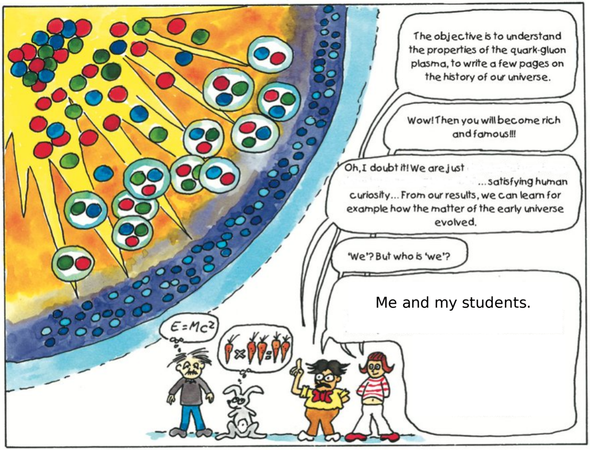
Lecture 1
A brief history of the Quark Gluon Plasma and why we study it



Adapted from a brochure by ALICE/CERN

A brief history of the Quark Gluon Plasma
A prevision from the 70*”s:

Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, England
(Received 6 January 1975)

- “Matter at densities higher than nuclear consists of a quark soup. The quarks become free at sufficiently high densities. A specific realization is an asymptocically free field theory.”

  Neutron stars, early universe, black hole formation

- “The high-density relation $p = 1/3\rho$ remains valid at all temperatures.”

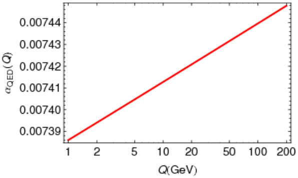
* D.Ivanenko, D.F.Kurdgelaidze D.F. “Remarks on quark stars” Lett. Nuovo Cimento 2 (1969) 13. N. Itoh “Hydrostatic Equilibrium of Hypothetical Quark Stars” Prog. of Theor. Phys. 44(1970) 291.

Asymptotic freedom

- Classical physics : forces on particles.
- Particle physics (QFT): particles interact via particle exchange.

• Eletromagnetic interaction: an electron emits a photon

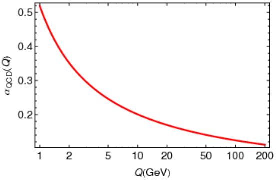
• Eletromagnetic interaction: electrons getting closer interact each time more $dist. \propto 1/Q$



QED: screening due to e^+e^- pairs

• Strong interaction: a quark emits a gluon

• Strong interaction: quarks getting closer interact each time less



QCD: the combined effect of $q\,\bar{q}$ and g is an anti-screening

$\rightarrow$ asymptotic freedom

Gross & Wilczek PRL 30 (1973) 1343, Politzer PRL30 (1973) 1346.

Surprising property but well established experimentally

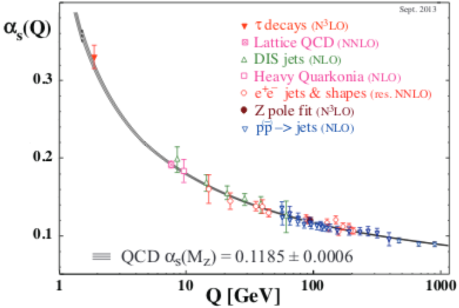
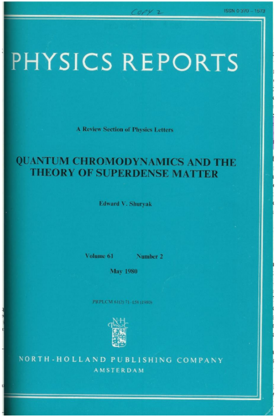


Figure 9.4: Summary of measurements of α_s as a function of the energy scale Q. The respective degree of QCD perturbation theory used in the extraction of α_s is indicated in brackets (NLO: next-to-leading order; NNLO: next-to-next-to leading order; res. NNLO: NNLO matched with resummed next-to-leading logs; N^3LO: next-to-NNLO).

Particle Data Group 2014

$\longrightarrow$ Nobel Prize 2004 (Gross, Politzer, Wilczek)

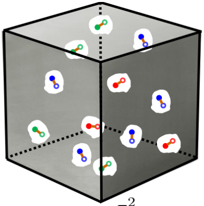
First review paper



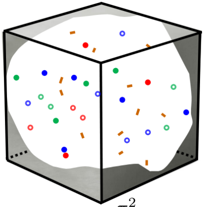
"Because of the apparent analogy with similar phenomena in atomic physics, we may call this new phase of matter the QCD (or quark-gluon) plasma."

Paradigm (for a long time): the constituents of the Quark Gluon Plasma interact via the strong force in the asymptotic free regime.

Orders of magnitude



$$P_\pi(T) = 3\,\frac{\pi^2}{90}\,T^4$$



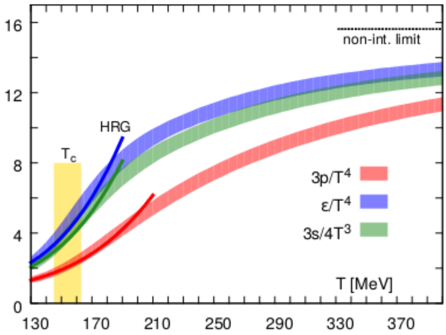
$$P_{QGP}(T) = g\,\frac{\pi^2}{90}\,T^4 - B$$

$$g \sim 37\text{–}47.5$$

$$\Rightarrow T_{trans.} \sim 140\,MeV, \epsilon_{trans} \sim 0.8\,GeV/fm^3$$

with $B^{1/4} \sim 200\,MeV$

Lattice QCD



HotQCD Collaboration arXiv:1407.6387

- $T_c = (154 \pm 9)\,MeV$, $\epsilon_c = (0.18 - 0.5)\ GeV/fm^3$, $\epsilon_{mat.nucl.} \sim 0.15\ GeV/fm^3$
- Cross-over (no first order transition),
- Tends towards a hadron gas at small T,
- Tends towards an ideal gas of quarks and gluons at large T.

Relativistic heavy ion collisions

- AGS: 1986-2000 $\sqrt{s} = 5\ GeV\ A$ $\sim$ 1000 hadrons
- SPS: 1986-2003 $\sqrt{s} = 20\ GeV\ A$ $\sim$ 2500 hadrons
- RHIC: 2000- $\sqrt{s} \leq 200\ GeV\ A$ $\sim$ 7500 hadrons
- LHC: 2010- $\sqrt{s} = 5.5\ TeV\ A$ $\sim$ 20000 hadrons

CERN 2000 PRESS RELEASE: New state of matter created at CERN.

http://press.web.cern.ch/press/PressReleases/Releases2000/PR01.00EQuarkGluonMatter.html

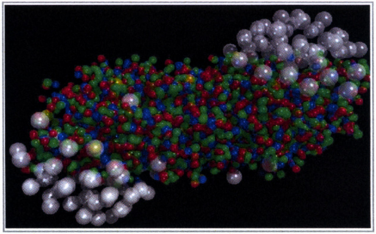
Press Release

New State of Matter created at CERN

PR01.00
10.02.00

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.

Theory predicts that this state must have existed at about 10 microseconds after the Big Bang, before the formation of matter as we know it today, but until now it had not been confirmed experimentally. Our understanding of how the universe was created, which was previously unverified theory for any point in time before the formation of ordinary atomic nuclei, about three minutes after the Big Bang, has with these results now been experimentally tested back to a point only a few microseconds after the Big Bang.



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The results from CERN present strong incentive for the future planned experiments. While all of the pieces of the puzzle seem to fit with a quark-gluon plasma explanation, it is essential to study this newly produced matter at higher and lower temperature in order to fully characterize its properties and definitively confirm the quark gluon plasma interpretation. The focus of heavy ion research now moves to the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory in the United States, which will start experiments this year. In 2005 CERN's Large Hadron Collider (LHC) experimental programme will include a dedicated heavy ion experiment, ALICE.

BNL 2005 PRESS RELEASE: RHIC Scientists serve Up “Perfect” Liquid.

http://www.bnl.gov/bnlweb/puba

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RHIC Scientists Serve Up "Perfect" Liquid

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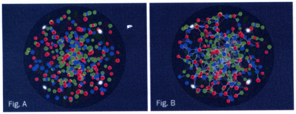
Physical Society in Tampa, Florida.

These summaries indicate that some of the observations at RHIC fit with the theoretical predictions for a quark-gluon plasma (QGP), the type of matter postulated to have existed just microseconds after the Big Bang. Indeed, many theorists have concluded that RHIC has already demonstrated the creation of quark-gluon plasma. However, all four collaborations note that there are discrepancies between the experimental data and early theoretical predictions based on simple models of quark-gluon plasma formation.



These images contrast the degree of interaction and collective motion, or "flow," among quarks in the predicted gaseous quark-gluon plasma state (Figure A, see mpeg animation) vs. the liquid state that has been observed in gold-gold collisions at RHIC (Figure B, see mpeg animation). The green "force lines" and collective motion (visible on the animated version only) show the much higher degree of interaction and flow among the quarks in what is now being described as a nearly "perfect" liquid. (Click + ENLARGE

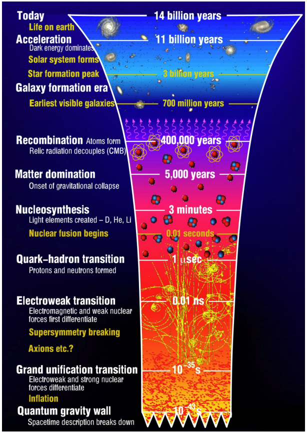
"We know that we've reached the temperature [up to 150,000 times hotter than the center of the sun] and energy density [energy per unit volume] predicted to be necessary for forming such a plasma," said Sam Aronson, Brookhaven's Associate Laboratory Director for High Energy and Nuclear Physics. But analysis of RHIC data from the start of operations in June 2000 through the 2003 physics run reveals that the matter formed in RHIC's head-on collisions of gold ions is more like a liquid than a gas.

$\longrightarrow$ Strongly interacting QGP or sQGP (not a plasma)

Why study the QGP?

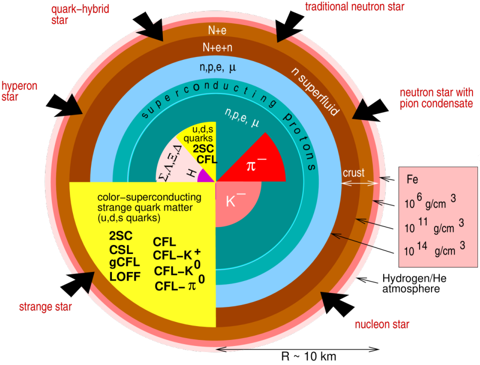
QGP is relevant to understand various problems in cosmology and astrophysics

- Early universe very hot and dense: solving Einstein equations, QGP existed at about $t = 1\mu s$



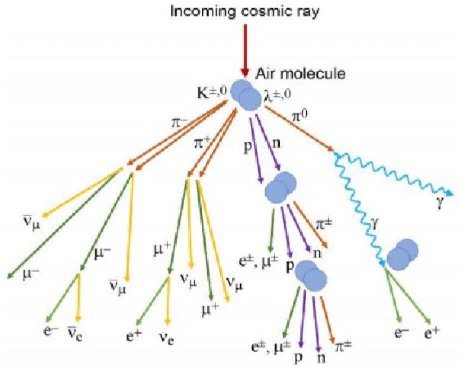
From Stephan Hawking Centre for Theoretical Cosmology

- QGP may exist at the center of compact stars



From Fridolin Weber-SDSU

- QGP should be created when high-energy cosmic rays (mostly protons) collide at energies higher than LHC with light atmospheric nuclei

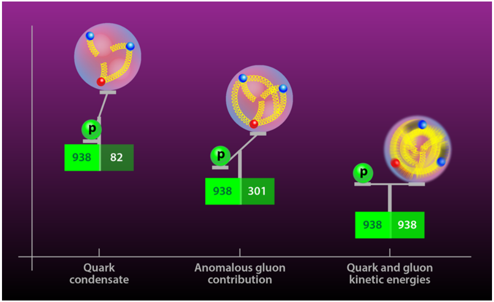


From John D. Wrbanek and Susan Y. Wrbanek NASA/TP-2020-220002

QGP may help shed some light on fundamental problems of the strong interaction

- What causes confinement? one of the Millennium Prize Problems by the Clay Mathematics Institute.
  if you solve it, you get a 1 000 000 dollars.

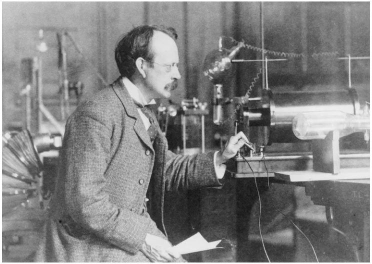
- Brout-Englert-Higgs mechanism generates the current quark masses $\sim$ 1% nucleon mass. QCD generates the remaining $\sim$ 99%. How?

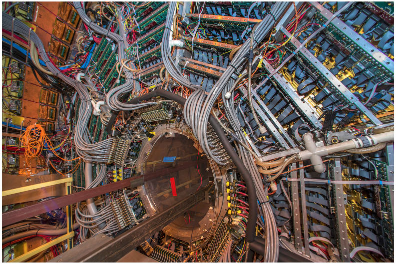


`https://physics.aps.org/articles/v11/118` (lattice QCD)

QGP is a new state of matter. What will we discover from this?

When J.J. Thomson discovered the electron in 1897, he had no idea what its collective properties would bring to humanity (R.Venugopalan?)





Thomson ans his cathode tube vs. STAR detector

For more on these accelerators RHIC and LHC, let us watch

RHIC-Exploring the Universe Within

https://www.bnl.gov/rhic/videos.php?v=147

What is CERN

https://www.youtube.com/watch?v=i0qjDZH-p7E

Homework 1

Watch

https://www.youtube.com/watch?v=amYYpGdWDtA

Answer (5 lines per question at most):

1. What is the diameter of RHIC? LHC?
2. Which were the 4 main experiments at RHIC that discovered the sQGP? Which are the main on-going experiments at LHC?
3. How much was spent to build RHIC and to maintain it every year? Same question for LHC.
4. Which “spin-offs” (practical applications) are cited in the 3 movies we have whatched?
5. Can RHIC and LHC be a threat to earth as was feared by some before the start of their running?

Cite your sources.

Please submit your answers by next week on e-disciplinas. We will discuss this homework during next class.