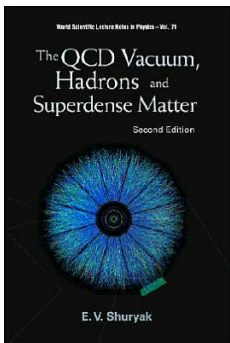


Wong, Introduction to High-Energy Heavy-Ion Collisions, World Scientific, 1994 (→ [Link](#))



Csernai, Introduction to Relativistic Heavy-Ion Collisions, 1994

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

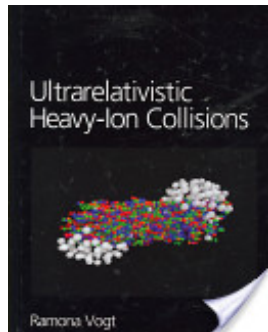


Shuryak, The QCD vacuum, hadrons, and superdense matter, World Scientific, 2004 (→ [Link](#))

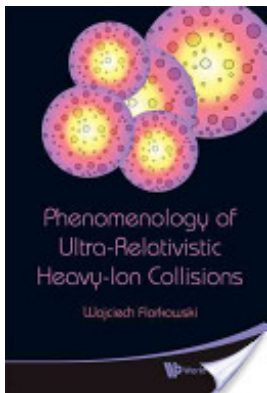
## Books (II)



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

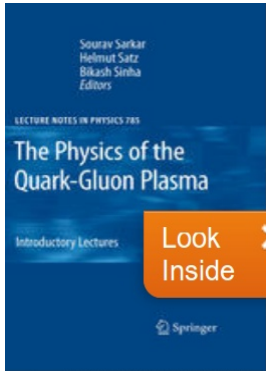


Vogt, Ultrarelativistic Heavy-Ion Collisions,  
Elsevier, 2007 (→ [Link](#))



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](#))

# Units in this lecture

Energy and momentum: GeV

Length: fm (“Fermi”) 1 fm =  $10^{-15}$  m

$$\hbar c = 0.197 \text{ GeV fm}$$

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

Temperature: in energy units, i.e.  $k_B T$  with  $k_B = 8.617 \cdot 10^{-5}$  eV/K  
e.g. room temperature 300 K corresponds to 1/40 eV

Natural units:  $\hbar = c = k_B = 1$

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

# Reminder: fundamental components of matter

three generations of matter  
(fermions)

	I	II	III		
mass	$\approx 2.4 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 172.44 \text{ GeV}/c^2$	0	$\approx 125.09 \text{ GeV}/c^2$
charge	$2/3$	$2/3$	$2/3$	0	0
spin	$1/2$	$1/2$	$1/2$	1	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> Higgs
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\gamma</math></b> photon	
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>Z</b> Z boson	
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>W</b> W boson	

QUARKS

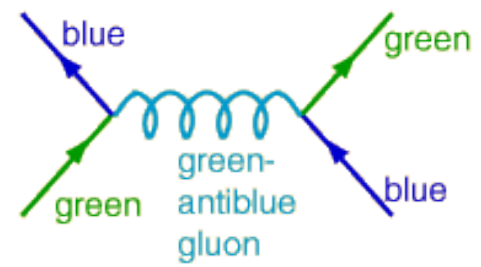
LEPTONS

SCALAR BOSONS

GAUGE BOSONS

Quarks come in three different colors: ● ● ●

Gluons: mediate interaction between quarks



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

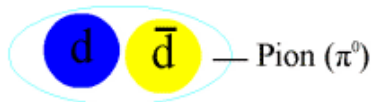
+ antiparticles

# Quarks and gluons

quarks don't occur freely in nature “confinement”

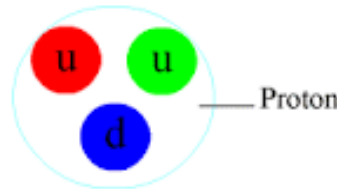
quarks are bound by the strong interaction in colorless hadrons

mesons

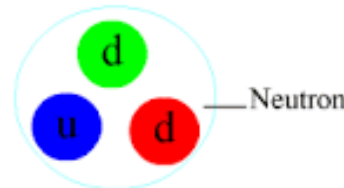


quark-antiquark

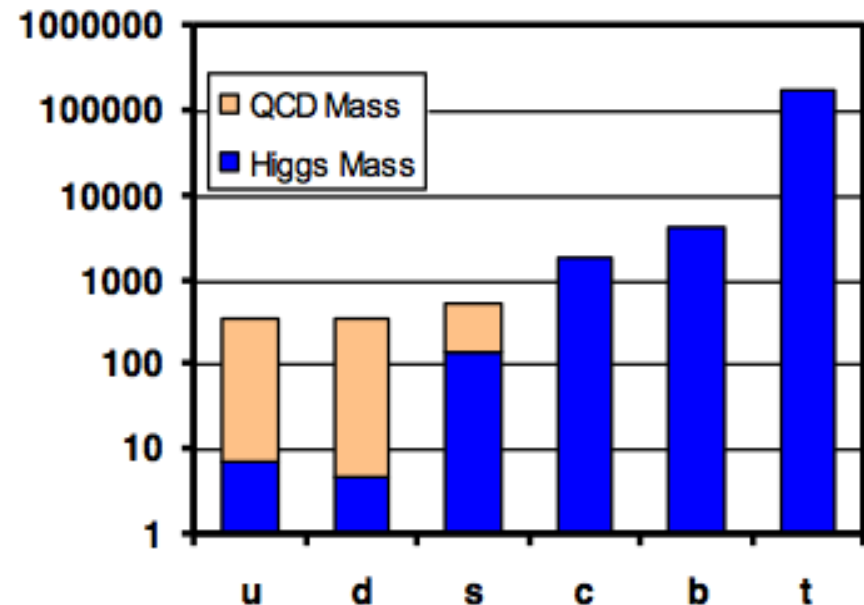
baryons



3 valence quarks



5 quarks and antiquarks form about 150 mesons and baryons, each mass scale set by “constituent quark masses, due to spontaneous 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

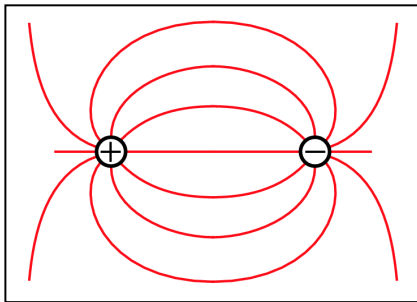
they interact strongly by exchange of colored gluons (8 different gluons from 3 colors and 3 anticolors)

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 Fritsch, Gell-Mann, Wess)

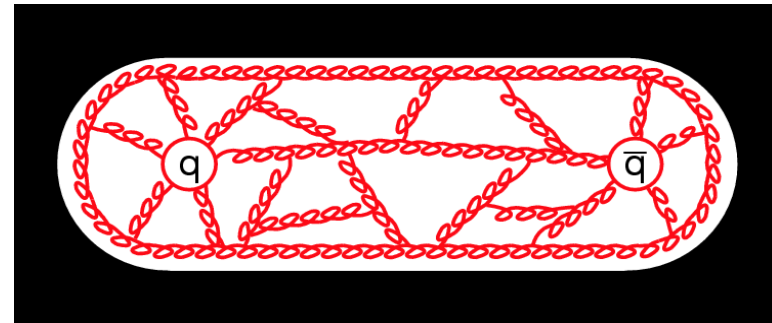
quarks are confined in hadrons, trying to pull them apart, the interaction becomes stronger

**QED:**



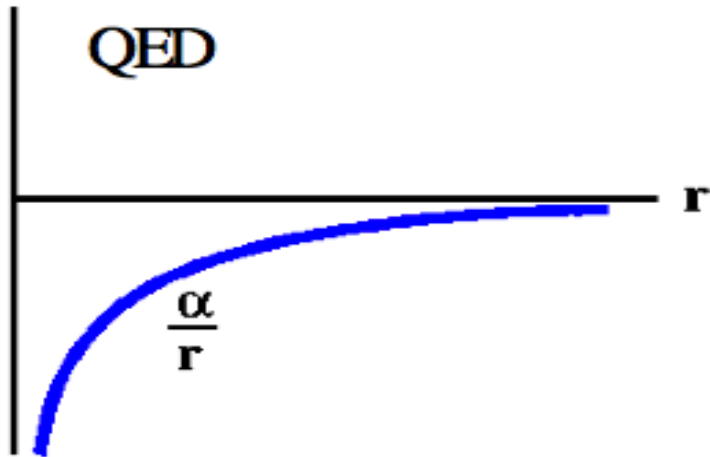
$$V(r) \propto \frac{\alpha}{r}$$

**QCD:**

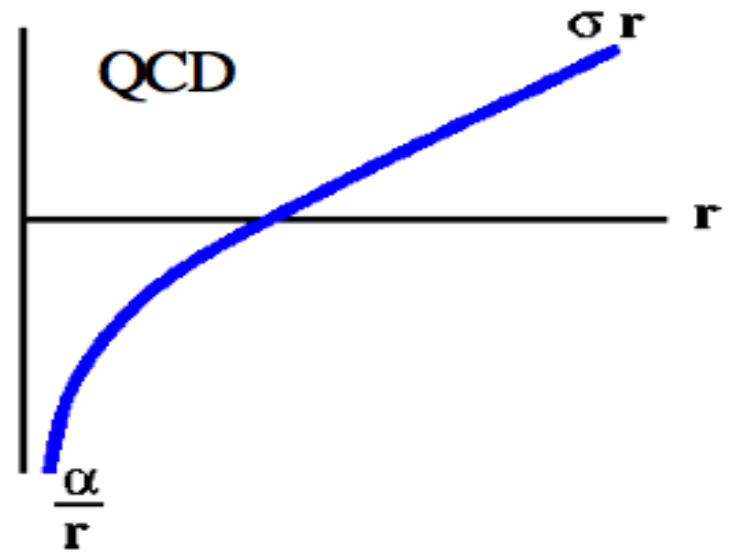


$$V(r) \approx -\frac{4\alpha_s(r)}{3r} + k r$$

# Strongly interacting matter described by QCD



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



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

linear rise due to confinement

# Strongly interacting matter described by QCD

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



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](#)

H. David Politzer   David J. Gross   Frank Wilczek

$\alpha_s$  drops with increasing  $q^2$   
or decreasing  $r$

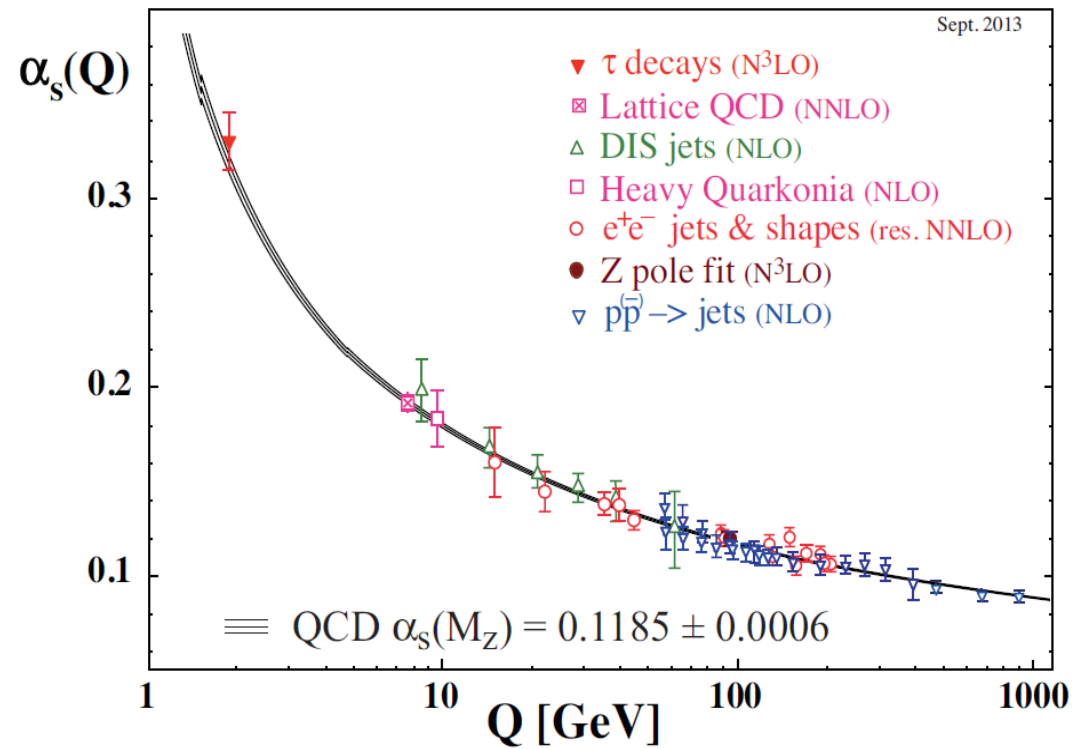
# Running coupling constants

REVIEW OF PARTICLE PHYSICS\*

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

in QED vacuum polarization leads to **increase** of coupling constant  $\alpha$  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  $\alpha_s$  with **decreasing**  $r$  or **increasing** momentum transfer  $q$



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

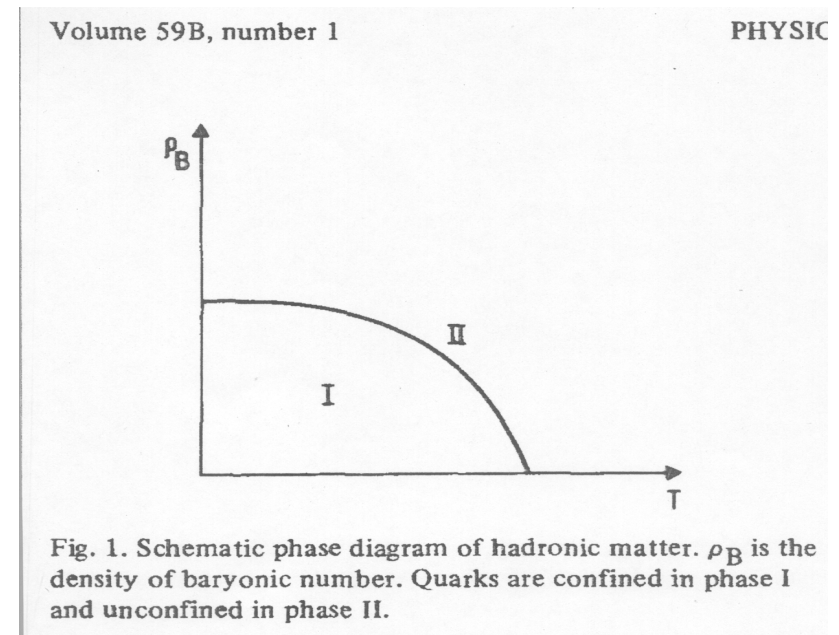
-> new state of strongly interacting matter

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

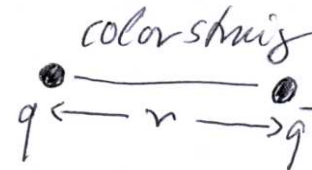


# Estimate of critical temperature for deconfinement

first estimate by Polyakov 1978

at  $T=0$ , energy in a color string  $E_{q\bar{q}} = \sigma r$

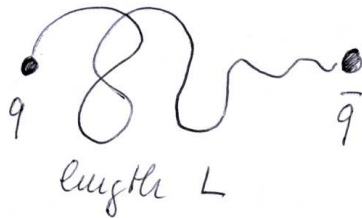
with string tension  $\sigma \approx 1\text{GeV}/\text{fm}$



for  $T > 0$ , free energy of string

$$F_{q\bar{q}}(L) = E_{q\bar{q}}(L) - TS(L)$$

$$= \sigma L - T \ln N(L) = \left( \sigma - \frac{T}{a \ln 5} \right) L = \sigma_{\text{eff}} L$$



with the number of string configurations

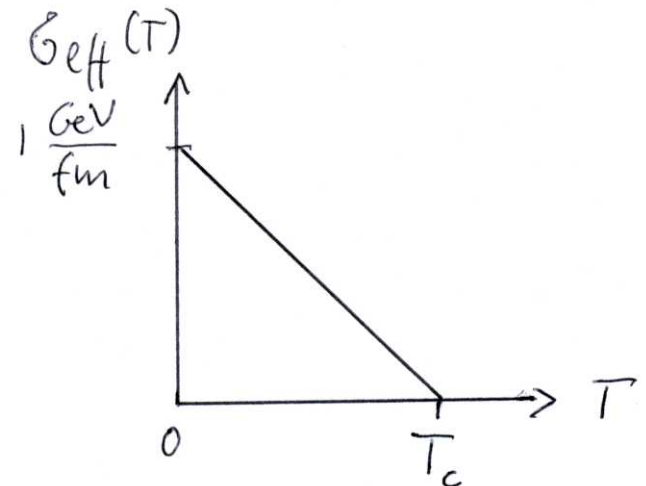
$$N(L) = 5^{L/a}$$

5 directions to go with typical stepsize  $a$

and typical string thickness  $a = 0.3 \text{ fm}$

critical temperature reached when  $\sigma_{\text{eff}} = 0$

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



# 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:  $\rho_m \propto (m_0^2 + m^2)^{-5/4} \exp(m/b)$

the energy density of a hadron gas becomes

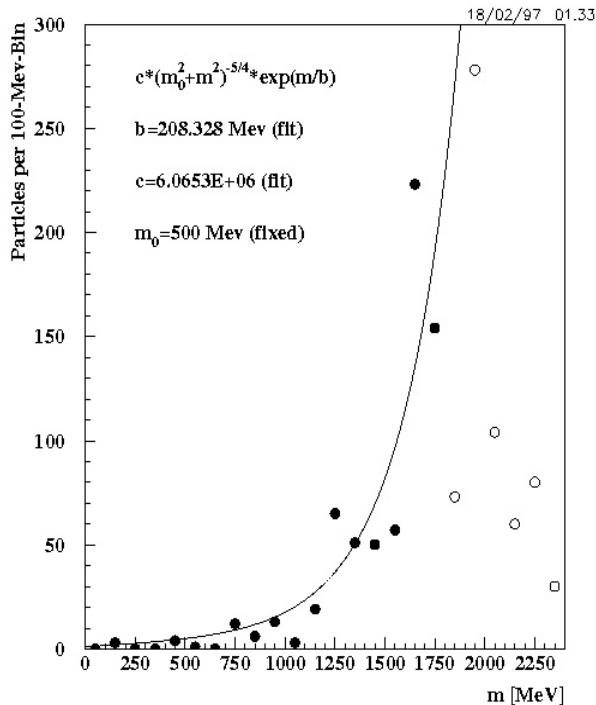
$$\epsilon(T) = \sum_{m_\pi}^M \epsilon(m_i, T) + \int_M^\infty \epsilon(m, T) \rho(m) dm$$

but for large masses  $m > M$   $\epsilon(m, T) \propto \exp(-m/T)$

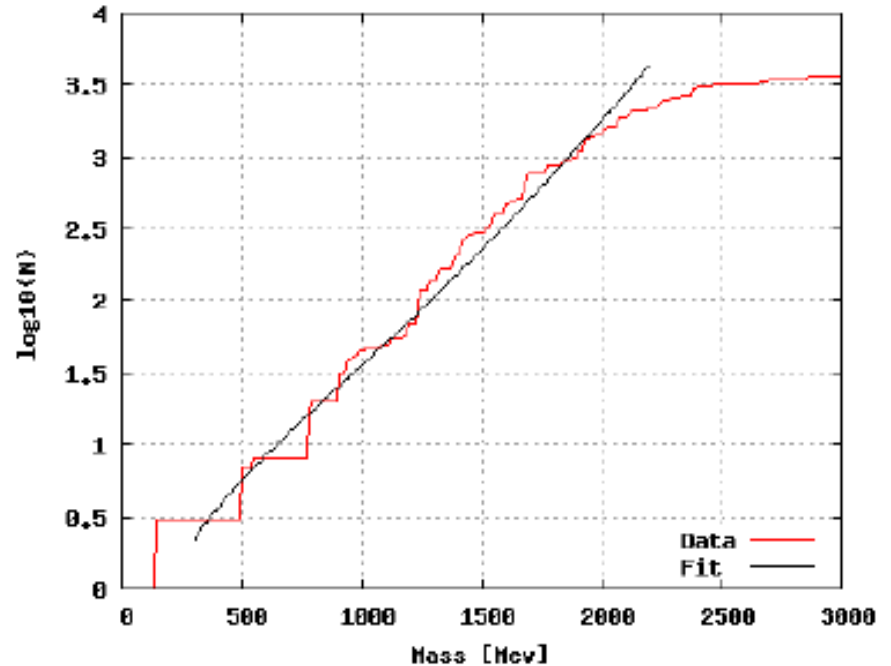
implying that integral diverges for  $T > b$

# Best estimate of Hagedorn temperature is still evolving

Known hadronic spectrum in 1997



Fit to integrated density of states as of PDG2008



$$f_{FIT}(m) = \log_{10} \left( \int_0^m \frac{c}{(x^2 + m_0^2)^{5/4}} \exp(x/T_H) \right) \quad \text{All hadrons } T_H = 177.086, c = 18726.494, \text{ range: } 300 - 2200 \text{ MeV}$$

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,  $\alpha_s$  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  $\alpha_s = 0.2-03$

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

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

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

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

in fact, this is a bit too low

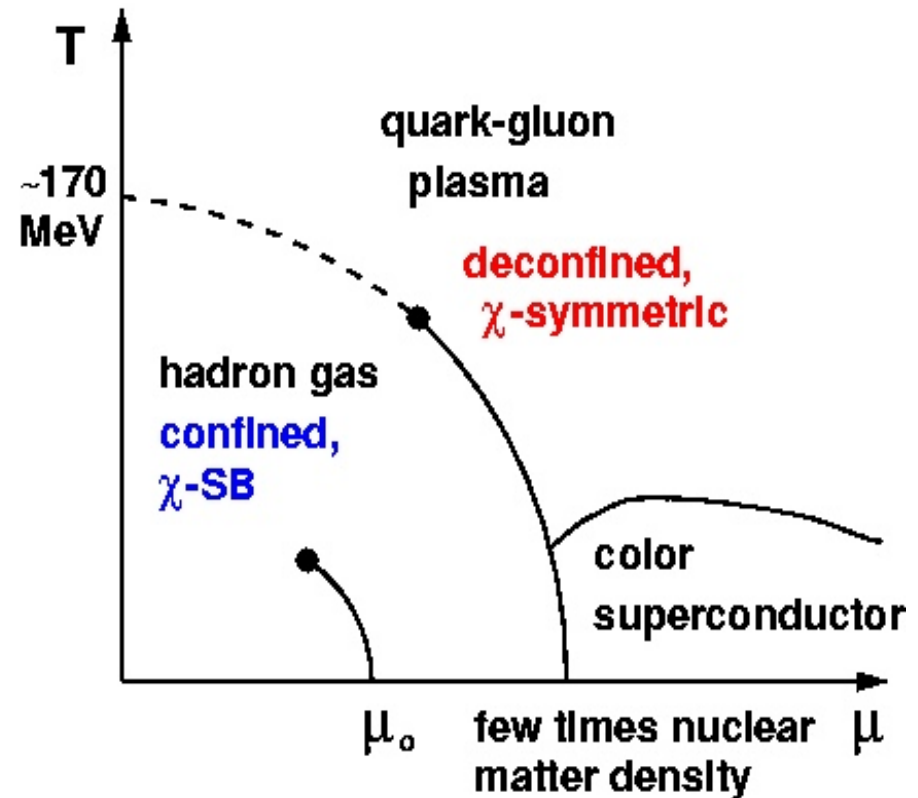
will see later, that in order for quark-gluon bubble to sustain the vacuum pressure from the outside minimally  $4 \rho_0$  is needed

# Modern phase diagram of strongly interacting matter

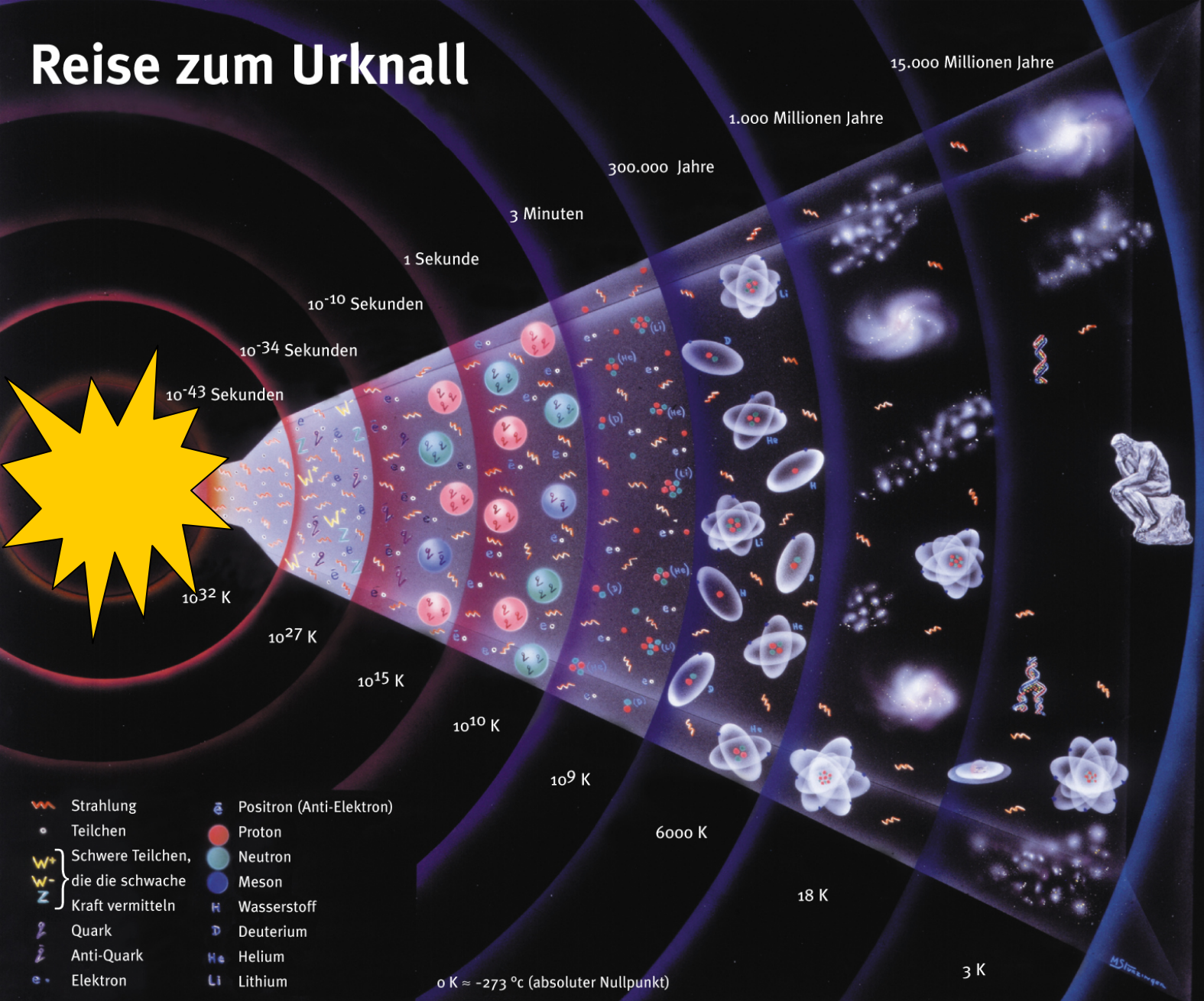
better knowledge of  
critical temperature at zero net baryon density  
nature of phase transition  
(see chapter 4)

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



- Strahlung
- Teilchen
- Schwere Teilchen, die die schwache Kraft vermitteln
- Quark
- Anti-Quark
- Elektron
- Positron (Anti-Elektron)
- Proton
- Neutron
- Meson
- Wasserstoff
- Deuterium
- Helium
- Lithium

0 K  $\approx$  -273 °C (absoluter Nullpunkt)

MS/Steininger

# returning to the big bang



nature

Quark-Gluon

Plasma

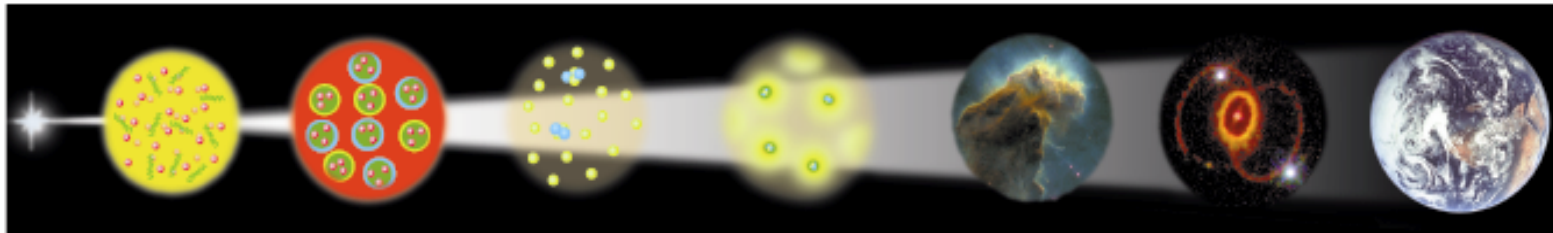
nucleons

nuclei

atoms

today

big bang



$10^{-6}$  sec

$10^{-4}$  sec

3 min

13.7 million

experiment

- W<sup>-</sup> } die die schwache Kraft vermitteln
- Z<sup>0</sup> }
- Q Quark
- Q̄ Anti-Quark
- e<sup>-</sup> Elektron
- M Meson
- H Wasserstoff
- D Deuterium
- He Helium
- Li Lithium

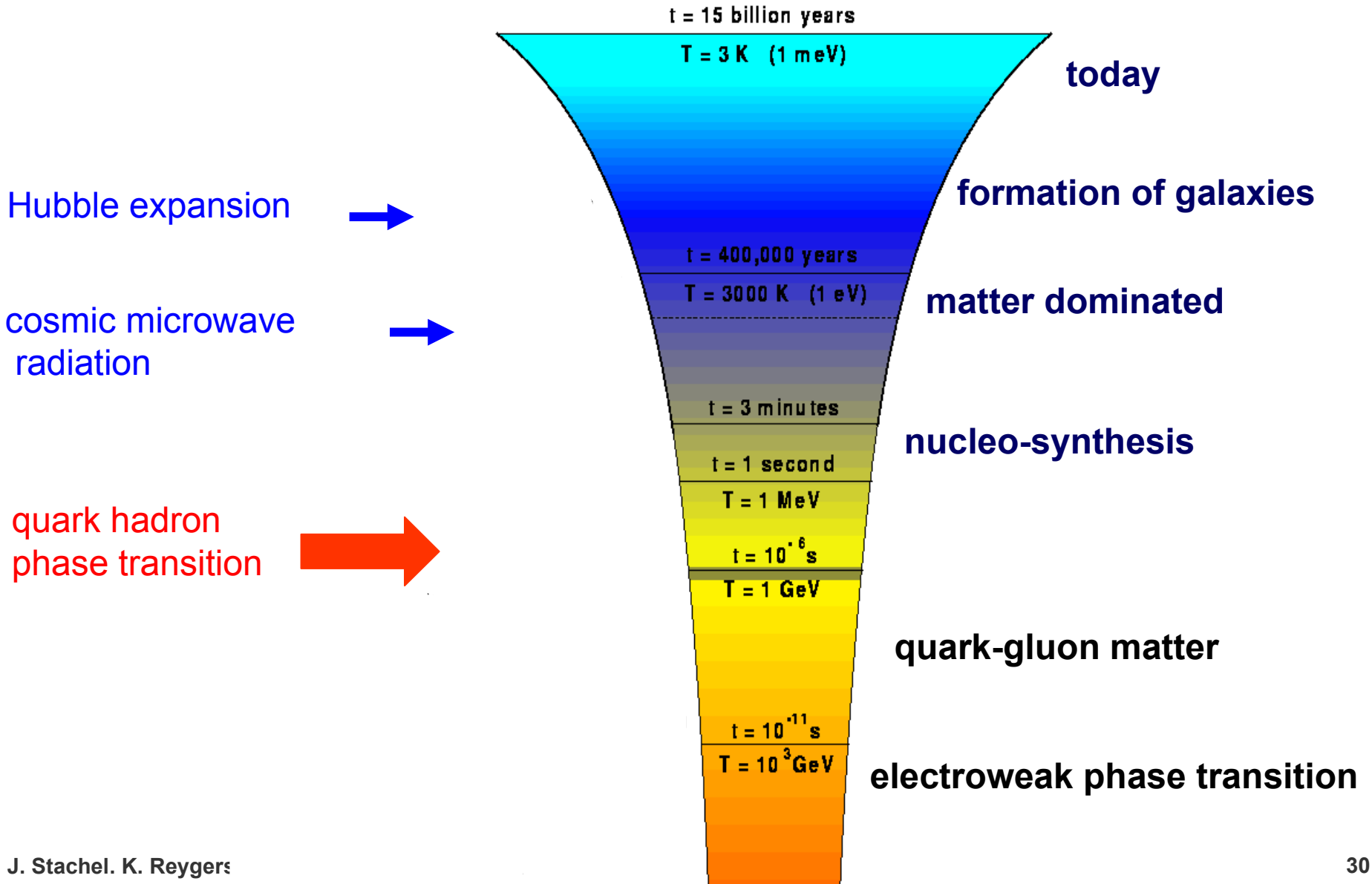
18 K

0 K ≈ -273 °C (absoluter Nullpunkt)

3 K

MSI/ST/ingen

# Tracing Back the Big Bang



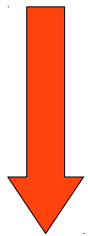
# How to make the Quark Gluon Plasma in Experiments

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

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

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

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

- beam of nucleus A colliding with equal energy and mass beam

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

and

$$E_{\text{cm}}^* = Am_n (2\gamma - 2)$$

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



CE•NR



## SPS : 1986 - 2003

- S and Pb ; up to  $\sqrt{s} = 20$  GeV/nucleon pair  
2500 prod hadrons

## LHC : starting 2009

- Pb ; up to  $\sqrt{s} = 5.5$  TeV/nucleon pair  
26000 prod. hadrons

## AGS : 1986 - 2000

- Si and Au ; up to  $\sqrt{s} = 5$  GeV /nucleon pair  
1000 prod. hadrons

## RHIC : 2000

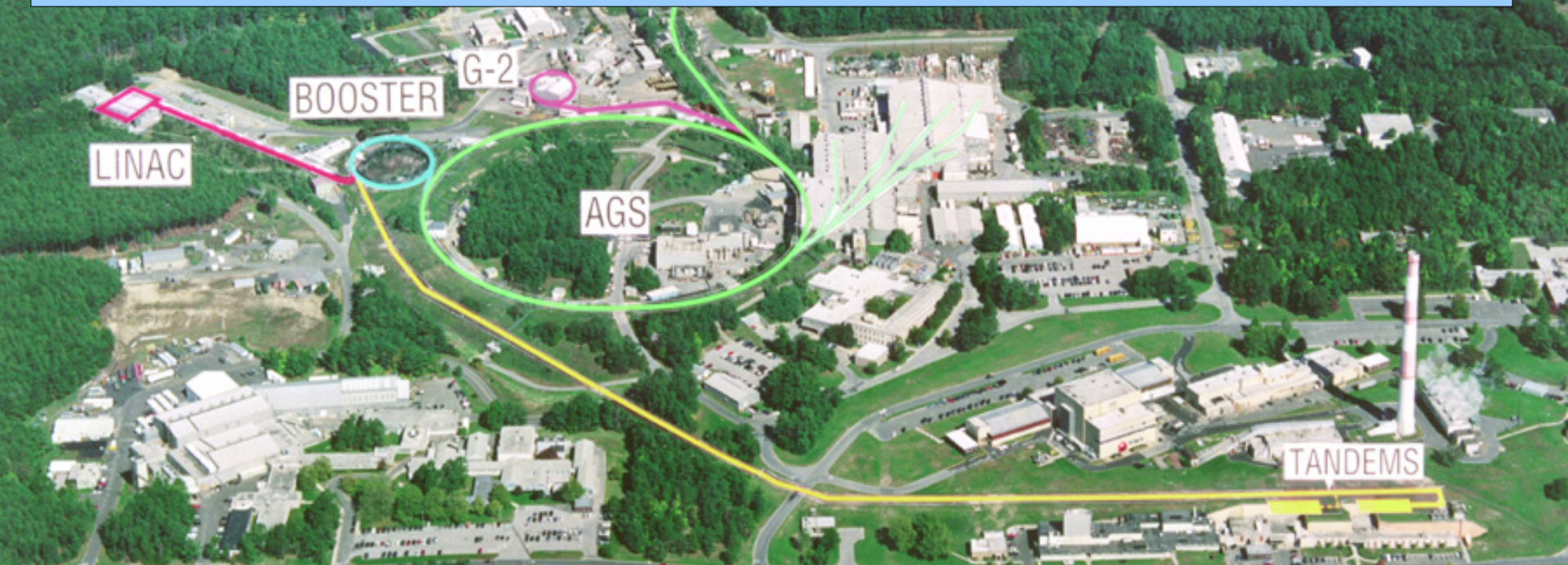
- Au ; up to  $\sqrt{s} = 200$  GeV /nucleon pair  
7500 prod. hadrons



# Brookhaven AGS 1986 - 2000

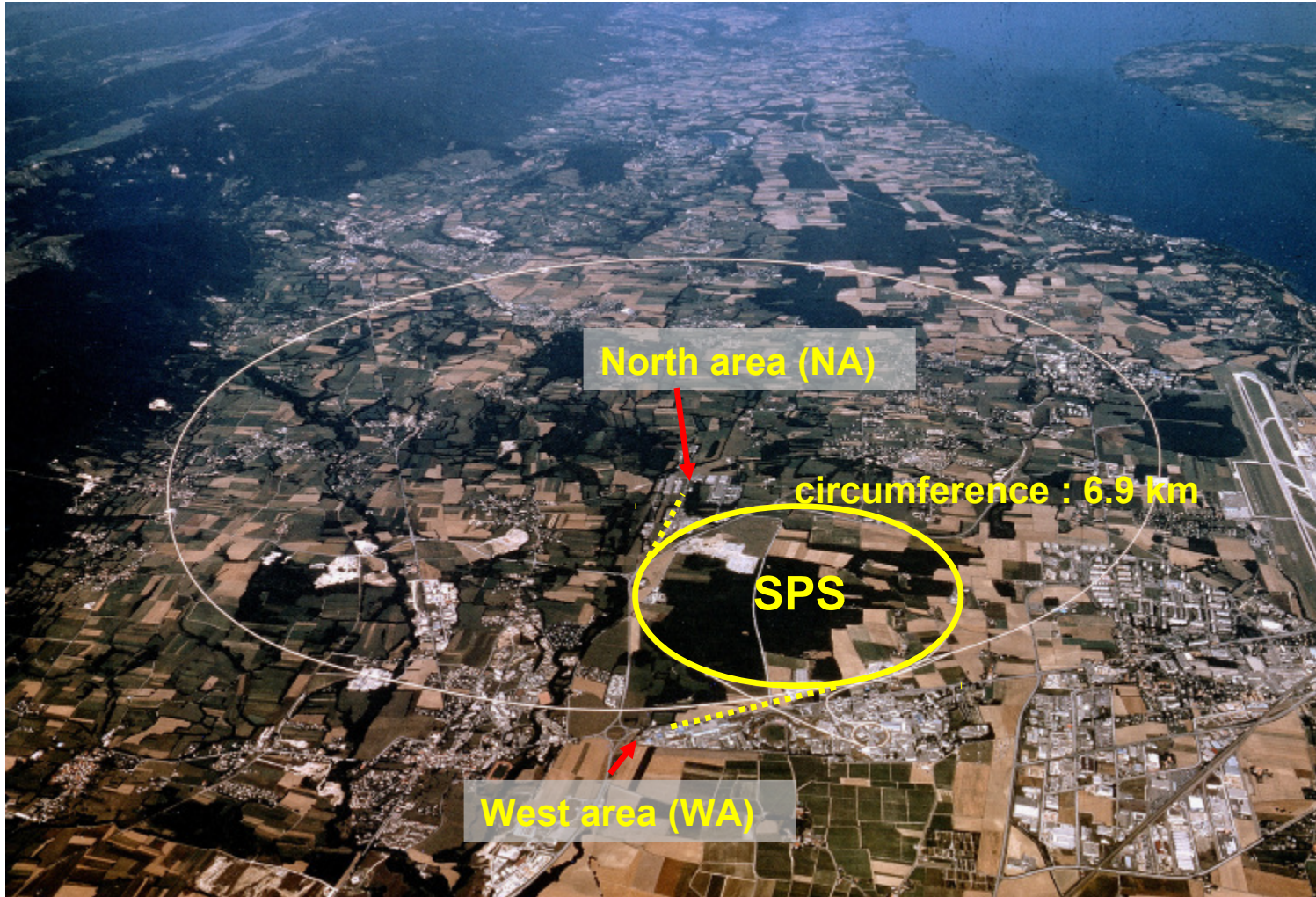
tandems inject beams via booster synchrotron into AGS  
circumference 1 km, warm magnets  
max momentum per nucleon  $29 Z/A \text{ GeV}/c$

Experiments E802/866  
E810  
E814/E877  
E864  
E917



# CERN SPS (1986 - 2003)

max momentum per nucleon 450 Z/A GeV/c

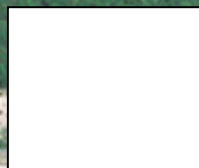


NA34/44  
NA38/50/60  
NA35/49/61  
NA45(CERES)  
NA52  
NA57

WA80/98, WA97 → NA57



RHIC



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

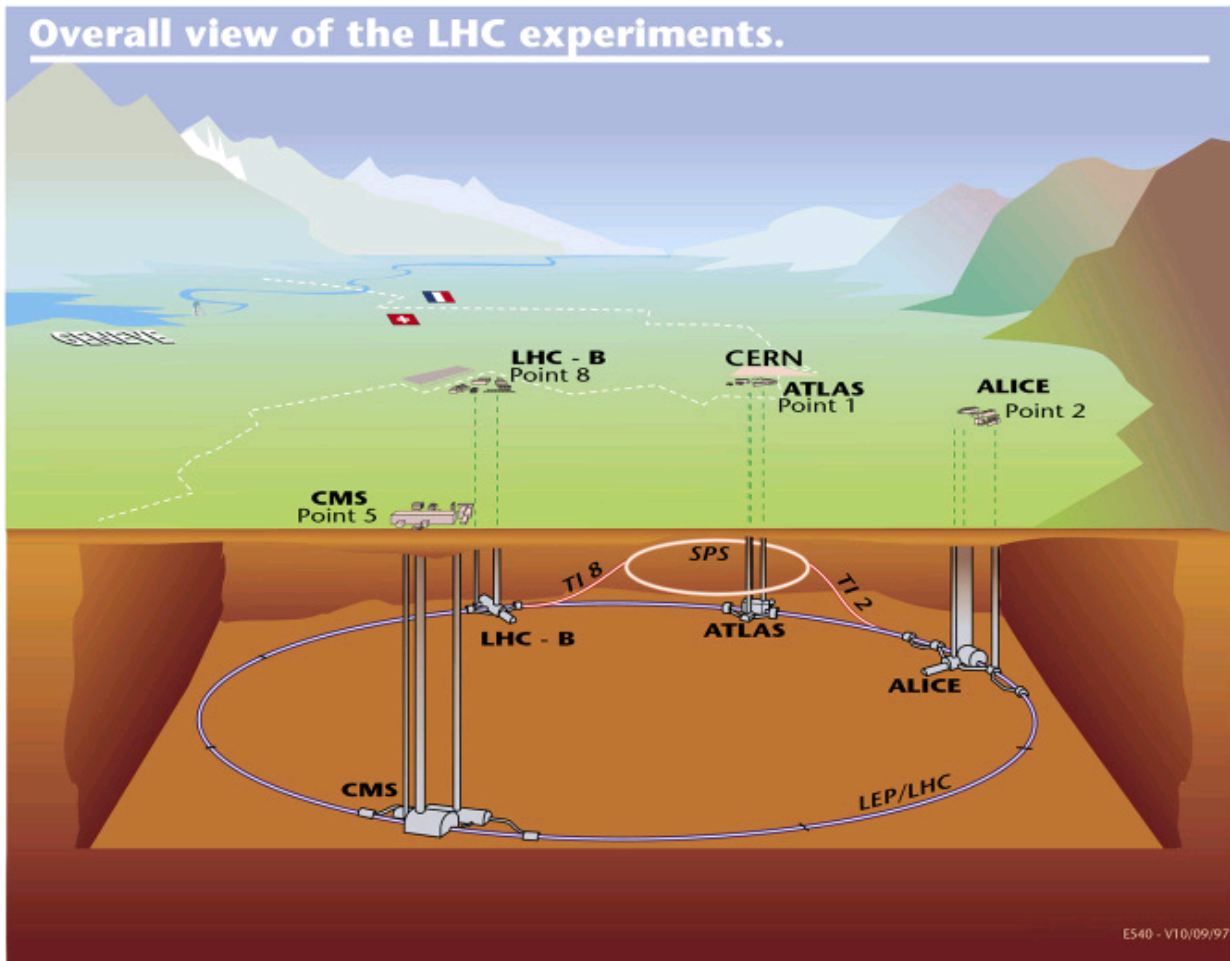
circumference 3.83 km, 2 independent rings, superconducting  
max energy  $Z \times 500 \text{ GeV} = 200 \text{ GeV}$  per nucleon pair in Au

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

2 large and 2 smaller (already completed) experiments

TANDEM

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

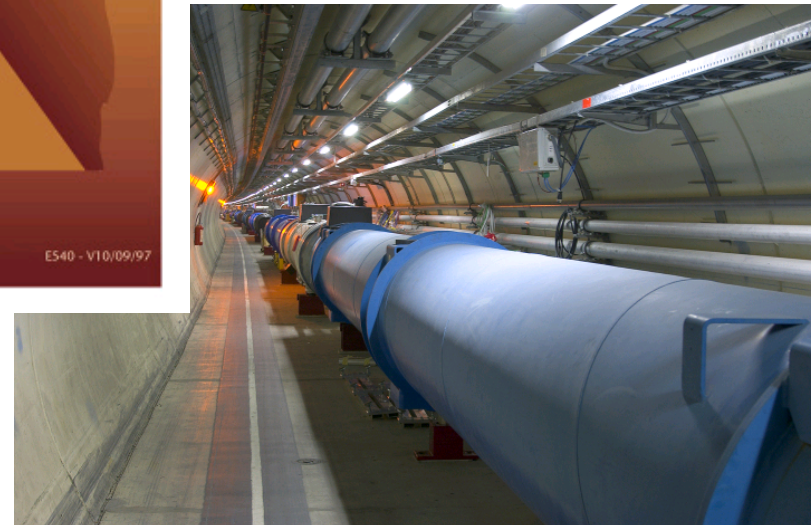


**p+p-collisions:**  
 $\sqrt{s} = 14 \text{ TeV}$  (sofar 8 TeV)  
collision rate: 800 MHz

**Pb+Pb collisions:**  
 $\sqrt{s} = 5.5 \text{ TeV}$  per colliding  
nucleon pair max.

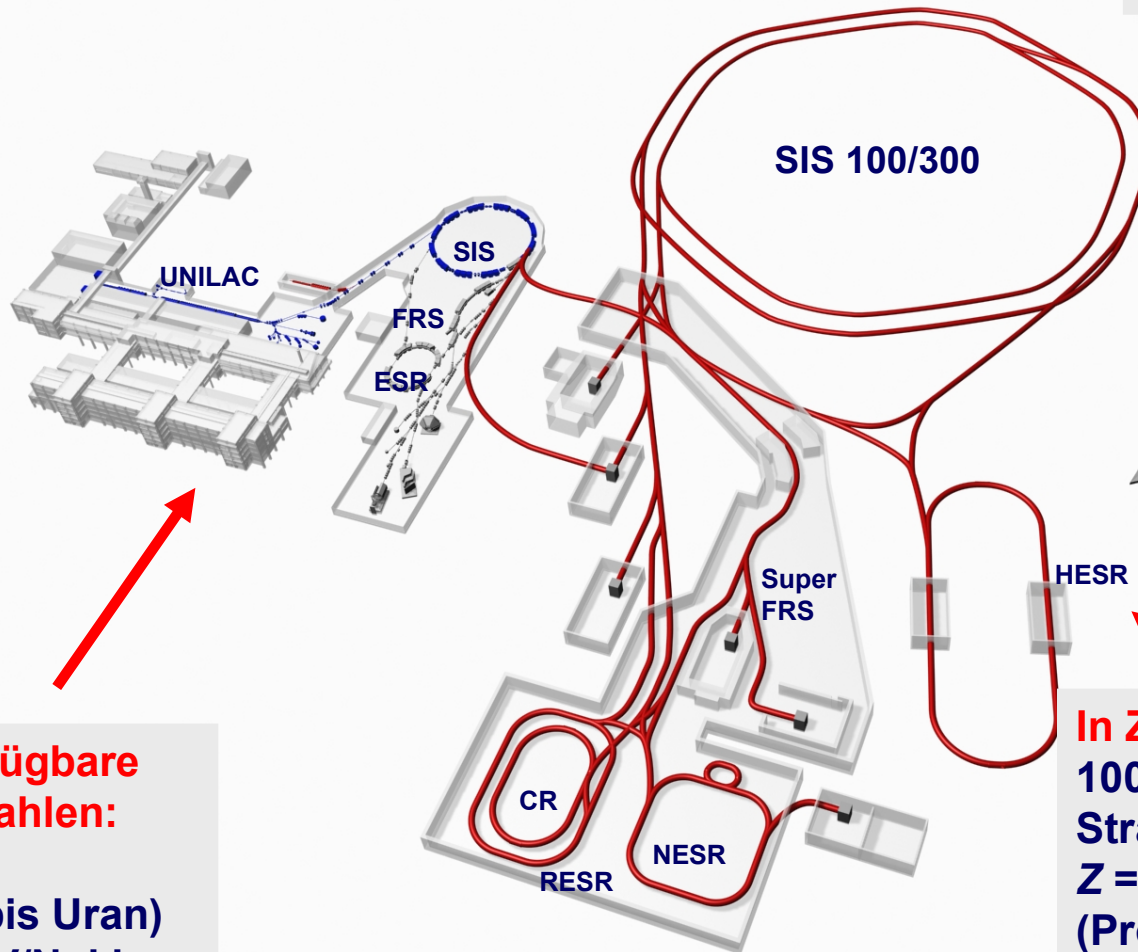
collision rate: 10 kHz

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



# GSI-Zukunftsprojekt: FAIR

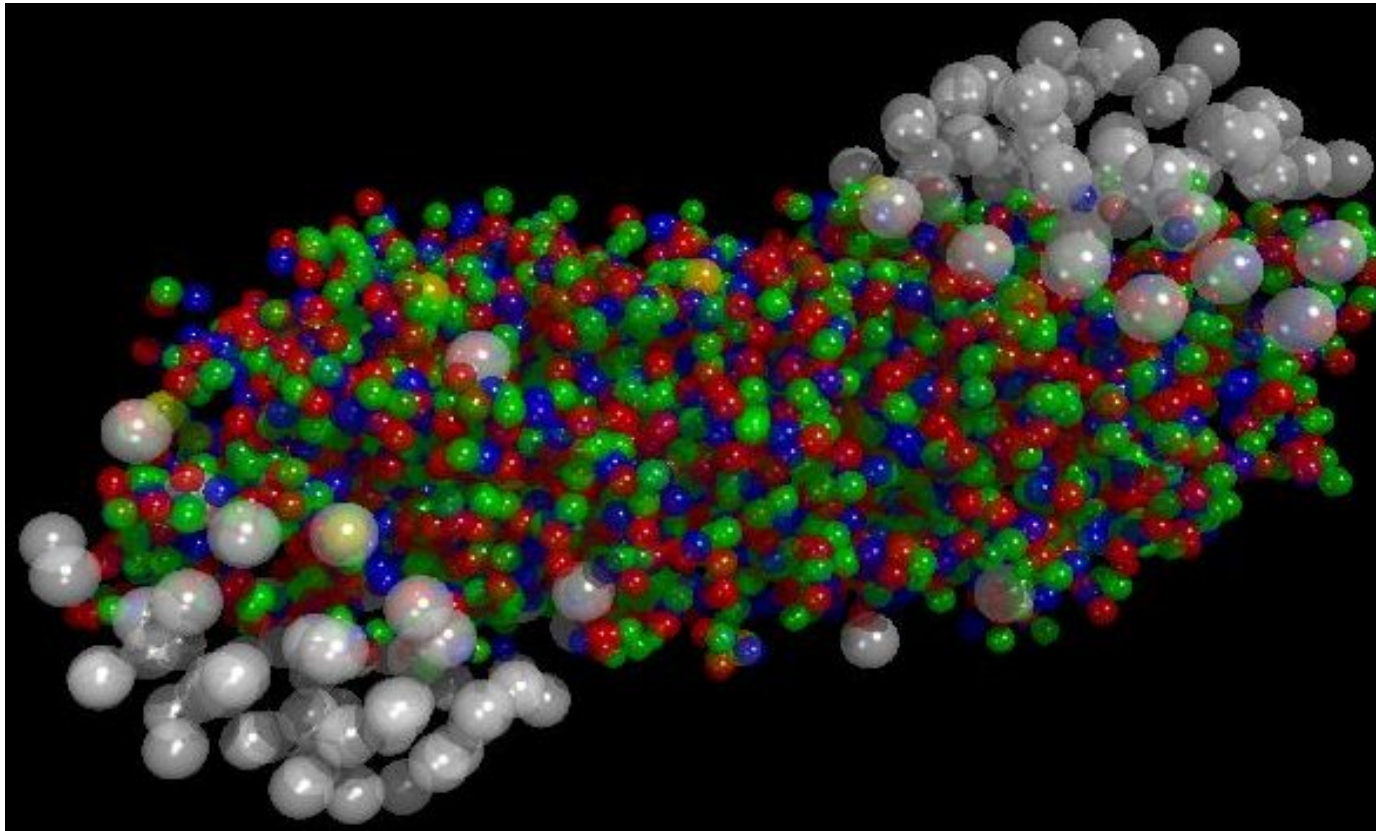
2016 Baubeginn  
2024 Fertigstellung



**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

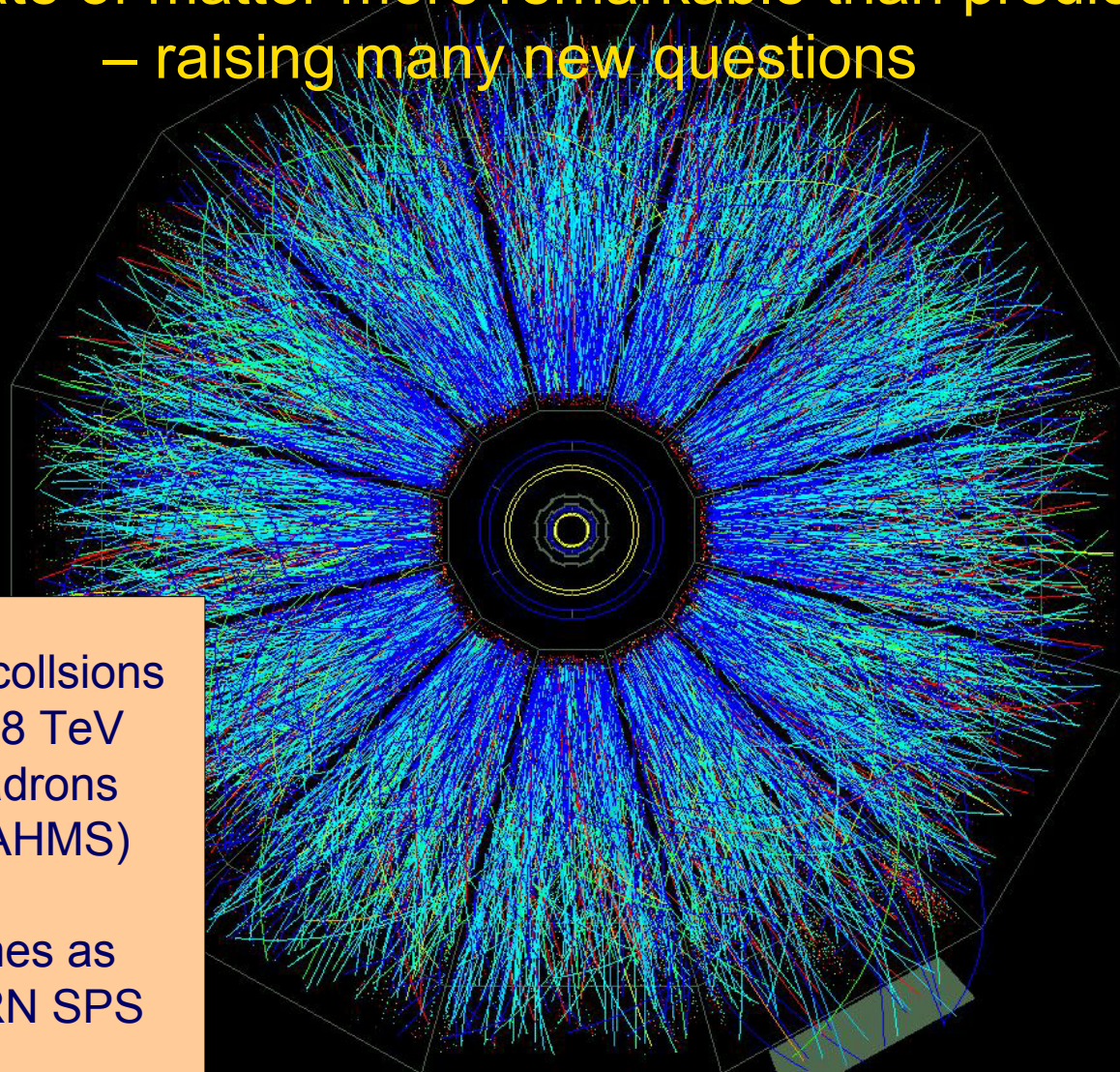


At a special seminar on 10 February, spokespersons from the experiments on CERN 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

**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 collisions  
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  $\tau = \sqrt{t^2 - z^2}$   
collision at  $t=0$ , before nuclei approach each other with speed-of-light

1<sup>st</sup> stage: liberation of quarks and gluons

time scale order 0.1 fm/c

2<sup>nd</sup> stage: rapid thermalization of quarks and gluons, after about 1 fm/c QGP temperature order of 500 MeV

3<sup>rd</sup> stage: expansion and cooling of QGP

$$T \propto \tau^{-1/3}$$

4<sup>th</sup> stage: hadronization when  $T_c$  is reached  
156.5 MeV

5<sup>th</sup> stage: expansion of hadron gas

6<sup>th</sup> stage: freeze-out = momentum distributions are frozen in  
time scale 10 fm/c

