Universe Evolution and Matter Origins
ALICE at LHC: the thermodynamics of strongly interacting matter
Thermodynamics of strongly interacting matter*  

* many interacting constituents
Thermodynamics of strongly interaction matter

How does the complexity of matter emerge from the dynamics of the strong interaction
What are the ultimate *constituents* of matter?

What are the basic *forces* among them?

What are the possible *states* of matter?

How do *transition* between these states occur?
What are the ultimate **constituents** of matter?

- basic constituents without individual physical existence
- hadrons are the single particle states in the physical vacuum
What are the ultimate *constituents* of matter?
What are the basic *forces* among them?

- gluon mediates the strong interaction
- color is the intrinsic charge
- quarks confined inside colorless space $\Lambda \sim 1$ fm
QCD: A quantum field theory

- Matter fields: 6 $s = \frac{1}{2}$ quarks
- Interaction fields: 8 massless gauge vector $g$
- 3 colors: non-abelian SU(3) gauge group
- Degrees of freedom change with $Q^2$
**QCD**: A rich phenomenology

- **QGP**: Color deconfined, Chiral symmetry broken
- **hadron gas**: Color confined, Chiral symmetry broken
- **quarkyonic ?**: Color deconfined, Chiral symmetry broken
- **color supraconductor ?**: Color Cooper pairs
Evolution of early universe

- **QGP:** Color deconfined
  Chiral symmetric

- **hadron gas:**
  Color confined
  Chiral symmetry broken

Temperature (MeV):
- 250
- 200
- 150
- 100
- 50

Time (μs):
- 10 μs
- 1 s

μB (MeV):
- 0
- 600
- 1200
Hot and cold
Dense and dilute

- **sun center**
- **super novae**
- **neutron star**
- **cup of coffee**
- **cooled ions**
- **ultra cold quantum gas**
- **QGP**

Temperature (°K)

Particles density (cm⁻³)
What are the ultimate **constituents** of matter? 
What are the basic **forces** among them? 
What are the possible **states** of matter? 
How do **transition** between these states occur?
Thermodynamics of strongly interaction matter

- statistical QCD
- heavy-ion collisions
What are the possible states of matter? How do transition between these states occur?

1 nucleon/m³  $10^{44}$ nucleon/m³  $10^{50}$ nucleon/m³

- Short range aspect of dense matter makes confinement disappear
- A state of matter where basic constituents are quarks

Quark Gluon Plasma
The fundamental questions about extreme matter

- What are the properties, are symmetries restored?
- Can one measure $T_H$?
- Transport parameters and EOS?
- Nature of microscopic excitations and $qp$?
- Is QGP a strongly coupled liquid?
macroscopic system of unbound color charges

confined (color insulator)  deconfined (color conductor)

transition = collective effect with phase transition
Statistical QCD 1

Macroscopic system of unbound color charges

$Z_3$ symmetry broken, confined hadronic state, few dof

$Z_3$ symmetry restored, deconfined plasma, many dof (??)

$T_H \sim 170$ MeV
Quark Gluon Plasma 2

macroscopic system of ~ massless quarks

effective q mass generated through EW symmetry breaking (Higgs mass)

constituent q mass generated through confinement (spontaneous $X_c$ symmetry breaking)
Statistical QCD 2

macroscopic system of ~ massless quarks

\[ \frac{m_q}{T} = 0.08 \]

\( T_H \sim 170 \text{ MeV} \)

X symmetry broken, constituent mass

X symmetry restored, effective mass
Heavy-ion collisions 1

explore the nuclear matter phase diagram

LHC: Pb-Pb @ 5.5 TeV

- QGP
- quarkyonic
- hadron gas
- color supraconductor
Heavy-ion collisions 2

\[ s_{\text{NN}} = 5500 \text{ GeV} \]

Why do we need collider energies to test properties of dense QCD matter which arise on typical scales \( T = 170 \text{ MeV} \)?

\[ s_{\text{NN}} = 200 \text{ GeV} \]
Heavy-ion collisions 2  Why do we need collider energies?

- Denser initial state (15 GeV/fm$^3$)
- Longer life time (10 fm/c)
- Bigger spatial extension (300 fm$^3$)
- Stronger collective phenomena
- Richer variety of hard probes
- Larger per event statistics

At present achievable temperatures, QGP has the properties of a liquid ($\alpha_s$ not small)
Heavy-ion collisions 3  
Collision dynamics

Initial state: classical color field (?)
equilibration - hydrodynamics - hadronization

Final hadronic state
Heavy-ion collisions 3

Initial state: classical color field

- Parton density saturates
- $\tau_{g\rightarrow gg}, \tau_{gg\rightarrow g} \gg \tau_{\text{collision}}$

$\sqrt{s}$ increases

Resolution power of probe increases

$\ln(1/x)$

$\ln(Q^2)$

Color Glass Condensate

Heavy-ion collisions 4

Hydrodynamics

$\tau$ initial conditions ($1/T$) $\ll \tau$ perturbative equilibration ($1/\alpha_s^2 T$)

QGP: a non abelian medium that does not carry quasi-particle excitations!
Heavy-ion collisions 3  Collision dynamics

Initial state: classical color field (?)

equilibration - hydrodynamics - hadronization

Final hadronic state
Heavy-ion collisions 5 Final State

Thermodynamic properties through hadronic radiation at $T_H$

▶ Denser initial state (15 GeV/fm$^3$)
Heavy-ion collisions 5  Final State

Thermodynamic properties through EM radiation

- Hotter initial condition ($T > 304$ MeV)
Thermodynamic properties through hadronic radiation at $T_H$
Heavy-ion collisions 5  Final State

Thermodynamic properties through hadronic radiation at $T_H$

Hadronisation temperature $T_H \sim 155$ MeV

Universal ($e^+e^-$, pp, AA) hadron production mechanism?
Heavy-ion collisions 4  Hydrodynamics

Hydro Dynamics of QGP !

- E-p conservation
- 2\textsuperscript{nd} law of thermodynamics
- properties of matter \ldots calculable from first principles
Heavy-ion collisions 4  Hydrodynamics

Initial conditions
- density, geometry, size, fluctuations

Hydro evolution
- almost linear time evolution

Hadronisation
- non-linear mapping of fluctuations

Collision time

Hydro

IC (IS) ? FS (data)
\( \varepsilon_2 : \) overlap geometry (impact parameter)

liquid + minimal shear viscosity

\( \nu_2 : \) mapped into momentum space
Heavy-ion collisions 4  Collectivity in action

\[ \nu_2\{SP, |\Delta \eta|>1\} \]

Pb-Pb \( s_{NN} = 2.76 \text{ TeV} \ 20-40\% \)

VISH2+1 (CGC, \( \eta/s=0.2 \))

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ALICE PRELIMINARY
Heavy-ion collisions 4  Hydrodynamics

initial conditions

density, geometry, size, fluctuations

hydro evolution

almost linear time evolution

hadronisation

non-linear mapping of fluctuations

collision time

Hydro*

IC (IS)  ?  FS (data)

* Need to control initial conditions
a parte

CMB - Big Bang - Universe

BB Model + parameters
a parte

CMB - Big Bang - Universe

CMB

isotropy, curvature, fluctuations

Big Bang model

almost linear time evolution

Today's Universe

non-linear mapping of fluctuations

Big Bang time

IC (IS) → BB model* → FS (data)

*a priori knowledge of initial conditions
Heavy-ion collisions 4 Hydrodynamics

\[ C(\Delta \phi) \]

Centrality 0-1%, |\(\eta\)| < 0.8
- \(|\Delta \eta| > 1\)
- \(v_{2,3,4,5}(2, |\Delta \eta| > 1)\)

\[ \Delta \phi (\text{rad.}) \]

- \(2.0 < p_{t,\text{trig}} < 3.0\)
- \(1.0 < p_{t,\text{assoc}} < 2.0\)

\[ V_{n1}[10^2] \]

Centrality
- 0-2%
- \(2 < p_t' < 2.5 \text{ GeV/c}\)
- \(1.5 < p_T^3 < 2 \text{ GeV/c}\)
Heavy-ion collisions 4  Hydrodynamics

fluctuation damping ↔ sound attenuation length

\[ \varepsilon_n : \text{density/geometry fluctuations} \]

liquid + minimal shear viscosity \((\Gamma = \eta/sT)\)

\[ \nu_n : \text{mapped into momentum space} \]

\( \eta/S = 0 \)

\( \eta/S = 1/4\pi \)
To conclude
To conclude: QGP

- is a strongly coupled plasma
- has a very short mean free path
- exhibits a high degree of collectivity and flows
- absorbs a significant fraction of high-energy partons
- ...
Fluid hydrodynamics in small systems

Hard probes \((p_T, m_T \gg T)\) : QGP at high resolution scale

- How do high \(p_T\) quarks, gluons, and quarkonia propagate in the QGP?
- Do they flow with the medium?
- \(q\) recombination a possible hadronization mechanism?
- Color screening probed with quarkonia states?
- ...
The Quark-Gluon Plasma, a nearly perfect fluid

L. Cifarelli$^1$, L.P. Csernai$^2$ and H. Stöcker$^3$ - DOI: 10.1051/epn/2012206

$^1$ Dipartimento di Fisica, Universita di Bologna, 40126 Bologna, Italy;
$^2$ Department of Physics and Technology, University of Bergen, 5007 Bergen, Norway;
$^3$ GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany

We are living in interesting times, where the World’s largest accelerator, the Large Hadron Collider, has its most dominant successes in Nuclear Physics: collective matter properties of the Quark-Gluon Plasma (QGP) are studied at a detail which is not even possible for conventional, macro scale materials.
LHC collides,
Particles fly in ALICE:
The QGP fireworks
Heavy-ion collisions 3

Initial state: classical color field

- parton density saturates
- $\tau_{g \rightarrow gg}, \tau_{gg \rightarrow g} \gg \tau_{\text{collision}}$

Color Glass Condensate
Heavy-ion collisions 4  Hydrodynamics

\[ \tau \text{ initial conditions } (1/T) \ll \tau \text{ perturbative equilibration } (1/\alpha_s^2 T) \]

QGP: a non abelian medium that does not carry quasi-particle excitations!
Heavy-ion collisions 4 Hydrodynamics

Will come back later!
Back to Hydro Dynamics of QGP !