Heavy Ion Collisions and Quark-Gluon Plasma

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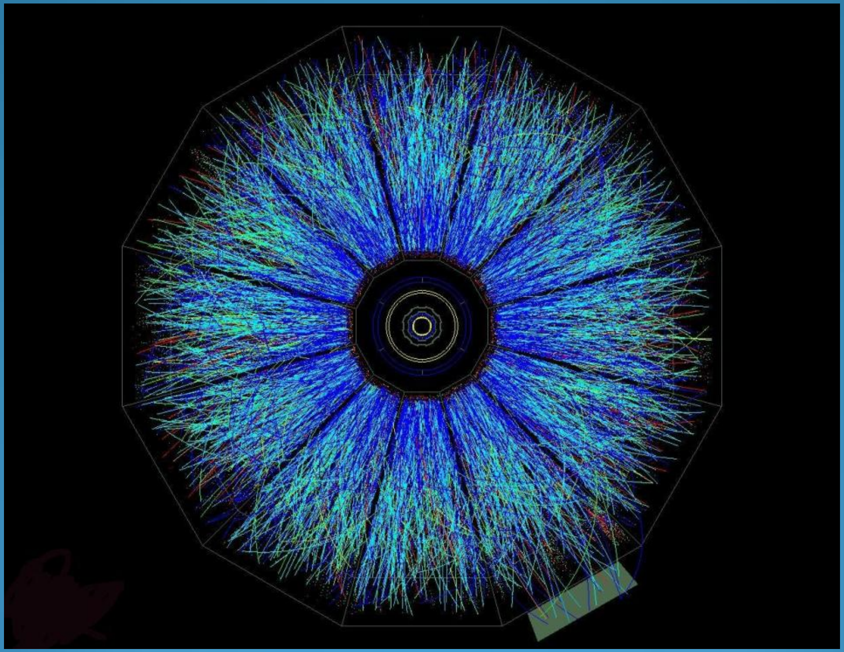


QGP event at STAR

Overview

- What is quark-gluon plasma?
- Why do we want to study quark-gluon plasma?
- How do we create quark-gluon plasma?
  - The past and present – SPS and RHIC
  - The future – LHC and ALICE
- How do we detect and identify quark-gluon plasma?

What is QGP?

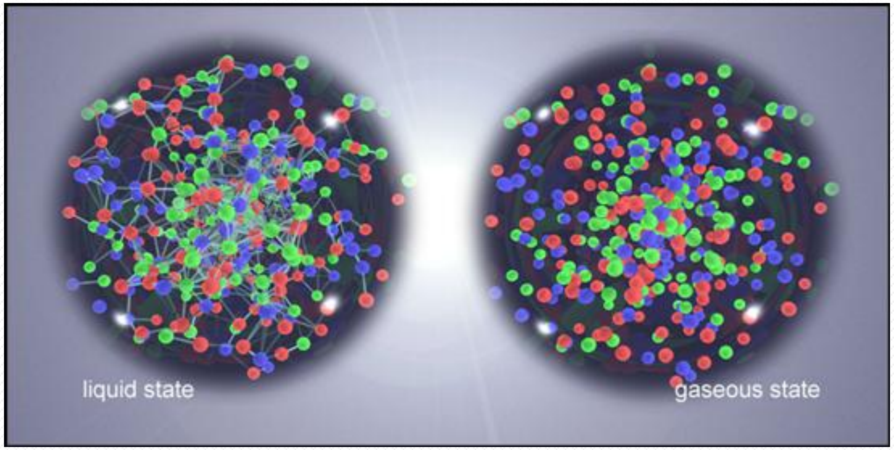
- Newly discovered QCD phase of matter (contrasts with hadronic matter) – discovery announced in 2000 (SPS).
- Extremely high temperature/pressure (transition at $\varepsilon_c \sim 170$ MeV per particle $\equiv 2 \times 10^{12}$ K ~ 1 GeV/fm^3. Note that this does not correspond to colliding beam energy, although of course higher beam energies lead to higher energy densities).
- Quarks and gluons (almost?) deconfined.
- Typically studied in heavy ion colliders.

What is QGP?

- Hadronic matter: particles with colour charge (quarks and gluons) are confined and bound into colour-neutral baryons or mesons.
- QGP: quarks and gluons are deconfined.
- Deconfinement: quarks and gluons free to move more than 1 fm (ie within the volume of the plasma).
- Called a plasma by analogy with "regular" plasma (though there are many important differences, and QGP is much more complicated).
  - "Regular" plasma: electric charges screened
  - QGP: colour charges screened

What is QGP?

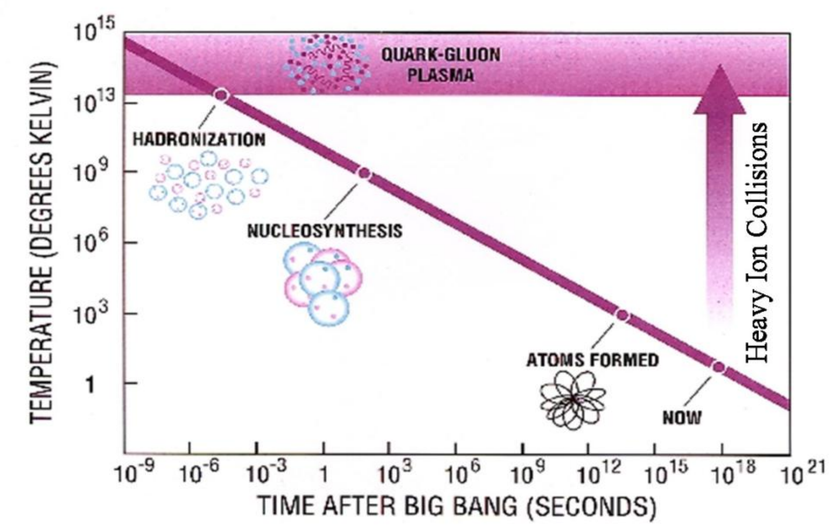
- Despite deconfinement, volume of QGP is still colour neutral (and has integer electric charge).
- Existed in early (t ~ tens of μs) universe – experiments really are unlocking the beginning of the universe!
- Cannot use pQCD -> lattice gauge theory (complicated and less well understood!)
- Should it behave like a liquid or a gas? Unsure from theory (some expected gas-like behaviour: wishful thinking?) – but from tentative evidence at RHIC it seems to behave as a low-viscosity liquid!



Liquid vs gaseous QGP behaviour

Why do we want to study QGP?

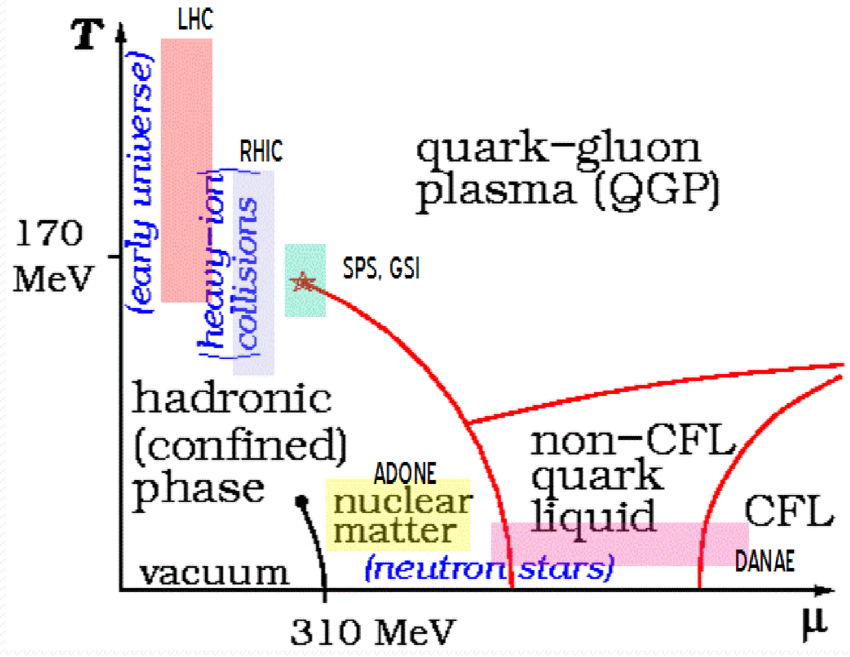
- Early universe: the universe is thought to have been in this state ~ tens of μs after the big bang, prior to hadronisation (and QGP may exist naturally today – cores of hot neutron stars?)
- Confinement studies: confinement (and related issues such as hadronisation) is still not fully understood (and there is no analytic proof that QCD should be confining at all). Studies of QGP (and especially the phase transition between the hadronic and QGP phases) should be enlightening!



Timeline of states of matter from big bang until now

Why do we want to study QGP?

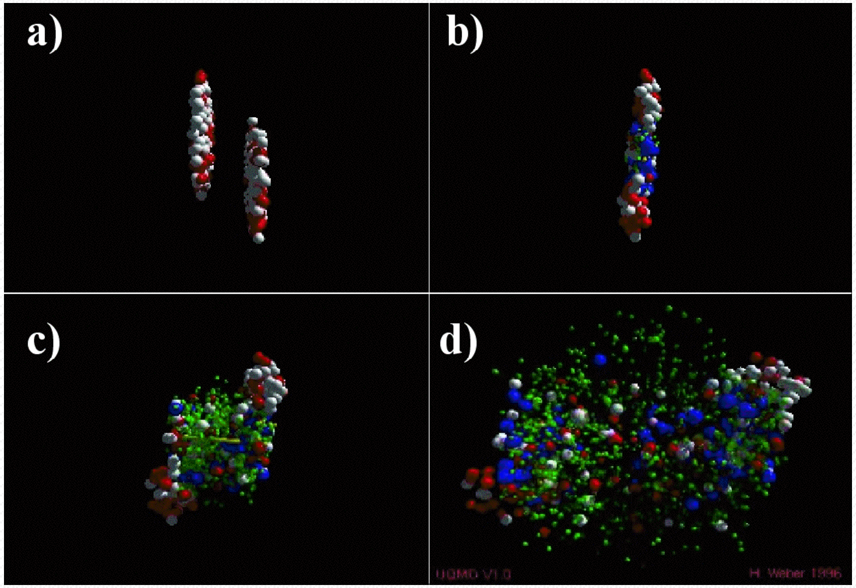
- Other QCD studies: QCD still relatively poorly understood and tested compared to QED and electroweak theory, especially non-perturbative!
- The hadronic/QGP transition is the only phase transition predicted by the standard model that is accessible to current experiments. Is it discontinuous (a first order phase transition) or a smooth change? May have consequences for early universe cosmology!



Expected QCD phase diagram, μ is quark chemical potential => quark density

How do we create QGP?

- Very large energy density required: heavy ion colliders.
- Lead at SPS (and ALICE), gold at RHIC.
- Heavy ions allow much larger energy density (over a large volume) collisions than are possible with lighter particles: require $\varepsilon_c \sim 1$ GeV/fm^3.
- Large number of inelastic nucleon-nucleon collisions, close to each other, at almost the same time (especially so due to Lorentz contraction – nuclei appear as disks).
- At LHC: 5.5 TeV per nucleon (CM) => ~1150 TeV (contrast 14 TeV in p-p!)



Simulation of the time-evolution of a heavy ion collision

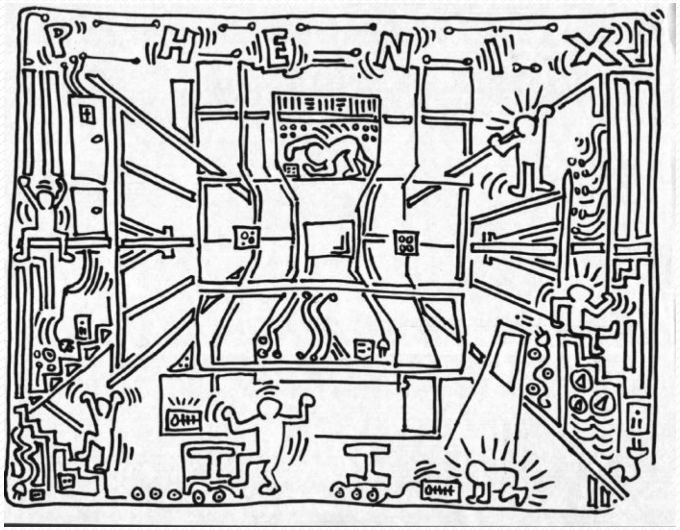
SPS (CERN)

- Super Proton Synchrotron tried to produce QGP in 1980s and 1990s: confusing name as it did this with Pb-Pb collisions!
- Heavy ion collisions began in 1986. Previously lighter nuclei were used: provided hints of QGP but no real proof.
- CERN announced the discovery of “a new state of matter” in 2000. Cagey language, but strong evidence that “real” QGP had been produced!
- 33 TeV Pb beam, 7 fixed target (Pb/Au) experiments: NA44, NA45, NA49, NA50, NA52, WA97 / NA57 and WA98 (each looked at different aspects).

The SPS beamline

RHIC (Brookhaven)

- Typically Au-Au collisions at 200 GeV per nucleon CM (but also Cu-Cu, d-Au, p-p).
- Operational since 2000, and may not be made obsolete by the LHC: can study spin polarised protons, and the two largest experiments (STAR and PHENIX, which are also the only two experiments still running) have much more comprehensive calorimetry than ALICE (and even after ALICE is upgraded with EMCal, it will still not have calorimeter coverage over all η and ϕ).
- Source of many of the doomsday fears that have been recycled for the LHC!
- Most current knowledge from here.
  - Elliptic flow
  - Jet quenching



The PHENIX experiment at RHIC

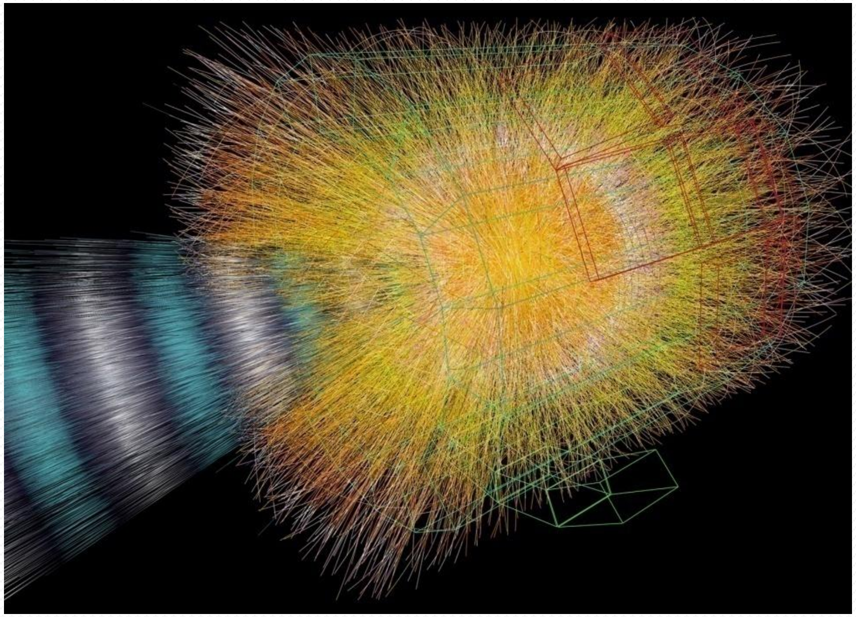
ALICE (back to CERN)

- The main heavy ion experiment at the LHC – built specifically for this (though has p-p physics objectives as well).
- “By then, I hope the QGP has been finally ‘discovered’ and we can go on with the business of studying its properties in detail.” – ALICE spokesman.
- Primary purpose is detailed study of QGP.
- Pb-Pb at 5.5 TeV per nucleon (CM)
- Capable of more direct QGP analysis than previously possible: direct result of higher collision energies and fireball temperatures: QGP lasts longer and hard processes more abundant (previously observation of QGP has been quite indirect).

The ALICE experiment

How do we detect QGP?

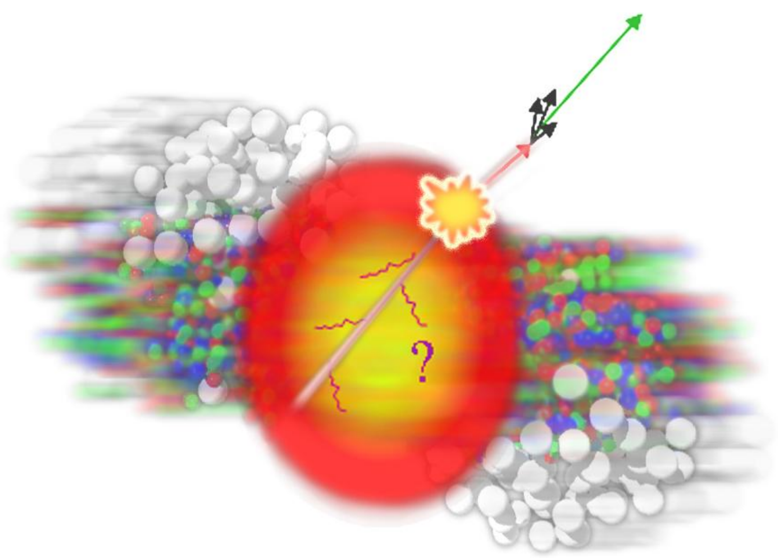
- Have to deal with very high track multiplicity: estimated up to 8000 per unit pseudorapidity at ALICE mid-rapidity!
- Typically require excellent tracking detectors: ALICE should be able to get good momentum resolution and PID on tracks over a large momentum range (100 MeV < p_t < 100 GeV). The ALICE TPC is the largest in the world, and the STAR TPC was similarly cutting-edge!
- Look for certain QGP "signatures".
- Unhelpfully, easily calculable QGP properties are hard to observe, and vice-versa! Positive QGP identification is tricky.



Reconstructed Pb-Pb collision at ALICE, from simulated data

QGP signature examples

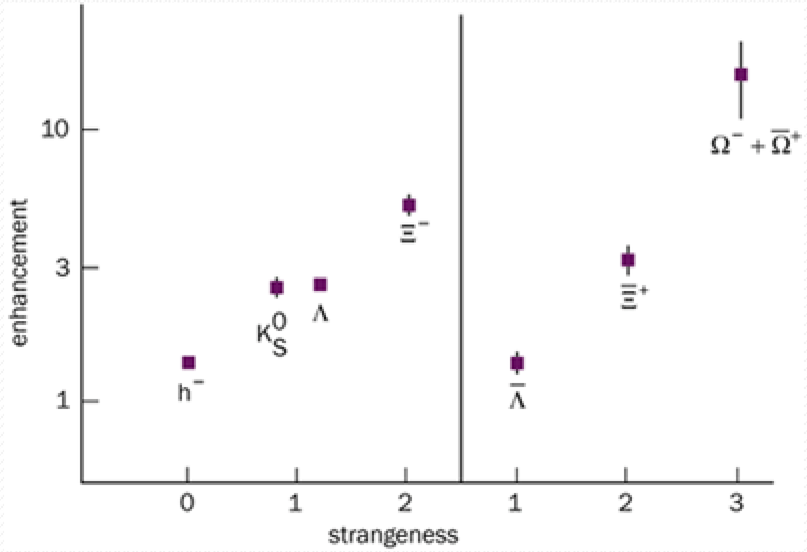
- Typically involve comparing observables with their characteristics in non-QGP medium (eg from p-p, p-A… Acquiring these baseline measurements will be a main focus during the p-p runs at ALICE).
- Many dilepton pairs produced from qqbar -> l^+l^- interactions. Mean free path of leptons in QGP relatively long: unlikely to interact again with medium after production: good tool for analysis of QGP properties as production rates and cross sections depend on momentum distributions of quarks in QGP!
- Jet quenching: jet p_t suppressed due to interaction with medium: scattering, gluon bremsstrahlung… Poorly understood, and only recently recognised! ALICE is being upgraded with EMCal to allow better study of this.



Asymmetric jet quenching

QGP signature examples

- J/ψ suppression: J/ψ form in hard processes in early stages of collision (when nucleons still have most of their initial momentum) but gluon interactions within QGP hinder binding (Debye screening). J/ψ easy to identify: leptonic decay modes. This was one of the key signatures observed in the initial discovery at the SPS.
- Abundant strangeness: strange quark mass of the order of transition temperature. Strange quarks more abundant in QGP than hadronic matter: more strange particles after fireball breaks up.
- Photon rates: similarly to dileptons, rates and momentum distributions depend on thermodynamic properties of QGP, but once produced are likely to leave the plasma without interacting. Photon production also occurs in a hot hadronic gas, (and large background makes direct photons difficult to distinguish).



Plot of strangeness enhancement in Pb-Pb collisions compared to p-Be at WA97

Image credits

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- Institut fur Kernphysik http://qgp.uni-muenster.de/AGWessels/img/Forschung/qgpTimeEvolutionLarge.gif
- CERN http://livefromcern.web.cern.ch/livefromcern/antimatter/history/historypictures/sps-half.jpg, http://aliceinfo.cern.ch/Public/en/Chapter4
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