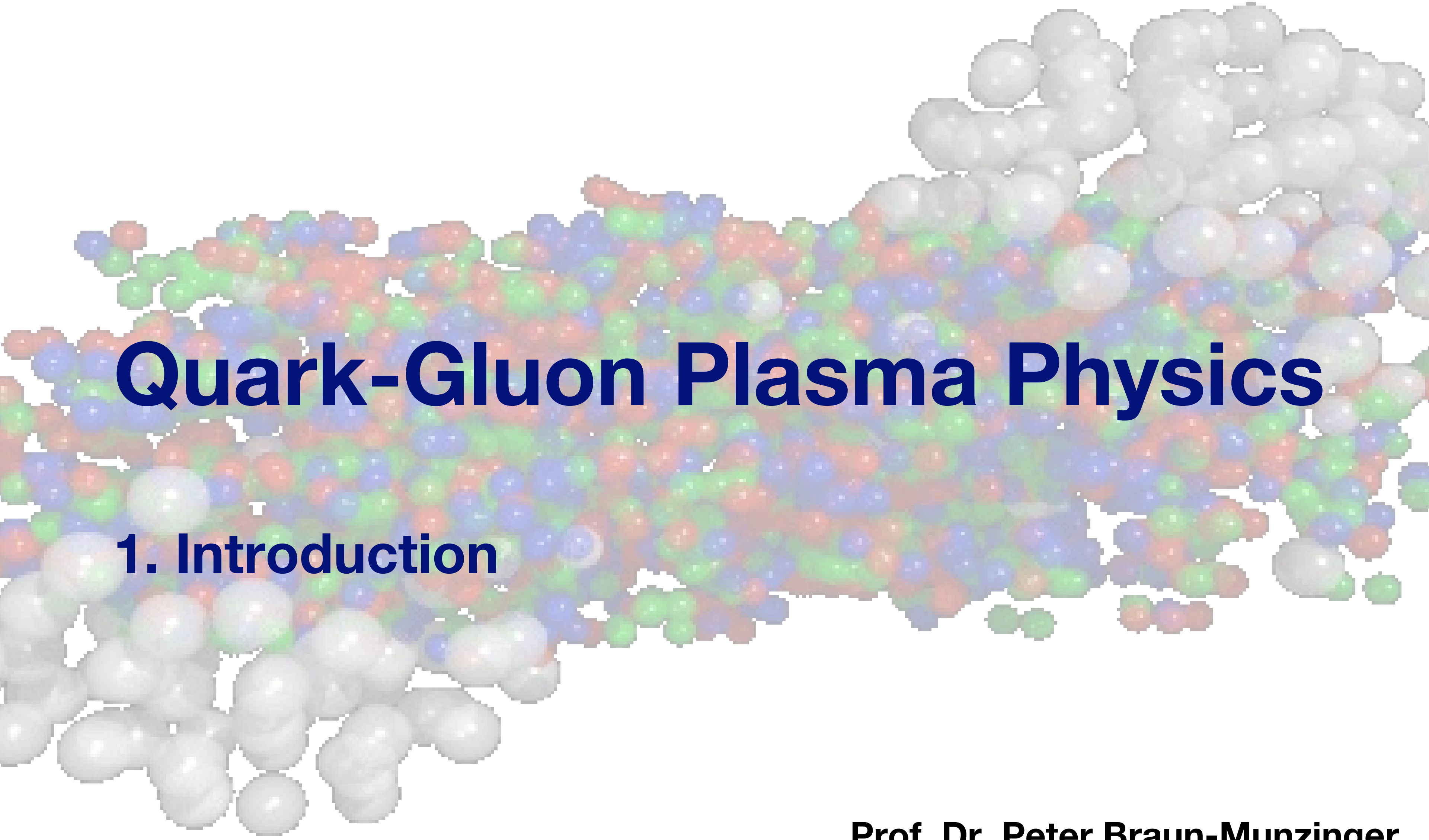
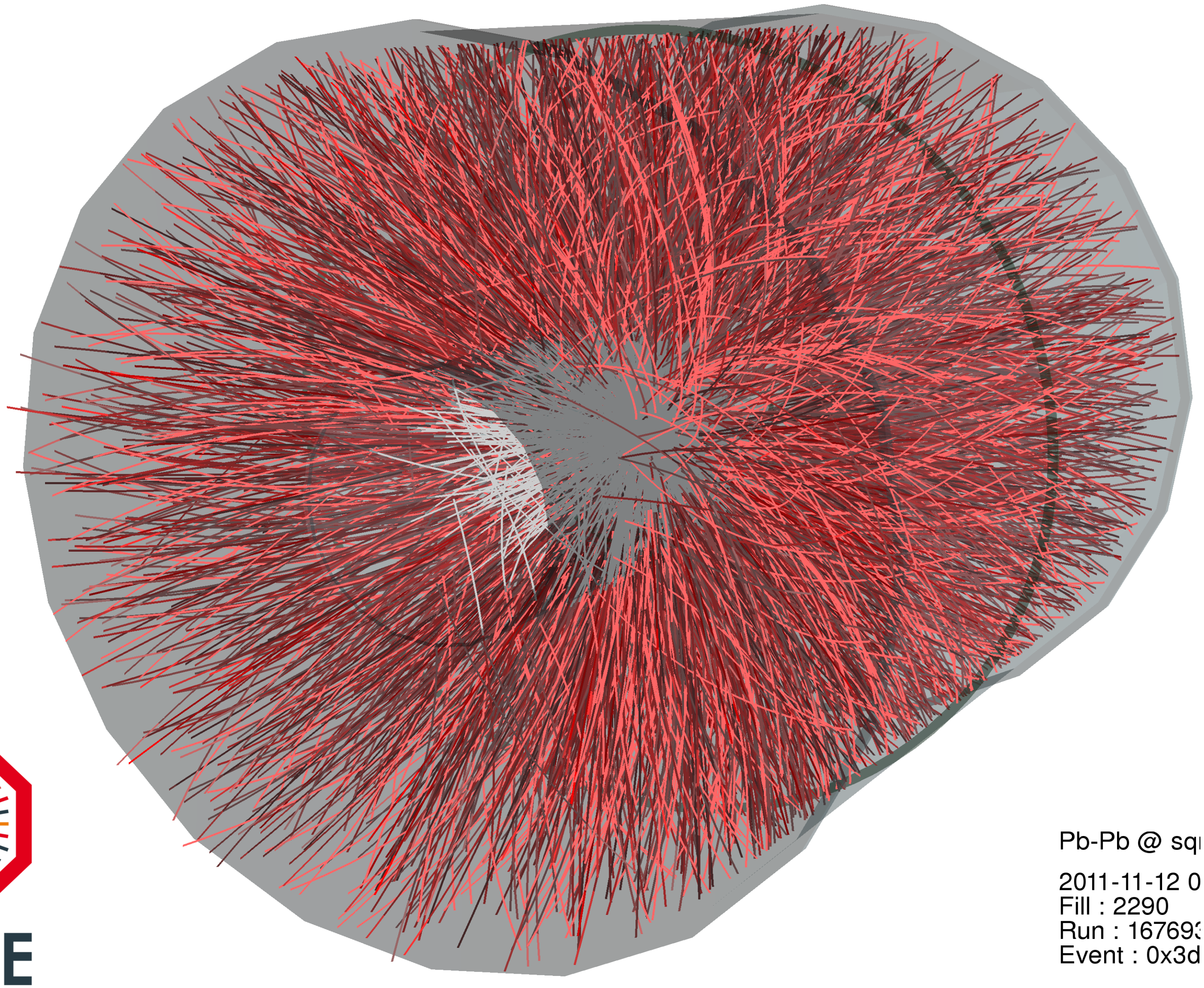


Quark-Gluon Plasma Physics

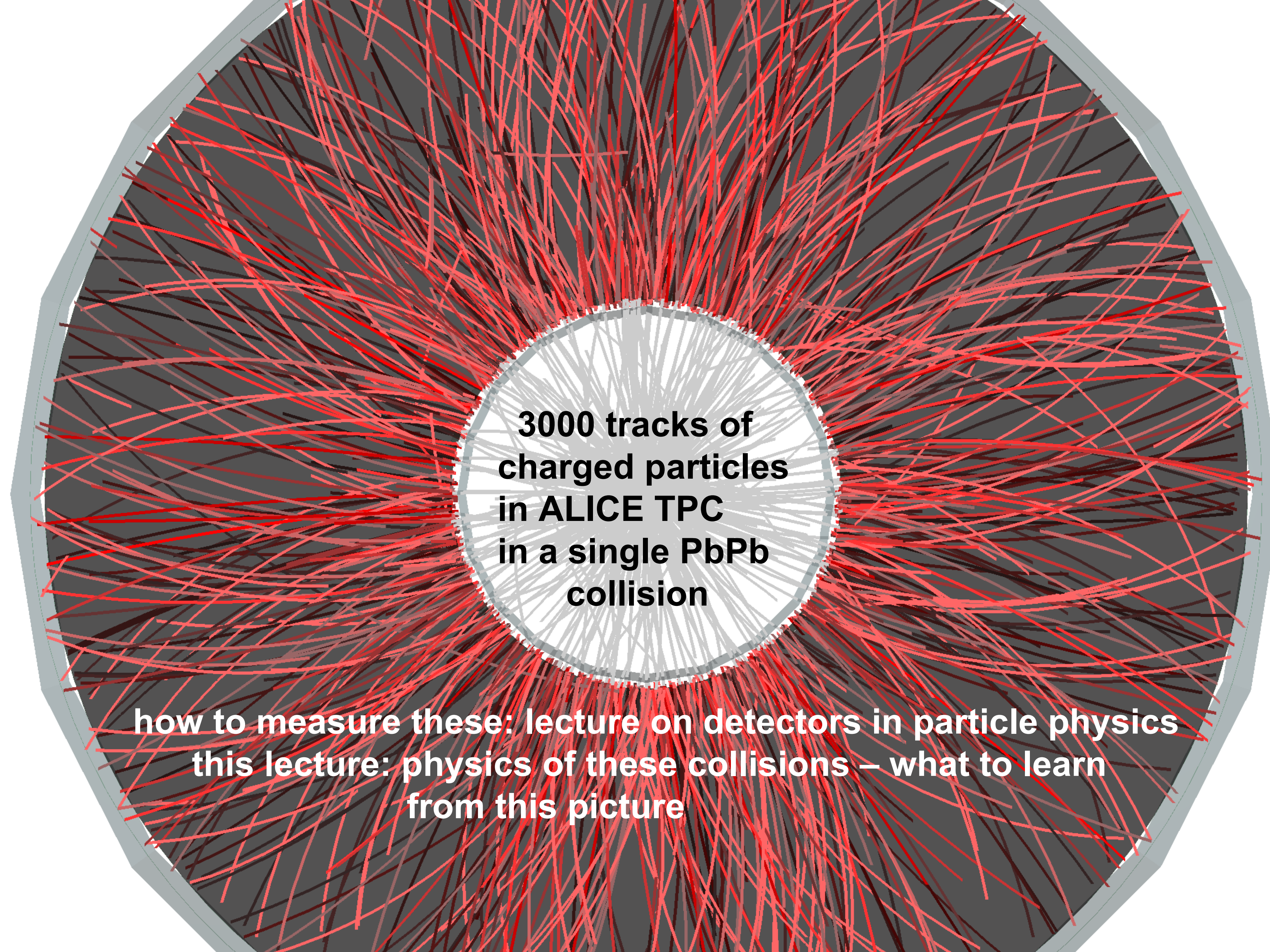
1. Introduction

Prof. Dr. Peter Braun-Munzinger
Prof. Dr. Klaus Reygers
Prof. Dr. Johanna Stachel
Heidelberg University
SS 2023

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

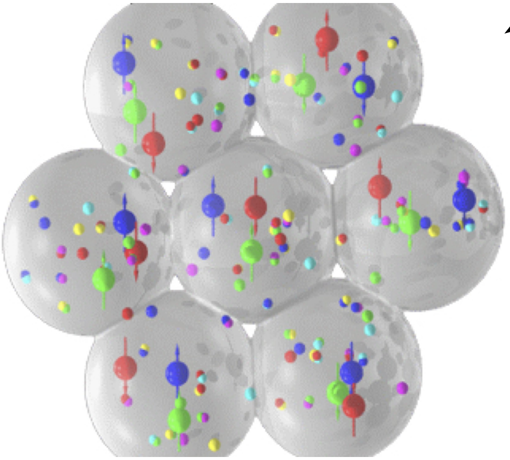


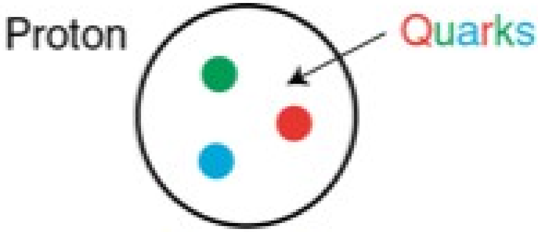
3000 tracks of
charged particles
in ALICE TPC
in a single PbPb
collision

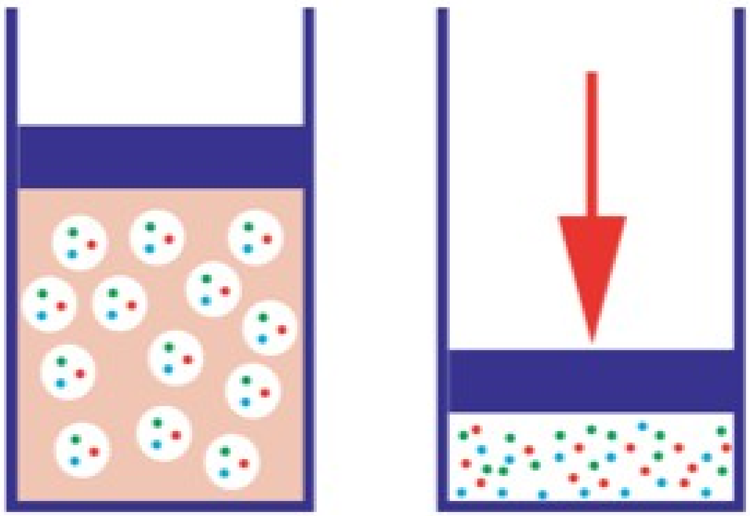
how to measure these: lecture on detectors in particle physics
this lecture: physics of these collisions – what to learn
from this picture

What is a Quark-Gluon Plasma?

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





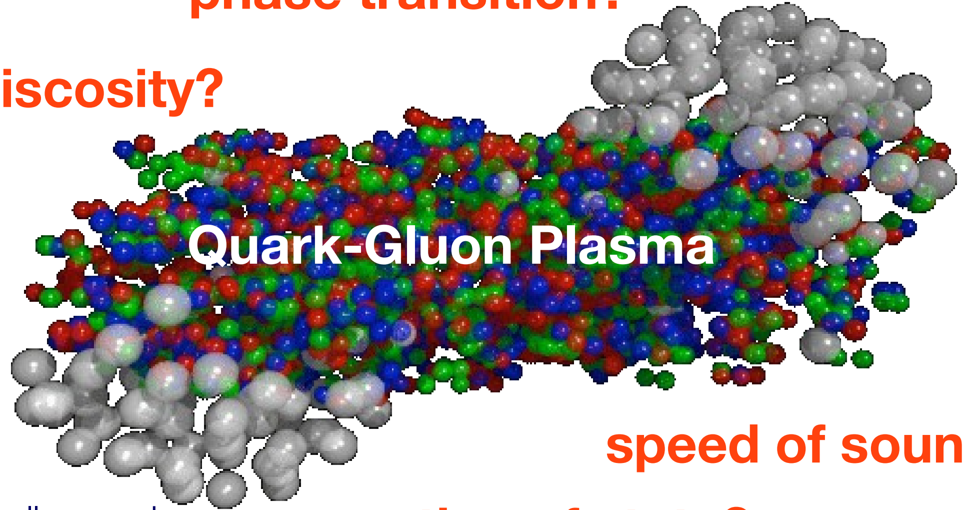


a Quark-Gluon Plasma is Matter

We want to study material properties of this state

Particle physics: reductionism

Heavy ion physics: emergent properties of QCD



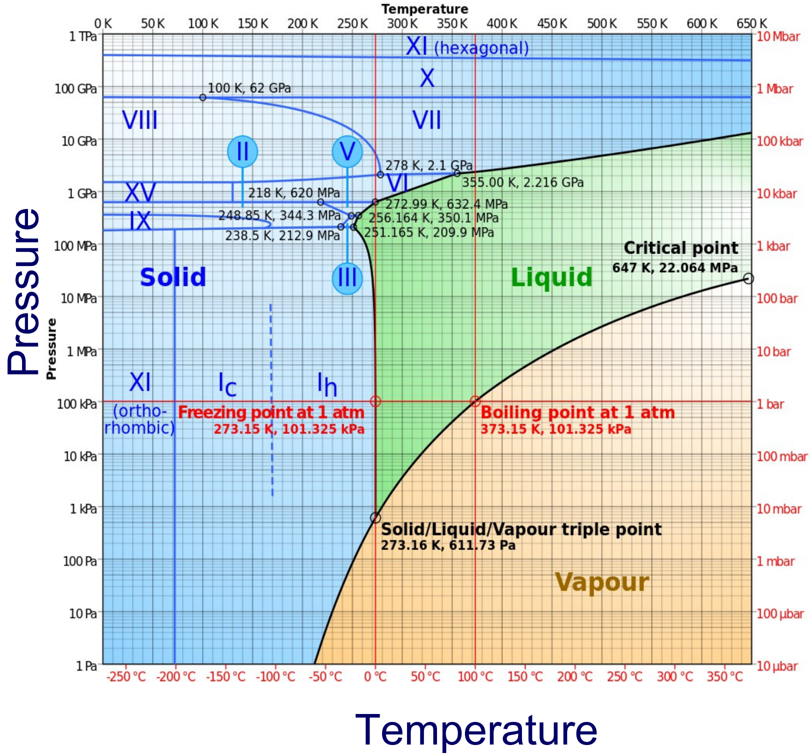
Quelle: urqmd.org

„More is different“

Philip W. Anderson, Science, 177 (1972) 393

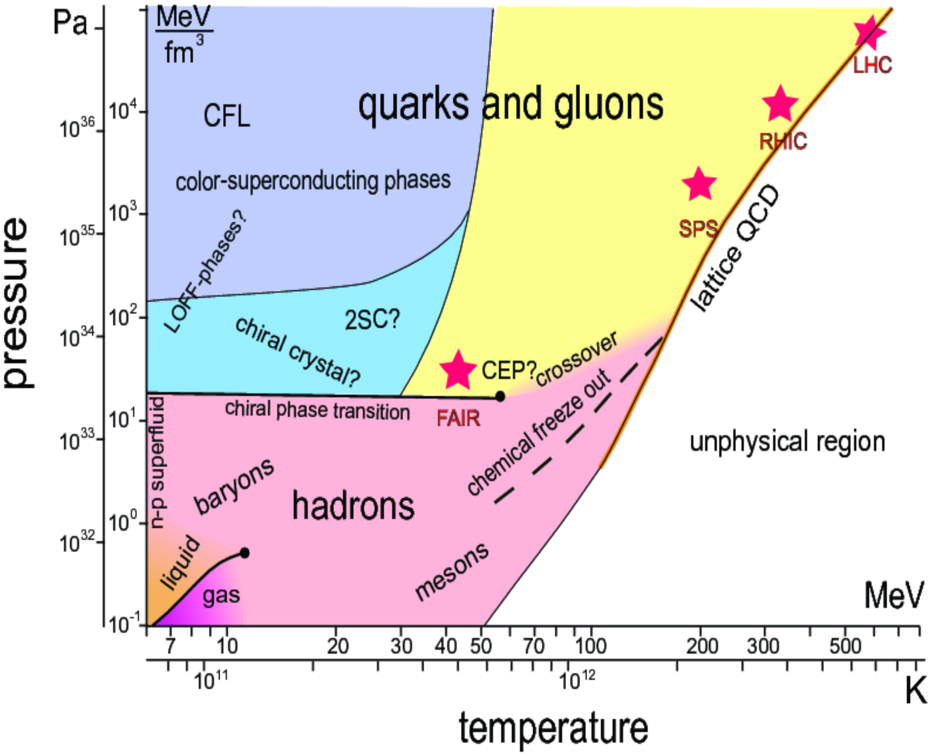
Phase diagrams and emergent properties

Water (Electromagnetism)



Quark Matter (QCD)

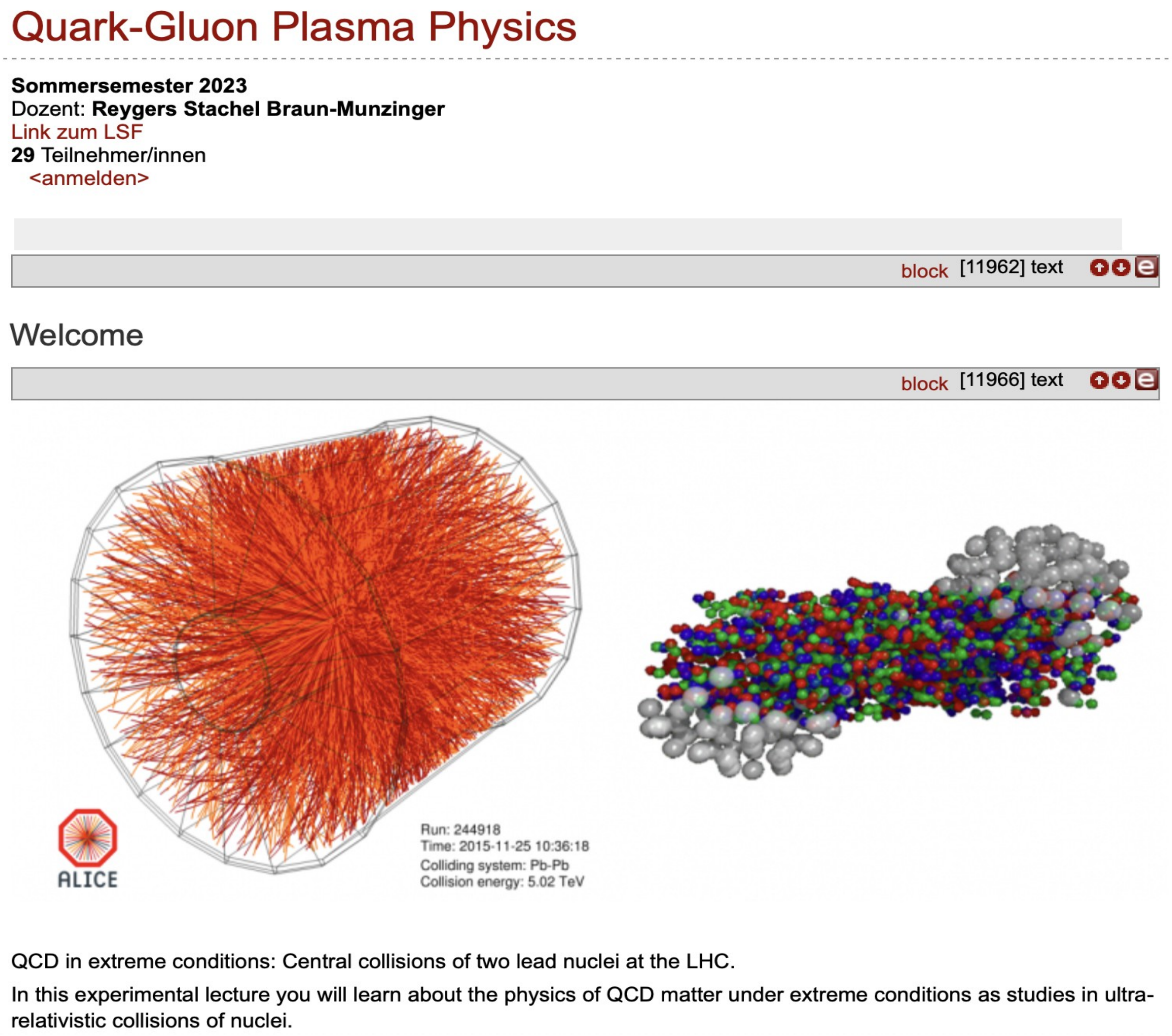
Wambach et al. arXiv:1111.5475



not straightforward to understand from first principles:
phase transitions, various phases, critical points
in QCD as fundamental as understanding of H_2O based on QED

Organizational matters

Website



Quark-Gluon Plasma Physics

Sommersemester 2023
Dozent: **Reygers Stachel Braun-Munzinger**
Link zum LSF
29 Teilnehmer/innen
<anmelden>

Welcome

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.

https://uebungen.physik.uni-heidelberg.de/vorlesung/20231/1699

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 pp 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. Physics of the Critical Endpoint and Fluctuations
9. Hard Scattering and Jets
10. J/Psi, Quarkonia and Open Charm
11. Thermal Photons and Dileptons
12. Future Perspectives

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, …)

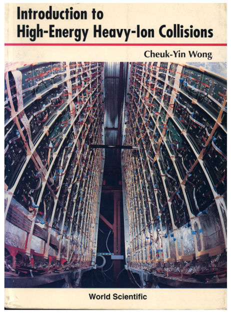
- Doctoral students

  - update on developments in areas besides own research topic

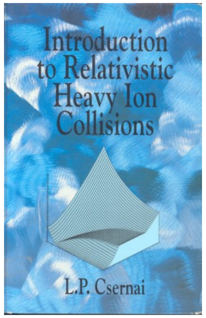
Requirement for successful participation

- no written exam
- each week about one/two homework problems, to be solved e.g. using jupyter notebook. Solutions presented by students during next lecture slot and discussed by everybody
- Some questions on previous lecture given at beginning of lecture in form of a quiz. Including additional questions on previous lecture by students.
- Successful participation: show solution of one homework problem and participate in discussions

Books (I)

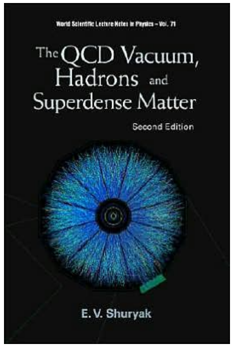


Wong, Introduction to High-Energy Heavy-Ion Collisions, World Scientific, 1994 (→ Link)



Csernai, Introduction to Relativistic Heavy-Ion Collisions, 1994

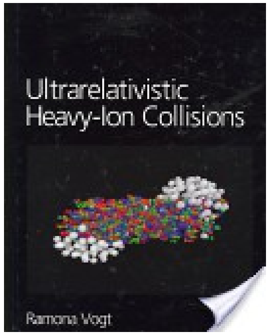
this book is now freely available as pdf (→ Link)



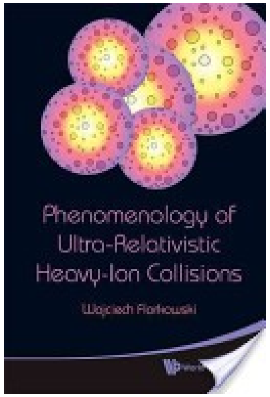
Shuryak, The QCD vacuum, hadrons, and superdense matter, World Scientific, 2004 (→ Link)

Books (II)

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

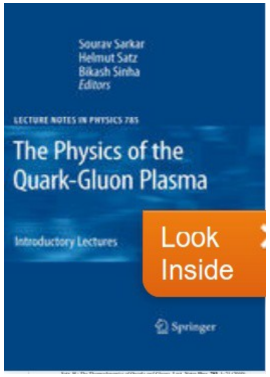


Vogt, Ultrarelativistic Heavy-Ion Collisions, Elsevier, 2007 (→ Link)



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

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

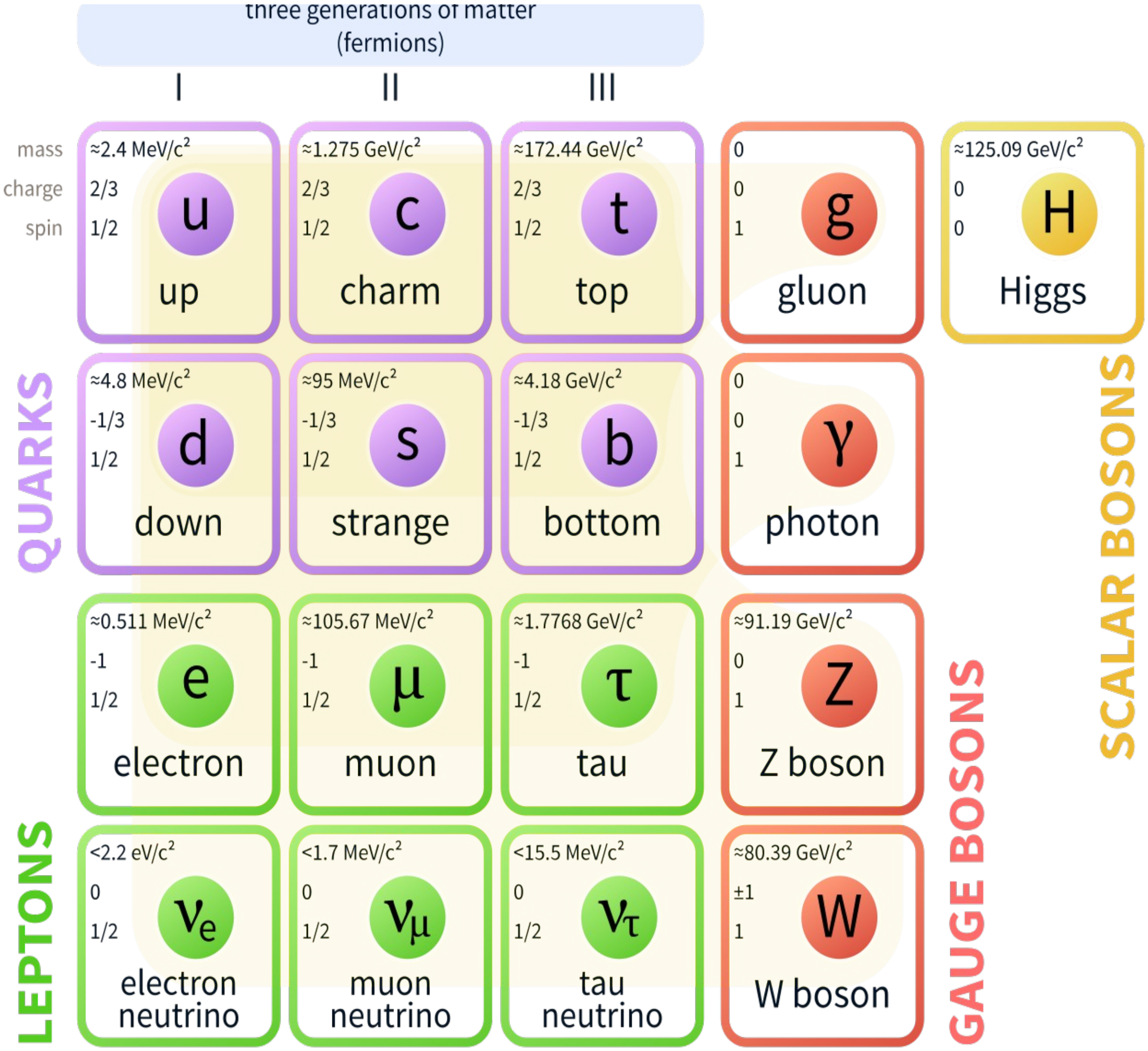
Time: fm/c   1 fm/c = 033 10^{-23} s

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

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

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

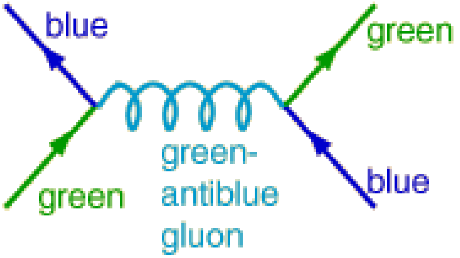
Reminder: fundamental components of matter



	three generations of matter (fermions) I	II	III		
QUARKS mass charge spin	≈ 2.4 MeV/c^2 2/3 1/2 u up	≈ 1.275 GeV/c^2 2/3 1/2 c charm	≈ 172.44 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	SCALAR BOSONS ≈ 125.09 GeV/c^2 0 0 H Higgs
QUARKS	≈ 4.8 MeV/c^2 -1/3 1/2 d down	≈ 95 MeV/c^2 -1/3 1/2 s strange	≈ 4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
LEPTONS	≈ 0.511 MeV/c^2 -1 1/2 e electron	≈ 105.67 MeV/c^2 -1 1/2 μ muon	≈ 1.7768 GeV/c^2 -1 1/2 τ tau	GAUGE BOSONS ≈ 91.19 GeV/c^2 0 1 Z Z boson	
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<1.7 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	GAUGE BOSONS ≈ 80.39 GeV/c^2 ±1 1 W W boson	

Quarks come in three different colors: 🔵 🟢 🔴

Gluons:
mediate interaction between quarks



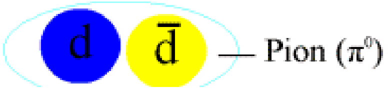
Feynman diagram for an interaction between quarks generated by a gluon.

Quarks and gluons

quarks don't occur freely in nature “confinement”

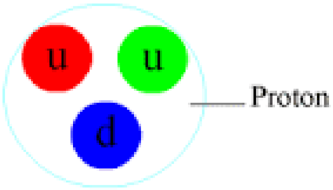
quarks are bound by the strong interaction in colorless hadrons

mesons

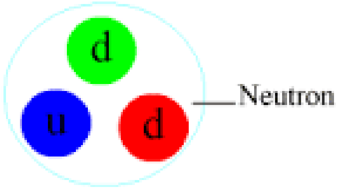


quark-antiquark

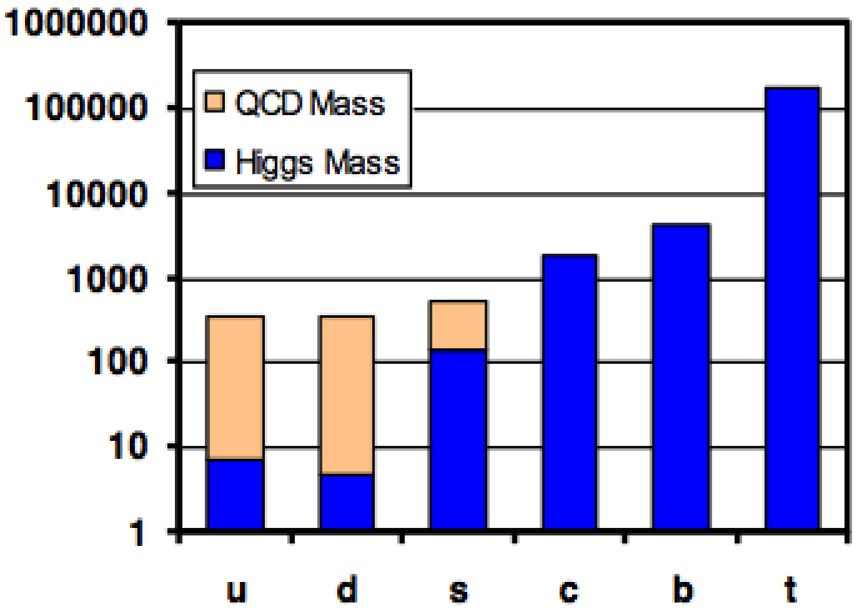
baryons



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



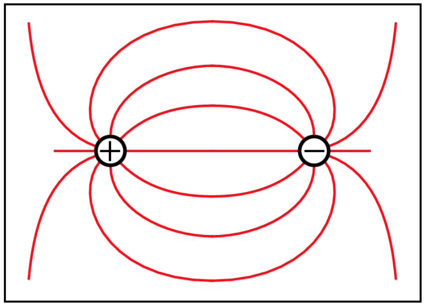
Strongly interacting matter described by QCD

quarks carry electric charge, color charge (1 of 3 possible), and several other quantum numbers
they interact 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 Yang Mills type (1973 Fritzsch, Gell-Mann, Wess)

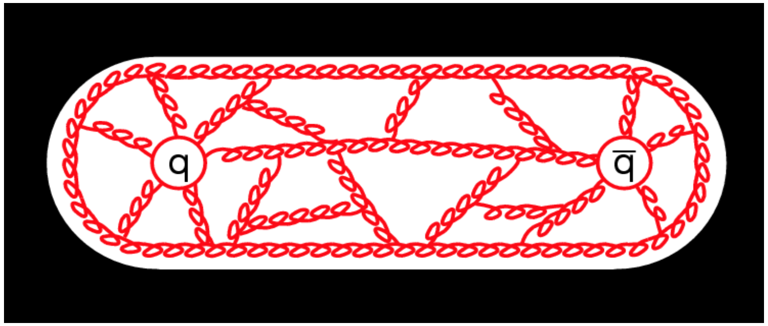
quarks are confined in hadrons, trying to pull them apart, the interaction becomes stronger

QED:



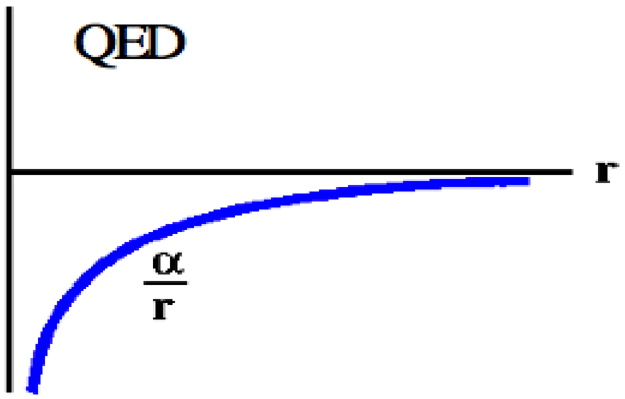
$$V(r) \propto \frac{\alpha}{r}$$

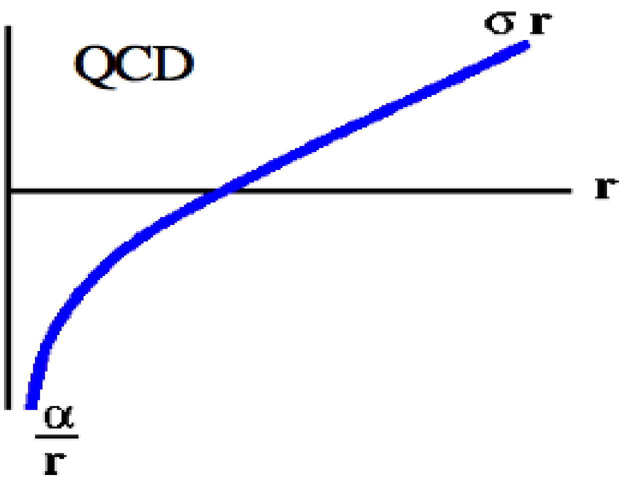
QCD:



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

Strongly interacting matter describped by QCD





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

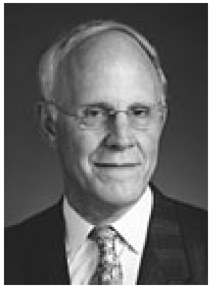
$$V(r) = -\frac{4\alpha_s(r)}{3r} + \boxed{k\,r}$$

linear rise due to confinement

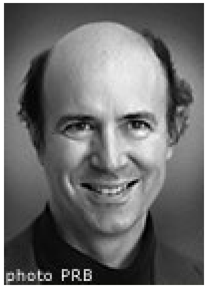
Strongly interacting matter described by QCD

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

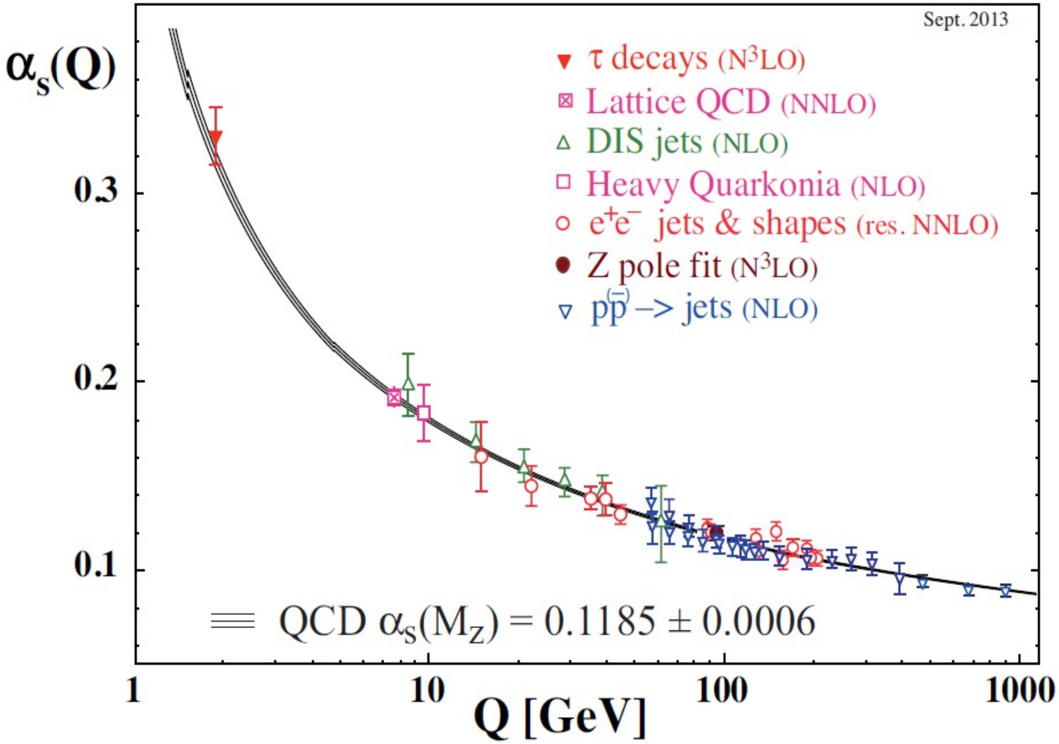
α_s drops with increasing q^2
or decreasing r

Running coupling constants

in QED vacuum polarization leads to increase of coupling constant $\in$ 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 $\in_s$ 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



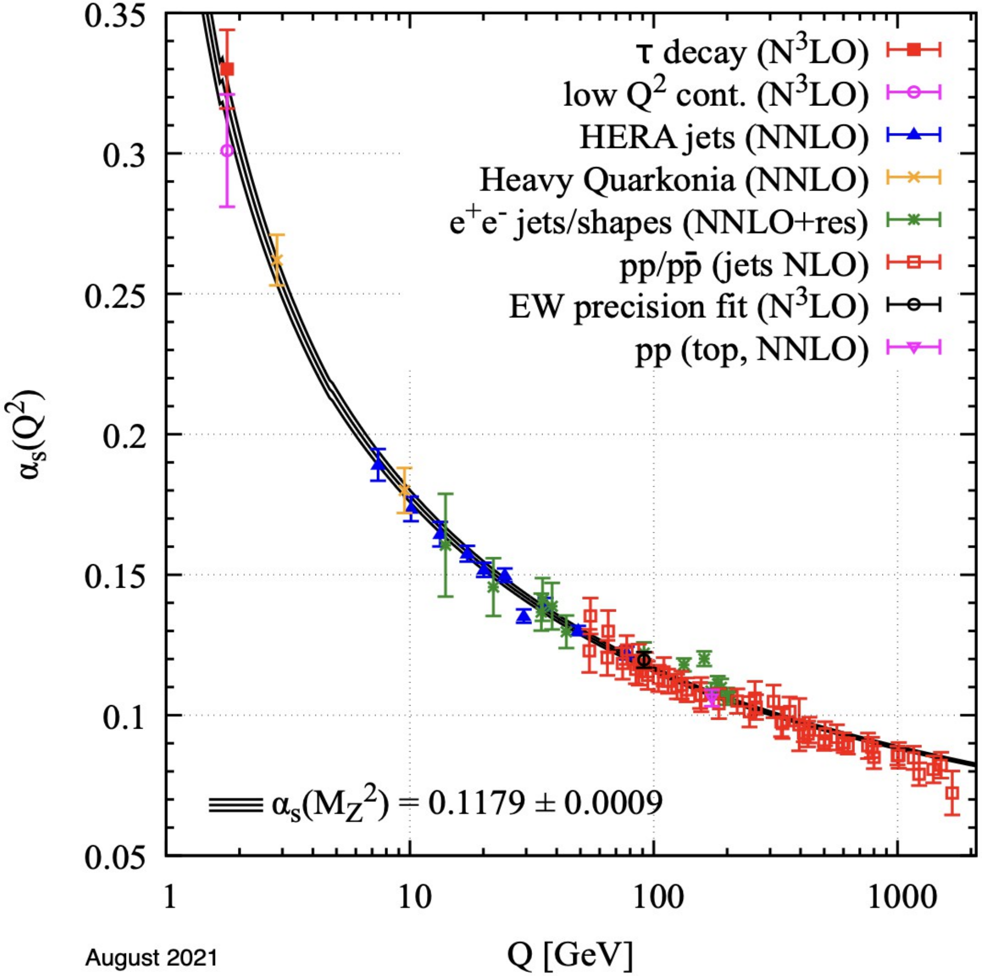
Summary of measurement of a_s a function of energy scale Q

Running coupling constants

in QED vacuum polarization leads to increase of coupling constant α 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 α_s with decreasing r or increasing momentum transfer q

Review of particle physics
Workman et al. (PDG) PTEP 2022 (2022) 083C01



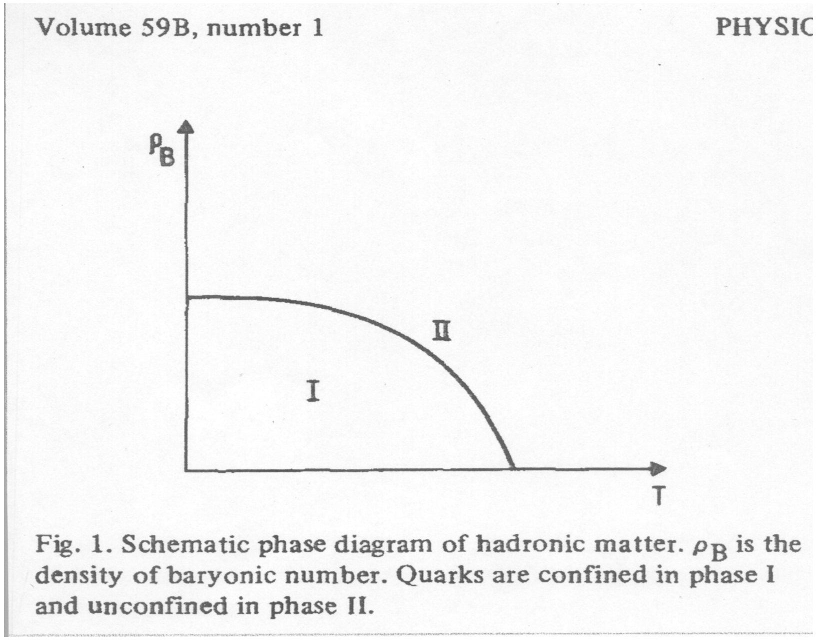
Summary of measurement of a_s a function of energy scale Q

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

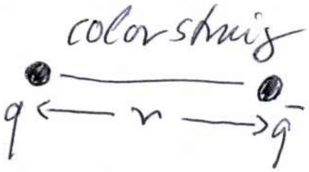
Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

Estimate of critical temperature for deconfinement

first estimate by Polyakov 1978

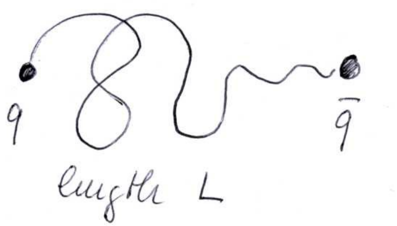
at T=0, energy in a color string $E_{q\bar{q}} = \sigma r$

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



for T > 0, free energy of string

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



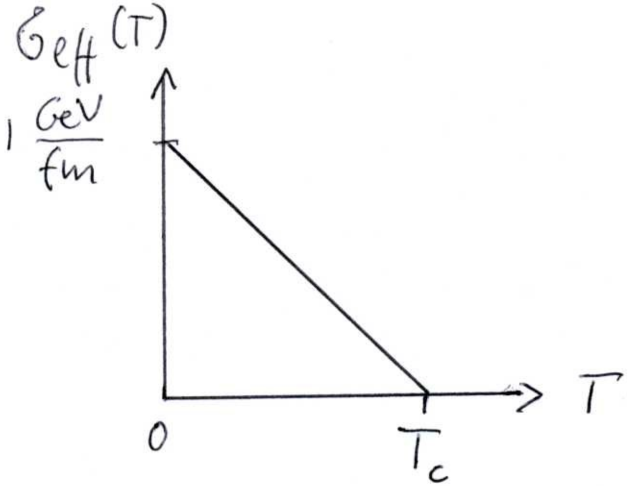
with the number of string configurations $N(L) = 5^{L/a}$

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: $\rho_\mathrm{m} \propto (\mathrm{m}_0^2 + \mathrm{m}^2)^{(-5/4)} \exp{(\mathrm{m/b})}$

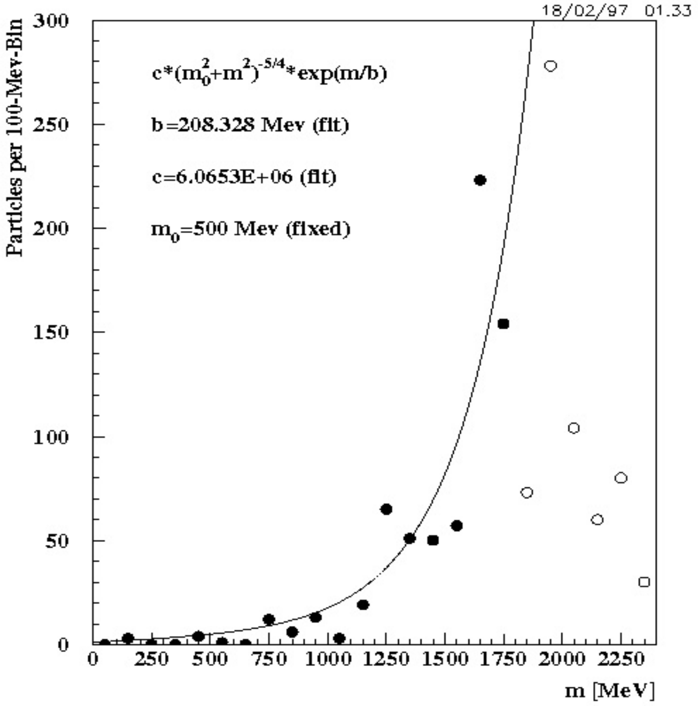
the energy density of a hadron gas becomes

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

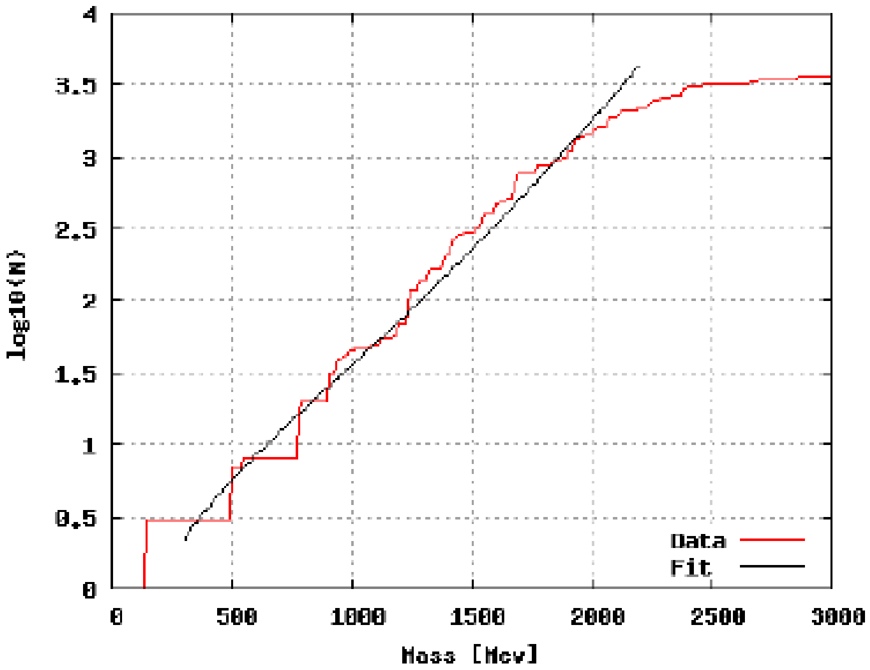
but for large masses m > M $\epsilon(m, \mathrm{T}) \propto \exp{(-\mathrm{m/T})}$
implying that integral diverges for T > b

Best estimate of Hagedorn temperature is still evolving

known hadronic spectrum in 1997



fit to integrated density of states as of PDG2008



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

Figure 3: 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, α_s not small
at T=200 MeV, typical kinetic energy for non-relativistic particle 3/2 kT = 300 MeV,
for relativistic particle 3 kT = 600 MeV

even in tails of Maxwell distribution α_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

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

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

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

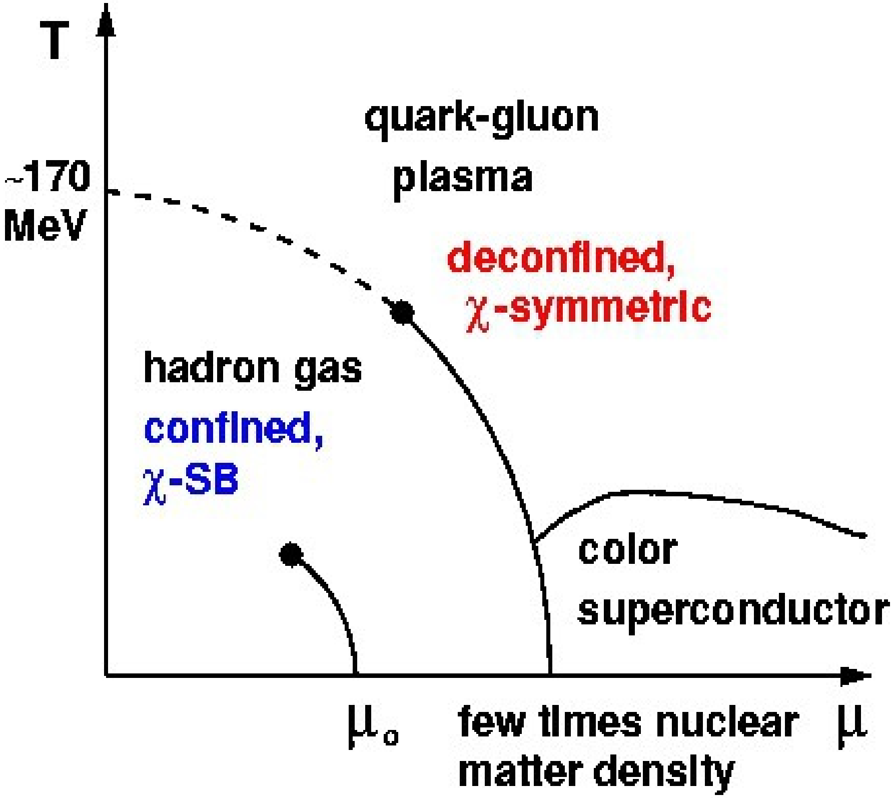
in fact, this is a bit too low
will see later, that in order for quark-gluon bubble to sustain the vacuum pressure from the outside minimally $4\ \rho_0$ is needed

Modern phase diagram of strongly interacting matter

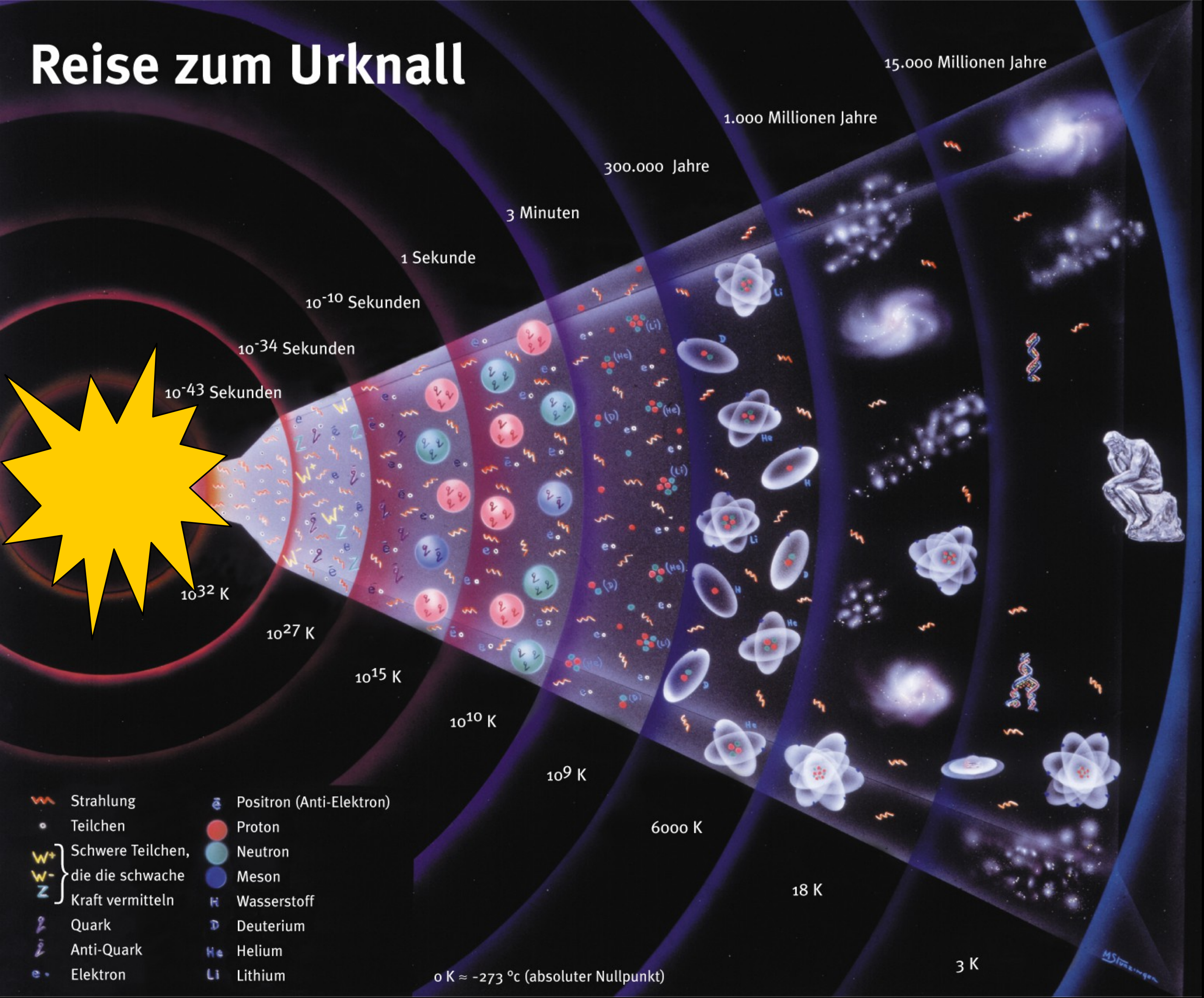
better knowledge of
  critical temperature at zero net baryon density
  nature of phase transition
(see chapter 4)

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

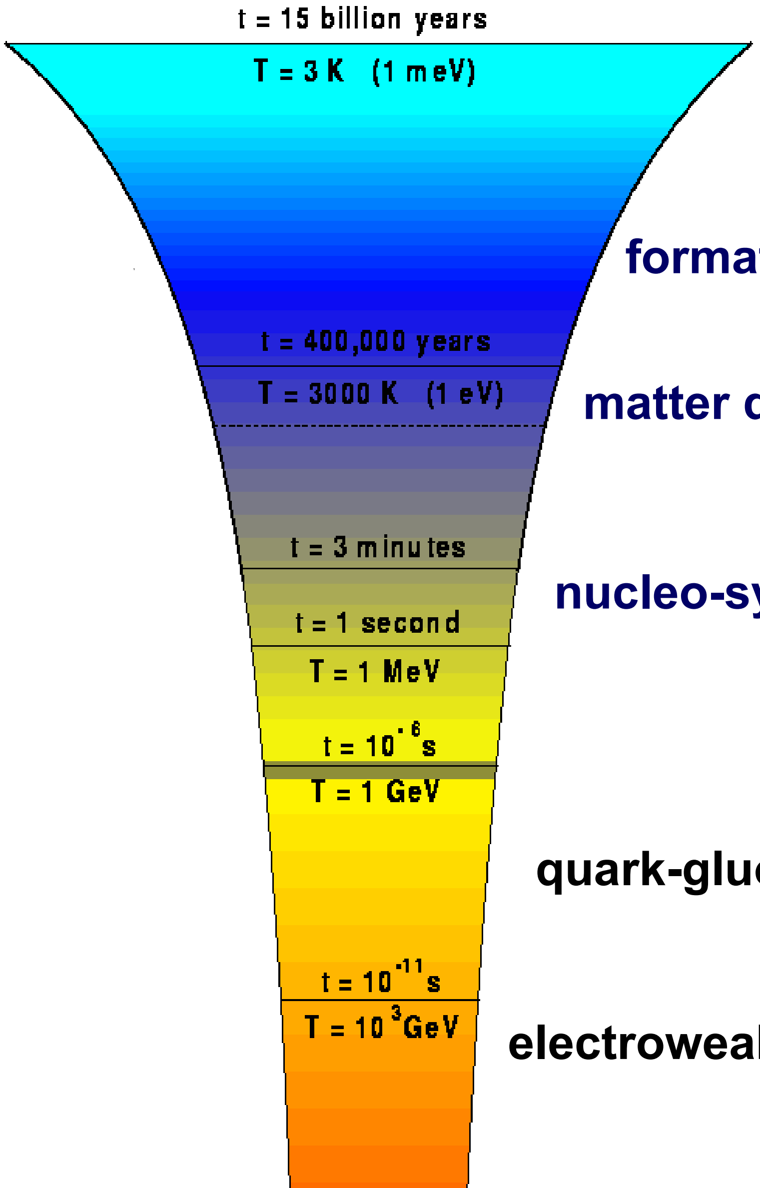
later we will see experimental data points in this phase diagram!
(see chapter 5)



Reise zum Urknall



Tracing Back the Big Bang



today

formation of galaxies

matter dominated

nucleo-synthesis

quark-gluon matter

electroweak phase transition

Hubble expansion →

cosmic microwave radiation →

quark hadron 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

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

- beams of nucleus A colliding with equal energy and mass

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

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 $\sqrt{s}$ =20 GeV/nucl pair

  2500 prod hadrons

LHC : 2009

- Pb ; up to $\sqrt{s}$ = 5.5 TeV/nucl pair

  30000 prod. hadrons

AGS : 1986 - 2000

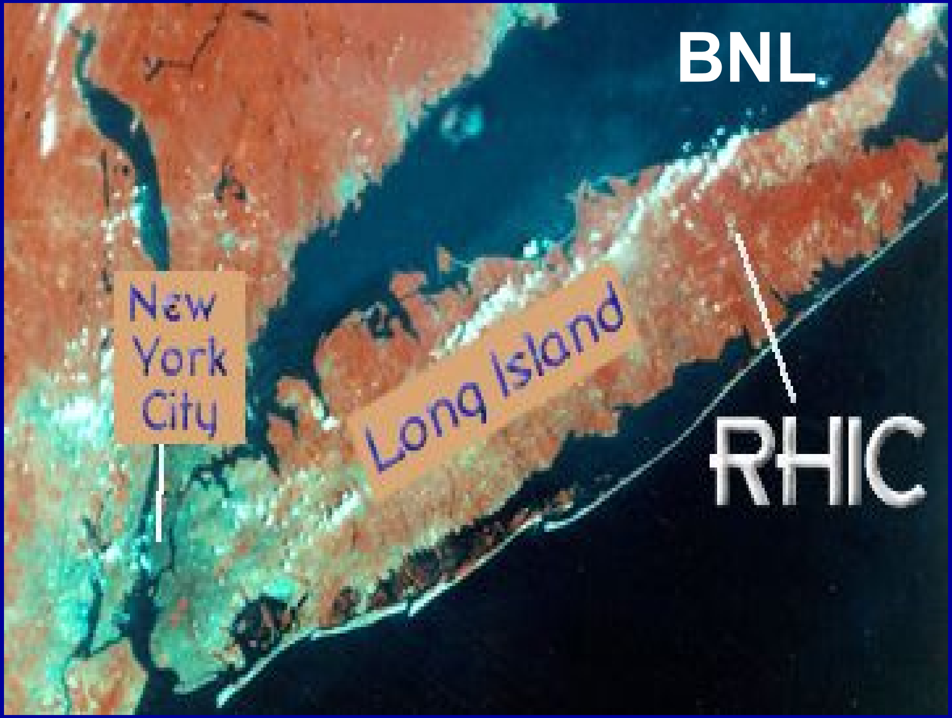
- Si and Au ; up to $\sqrt{s}$ =5 GeV /nucl pair

  1000 prod. hadrons

RHIC : 2000

- Au ; up to $\sqrt{s}$ = 200 GeV /nucl pair

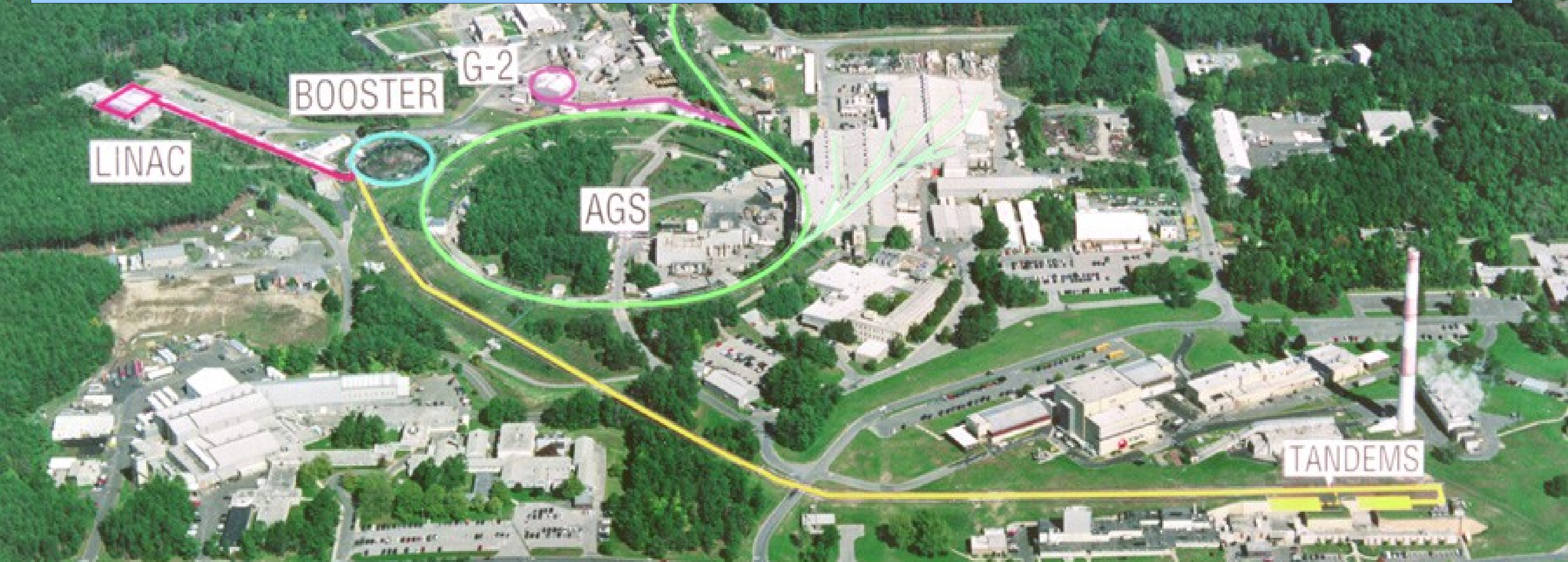
  7500 prod. hadrons



Brookhaven AGS 1986 - 2000

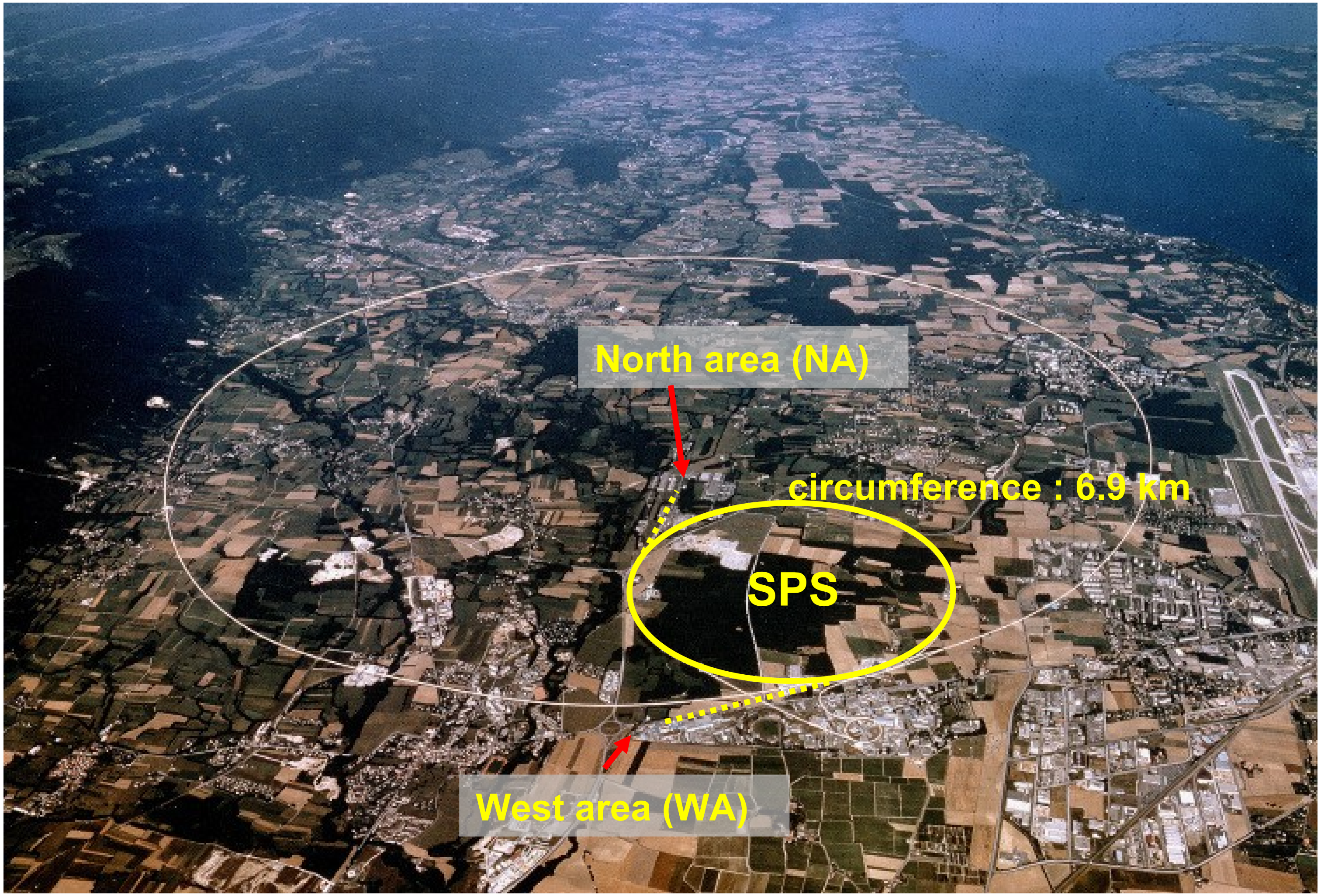
tandems inject beams via booster synchrotron into AGS
circumference 1 km, warm magnets
max momentum per nucleon 29 Z/A GeV/c

Experiments E802/866
E810
E814/E877
E864
E917



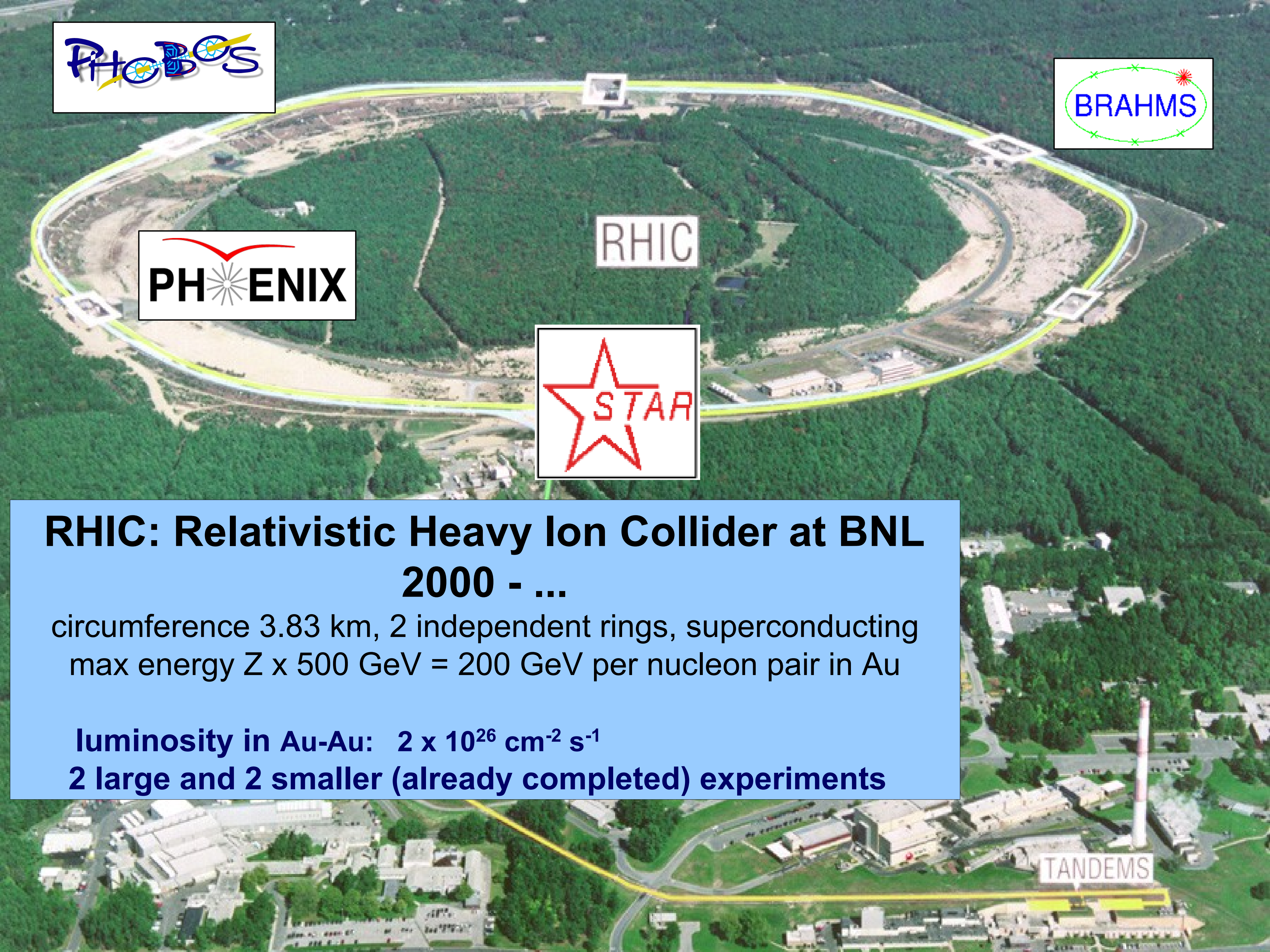
CERN SPS (1986 - 2003)

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

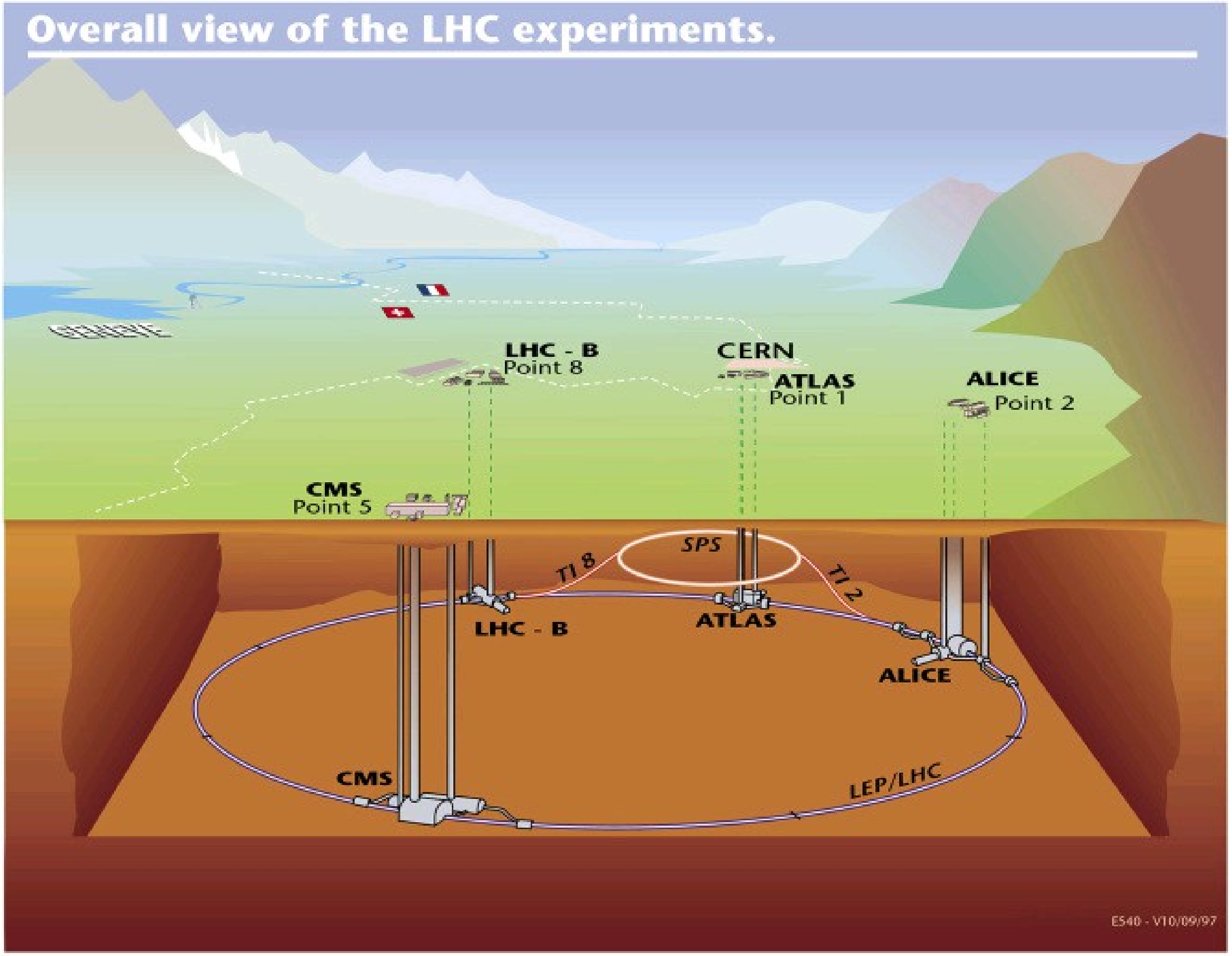


RHIC: Relativistic Heavy Ion Collider at BNL
2000 - ...

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

luminosity in Au-Au: 2 x 10^{26} cm^{-2} s^{-1}
2 large and 2 smaller (already completed) experiments

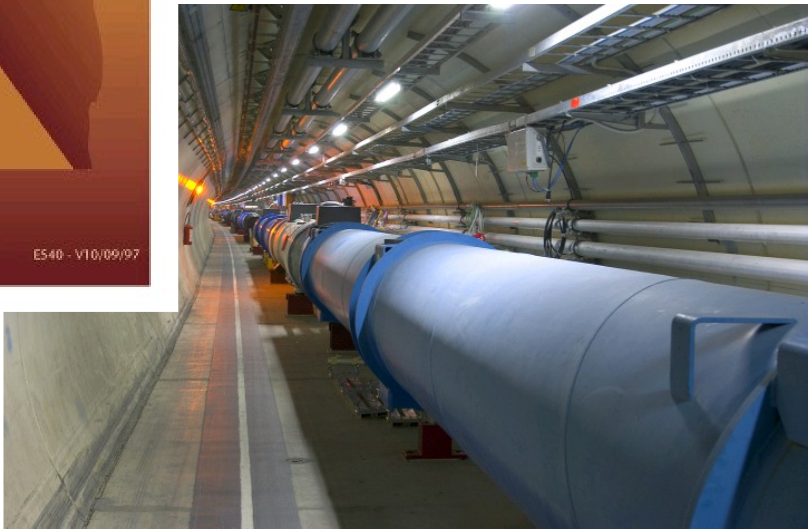
CERN: Large Hadron Collider (LHC) – 2009 - ...



p+p-collisions:
$\sqrt{s}$ = 14 TeV (so far 13 TeV)
collision rate: 800 MHz

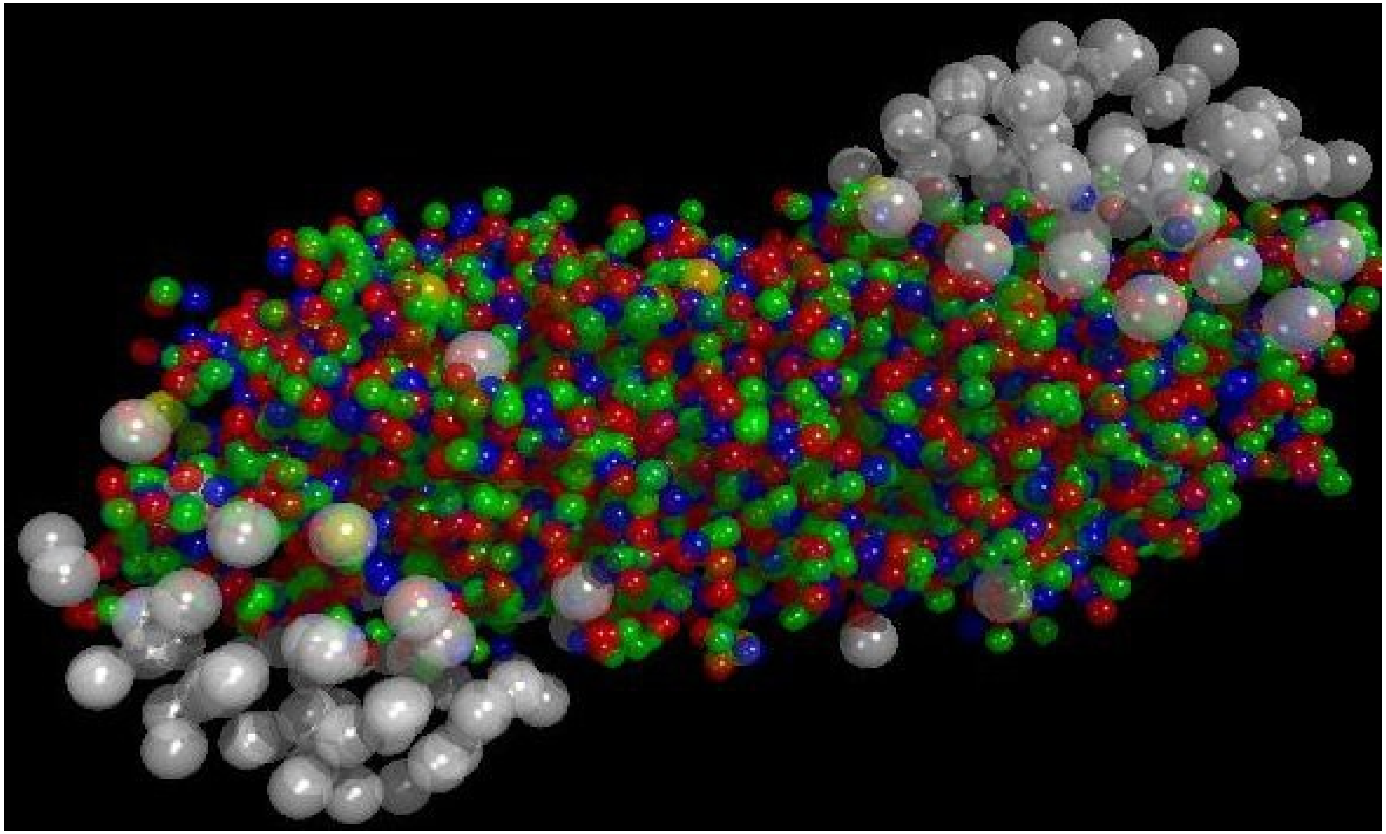
Pb+Pb collisions:
$\sqrt{s}$ = 5.5 TeV per colliding nucleon pair max.
collision rate: 50 kHz

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



CERN Press Release February 2000:

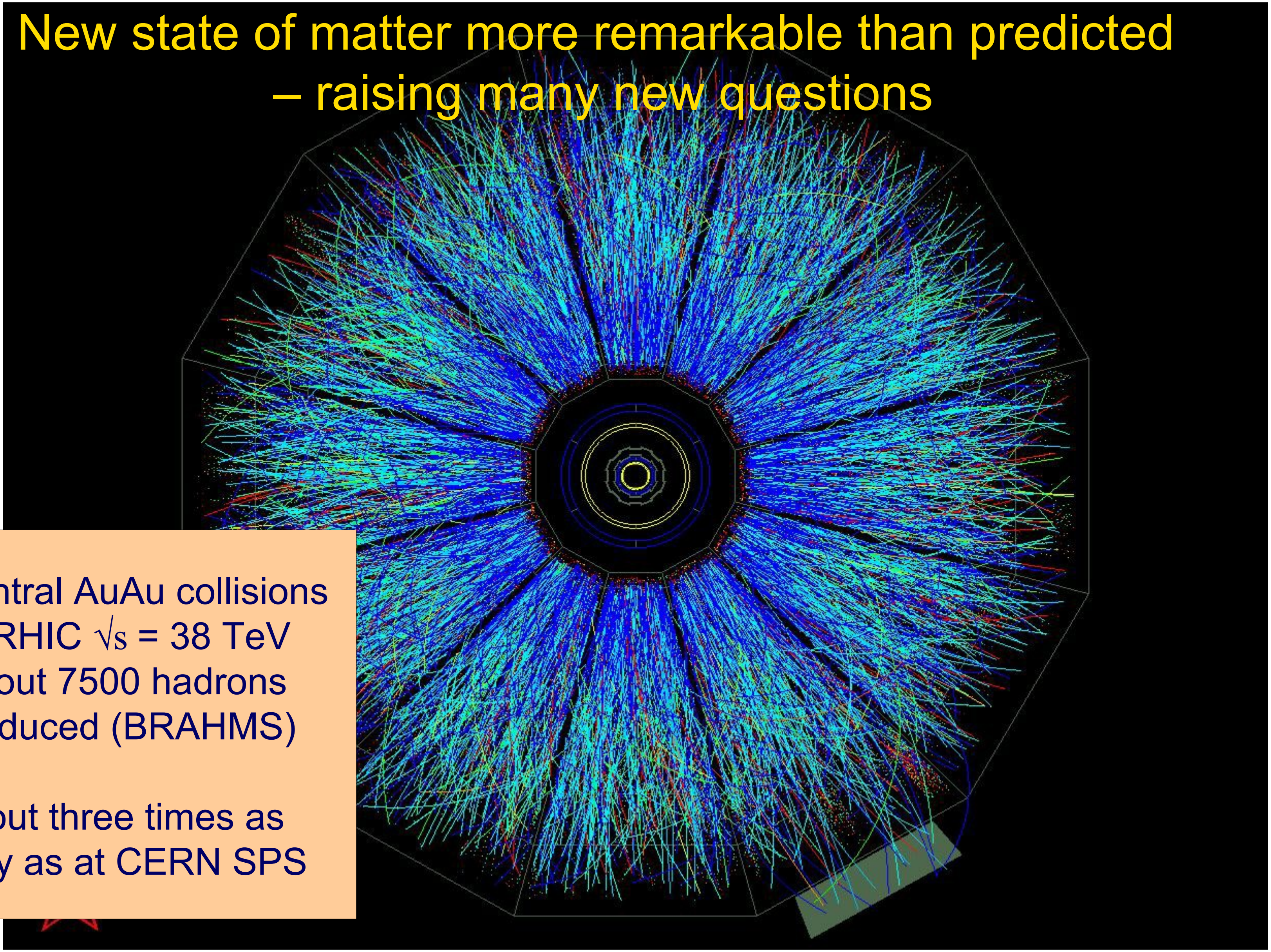
New State of Matter created at CERN



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



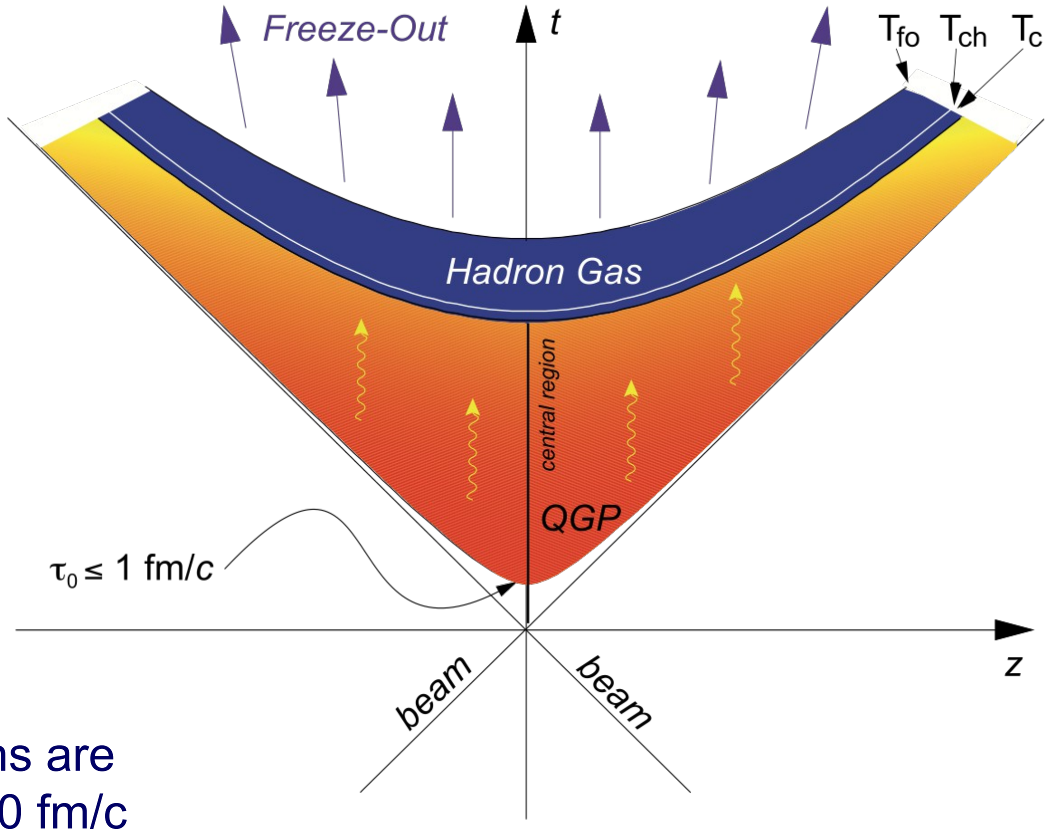
New state of matter more remarkable than predicted – raising many new questions

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



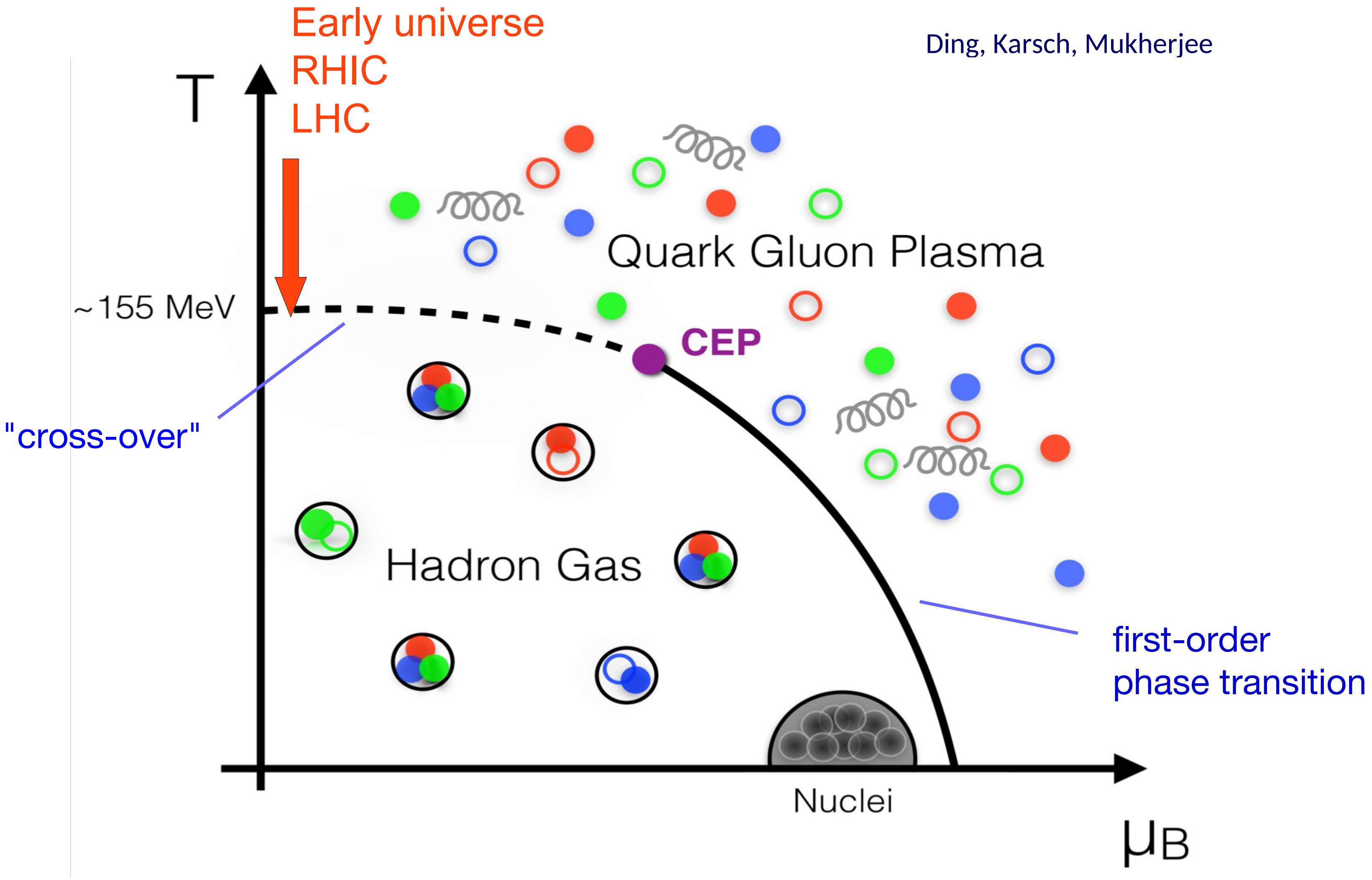
- liberation of quarks and gluons
  time scale order 0.1 fm/c
- rapid thermalization of quarks and gluons, after about 1 fm/c QGP
  temperature order of 500 MeV
- expansion and cooling of QGP

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

- hadronization when T_c is reached
  156.5 MeV

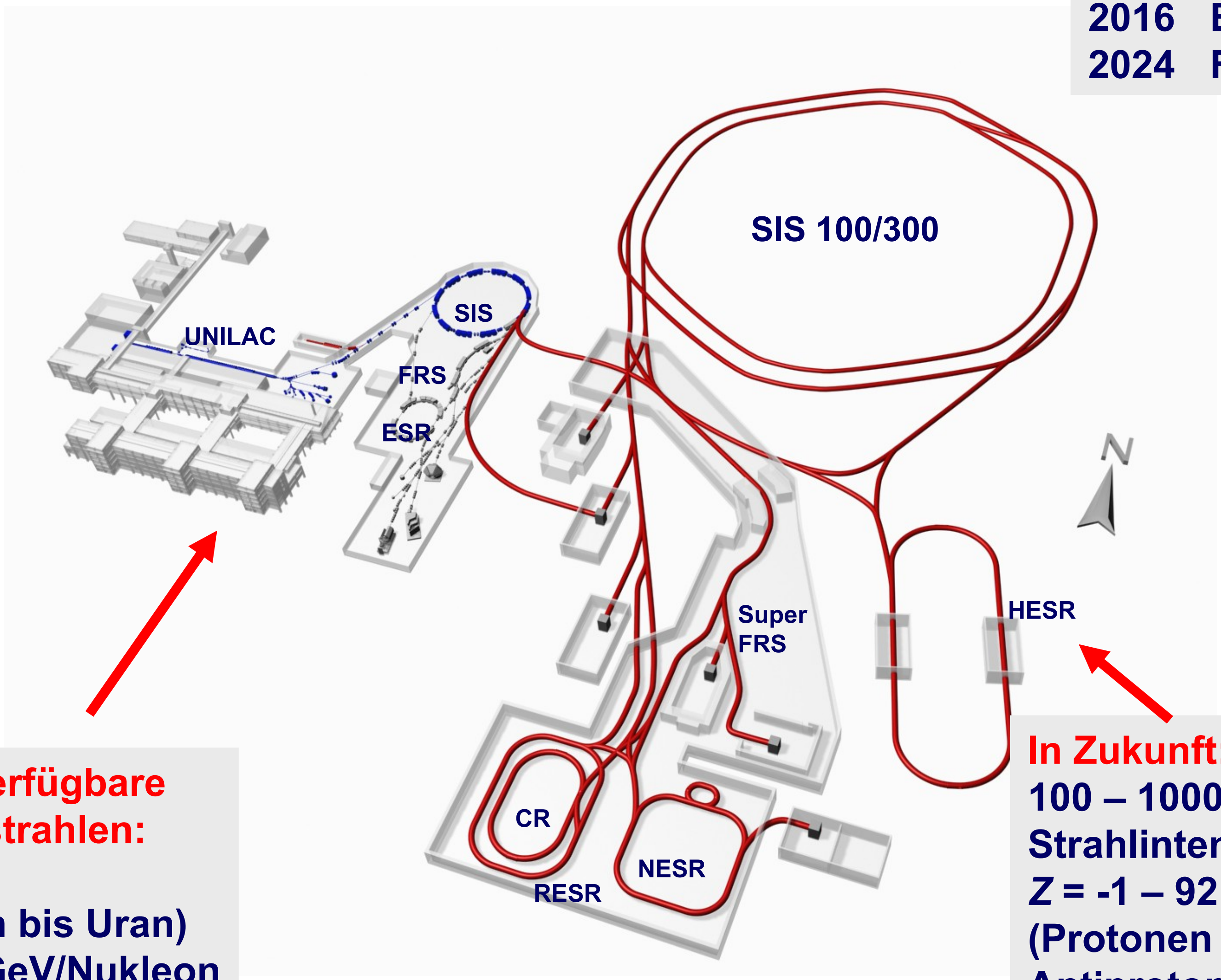
- expansion of hadron gas
- freeze-out = momentum distributions are
  frozen in, after about 10 fm/c

Conjectured phase diagram of QCD matter



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