首届ALICE实验与重离子物理讲习班

The 1st ALICE Experiment and Heavy-Ion Physics School

夸克-胶子等离子体五十年：过去、现在和未来

(第一讲)

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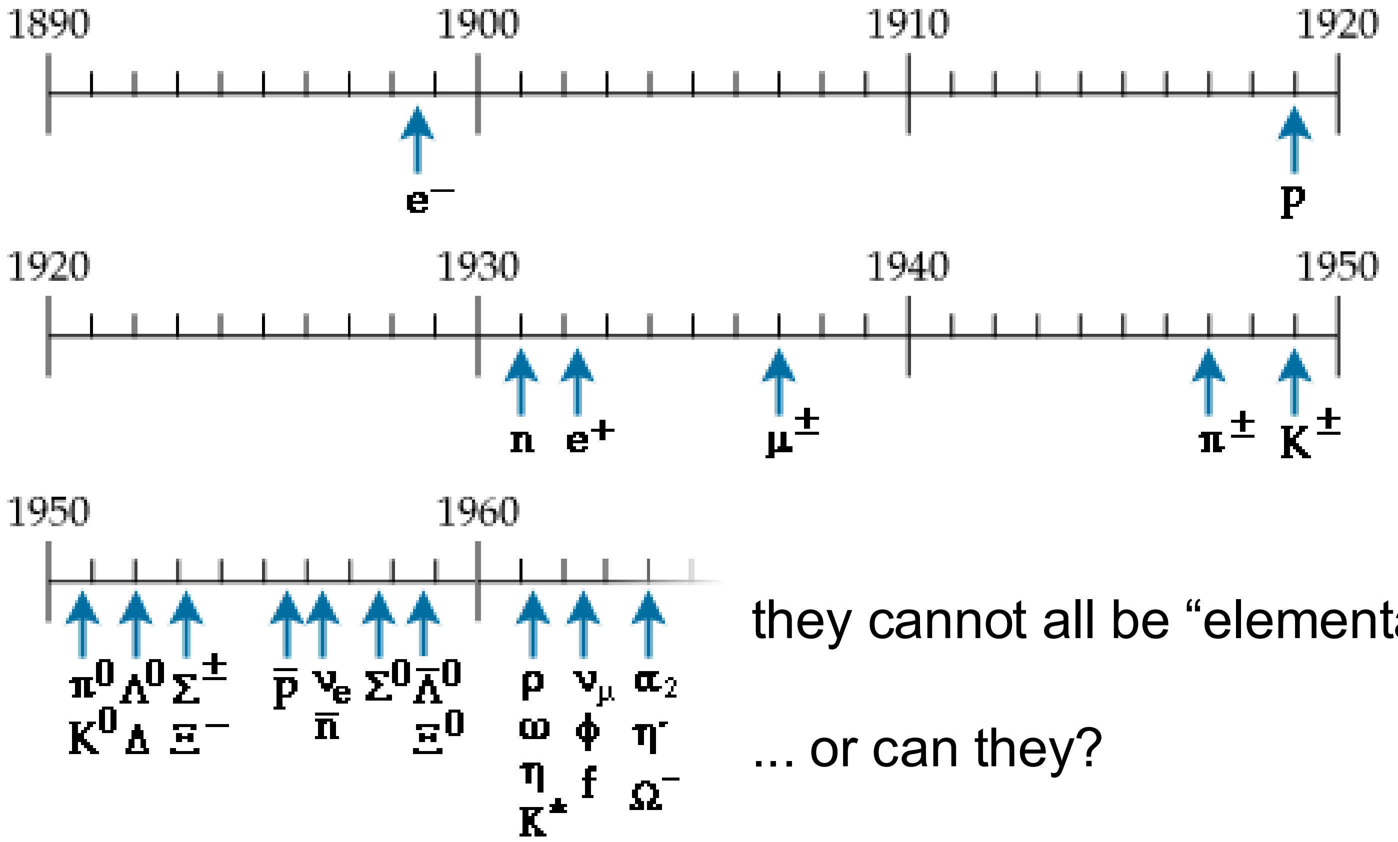
上海，复旦大学，2025年11月

A bit of history: discovery of subnuclear particles



they cannot all be "elementary"...

... or can they?

Statistical Bootstrap and Hagedorn Temperature

- very elegant idea:
  - hadrons are made of hadrons which in turn are made of hadrons which in turn...
  - no fundamental hadron ("nuclear democracy")
  - very popular in the sixties (pre-quarks)

    (very much "sixties", in fact: F Capra takes the idea and runs away with it in "The Tao of Physics")

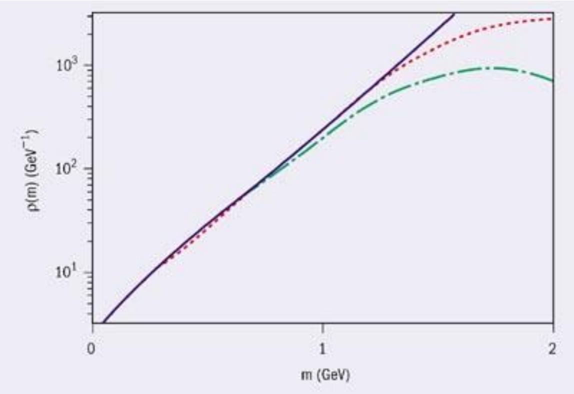
- pioneered by Geoffrey Chew (UC Berkeley)
  - e.g.: G. Chew (1962). *S-Matrix theory of strong interactions*. New York: W A Benjamin

- developed by Rolf Hagedorn (CERN) into a full-fledged theory of strong interactions
  - e.g.: R Hagedorn: Statistical thermodynamics of strong interactions at high energies 1965 Nuovo Cim. Suppl. 3 147

- very successful in calculating hadronic collision cross sections
  - e.g.: H Grote, R Hagedorn and J Ranft, Atlas of particle spectra, CERN-report (1970)
  - calculated based on hadron exchange → <u>need to know spectrum of all existing hadrons</u>

Spectrum of hadron masses

- spectrum of hadrons from “bootstrap equation”: $\rho(m) \propto m^{-3} \exp(\frac{m}{T_H})$
  - exponential growth of number of hadrons at higher and higher masses!
  - controlled by “Hagedorn temperature”, T_H ~ 150-160 MeV



green: states known in 1967
red: states known by mid-1990’s
blue: expected spectrum for T_H = 158 MeV

- btw, still holds: very similar results from lattice QCD
  - e.g.: A Majumder, B Müller, PRL 105:252002,2010
  - that’s why bootstrap theory worked well for hadron interactions!
    (the idea was very deep, even if the picture was not the correct fundamental one!)

Hagedorn temperature: a limiting value?

e.g. following K Redlich, H Satz in “Melting Hadrons, Boiling Quarks”, J Rafelski ed (Springer, 2016)

- partition function for a system of non-interacting pions:

$$\ln \mathcal{Z}(T,V) = \frac{VTm_0^2}{2\pi^2} K_2(\frac{m_0}{T})$$

- interactions as resonance formation:
  - interacting system of pions ←→ non-interacting gas of all possible resonances

$$\ln \mathcal{Z}(T,V) = \sum_i \frac{VTm_i^2}{2\pi^2} \rho(m_i) K_2(\frac{m_i}{T}) \approx \frac{VT}{2\pi^2} \int dm\, m^2 \rho(m) K_2(\frac{m}{T})$$

- inserting Hagedorn’s spectrum:

$$\ln \mathcal{Z}(T,V) \approx V \left[\frac{T}{2\pi}\right]^{3/2} \int \frac{dm}{m^{3/2}} e^{-\left[\frac{m}{T} - \frac{m}{T_H}\right]}$$ ← diverges for T → T_H

  - energy pumped into such a system, goes to creating heavier and heavier resonances
  - asymptotically reaching T_H

→ T_H would then be the maximum possible temperature!

... but Quarks enter the scene...

- the other main idea proposed in the 60’s to explain the multitude of hadrons
- 1961: “eightfold way” (SU(3) flavour symmetry, Murray Gell-Mann)
- 1965: quark hypothesis (Murray Gell-Mann, George Zweig)
- 1968: observation of “partons” in Deep Inelastic Scattering at SLAC
- 1970: GIM mechanism (Sheldon Glashow, John Iliopoulos, Luciano Maiani)
  - to explain absence of flavour-changing neutral currents
  - proposal of fourth quark (charm) → cancellation of flavour-changing terms
- 1974: discovery of charm (J/ψ) at Brookhaven and SLAC (+ Frascati 5 days later)

→ quark hypothesis widely accepted, and then ...

1974: Lee and Wick: a key precursor

PHYSICAL REVIEW D VOLUME 9, NUMBER 8 15 APRIL 1974

Vacuum stability and vacuum excitation in a spin-0 field theory*

T. D. Lee and G. C. Wick
Columbia University, New York, New York 10027
(Received 17 January 1974)

The theoretical possibility that in a limited domain in space the expectation value $\langle \phi(x) \rangle$ of a neutral spin-0 field may be abnormal (that is to say quite different from its normal vacuum expectation value) is investigated. It is shown that if the ϕ^3 coupling is sufficiently large, then such a configuration can be metastable, and its physical size may become substantially greater than the usual microscopic dimension in particle physics. Furthermore, independent of the strength of the ϕ^3 coupling, if $\phi(x)$ has sufficiently strong scalar interaction with the nucleon field, the state that has an abnormal $\langle \phi(x) \rangle$ inside a very heavy nucleus can become the minimum-energy state, at least within the tree approximation; in such a state, the "effective" nucleon mass inside the nucleus may be much lower than the normal value. Both possibilities may lead to physical systems that have not yet been observed.

- scalar field $\Phi(x)$
- extreme conditions (e.g. high T) → vacuum expectation value $\langle\Phi\rangle$ may vanish
- → nucleons become effectively massless!

1975, Cabibbo and Parisi: “quark liberation” at high T

Volume 59B, number 1 PHYSICS LETTERS 13 October 1975

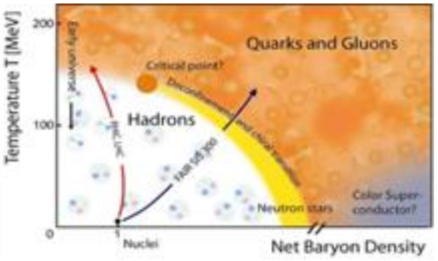
EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. CABIBBO
Istituto di Fisica, Universitá di Roma,
Istituto Nazionale di Fisica Nucleare, Sezione di Rome, Italy

G. PARISI
Istituto Nazionale di Fisica Nucleare, Frascati, Italy

Received 9 June 1975

The exponentially increasing spectrum proposed by Hagedorn is not necessarily connected with a limiting temperature, but it is present in any system which undergoes a second order phase transition. We suggest that the “observed” exponential spectrum is connected to the existence of a different phase of the vacuum in which quarks are not confine



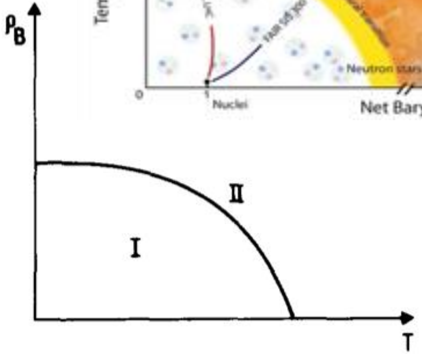


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

- T_H not maximum attainable, simply: for $T > T_H$ quarks not confined any more

1975, Collins and Perry: "quark soup" in neutron stars?

VOLUME 34, NUMBER 21 PHYSICAL REVIEW LETTERS 26 MAY 1975

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)

We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.

the basic argument is contained in only a few lines...

A neutron has a radius[10] of about 0.5–1 fm, and so has a density of about 8×10^{14} g cm^{-3}, whereas the central density of a neutron star[1,2] can be as much as 10^{16}–10^{17} g cm^{-3}. In this case, one must expect the hadrons to overlap, and their individuality to be confused. Therefore, we suggest that matter at such high densities is a quark soup.

1978, the name is coined

ЯДЕРНАЯ ФИЗИКА
JOURNAL OF NUCLEAR PHYSICS
т. 28, вып. 3(9), 1978

by E V Shuryak in Yadernaya Fizika 28 (1978) 403: "Kvark-Glyuonnaya Plazma"

КВАРК-ГЛЮОННАЯ ПЛАЗМА И РОЖДЕНИЕ ЛЕПТОНОВ, ФОТОНОВ И ПСИОНОВ В АДРОННЫХ СОУДАРЕНИЯХ

Э. В. ШУРЯК

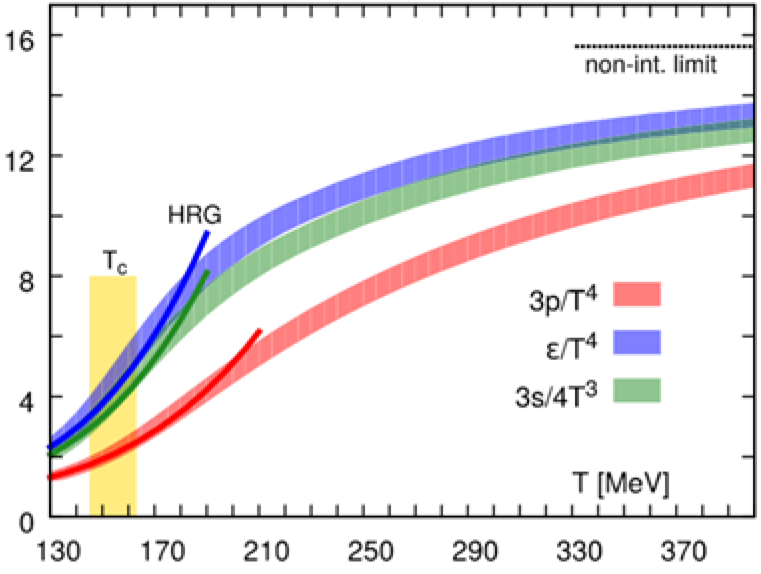
ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

(Поступила в редакцию 14 марта 1978 г.)

Предлагается теория явлений, связанных с массами M и поперечными импульсами $p_\perp$, такими, что 1 *Гэв*$\leqslant M$, $p_\perp \ll \sqrt{s}$. Для их описания применяется модель локально-равновесной кварк-глюонной плазмы, разлетающейся по определенному закону. Применение квантовой хромодинамики для вычисления скоростей ряда реакций в такой плазме позволяет вычислить спектры масс дилептонов, распределение по $p_\perp$ лептонов, фотонов, пионов и адронных струй, сечения рождения пар очарованных кварков и различных состояний чармония (псионов): J/ψ-, χ-, ψ'-мезонов. Результаты согласуются с экспериментальными данными.

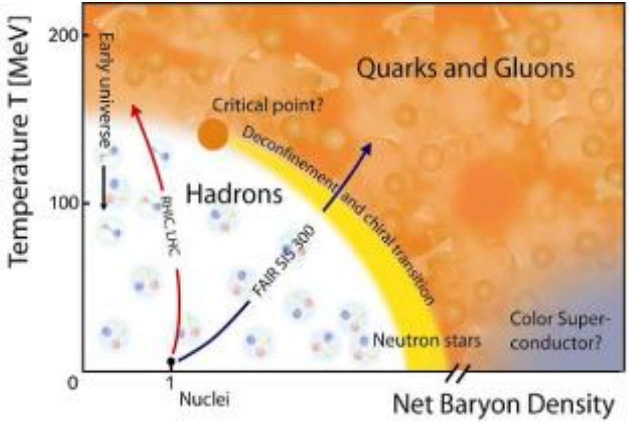
Lattice QCD

- the rigorous way of performing calculations in the non-perturbative regime of QCD
- discretisation on a space-time lattice
  - → ultraviolet (i.e. large-momentum scale) divergencies can be avoided

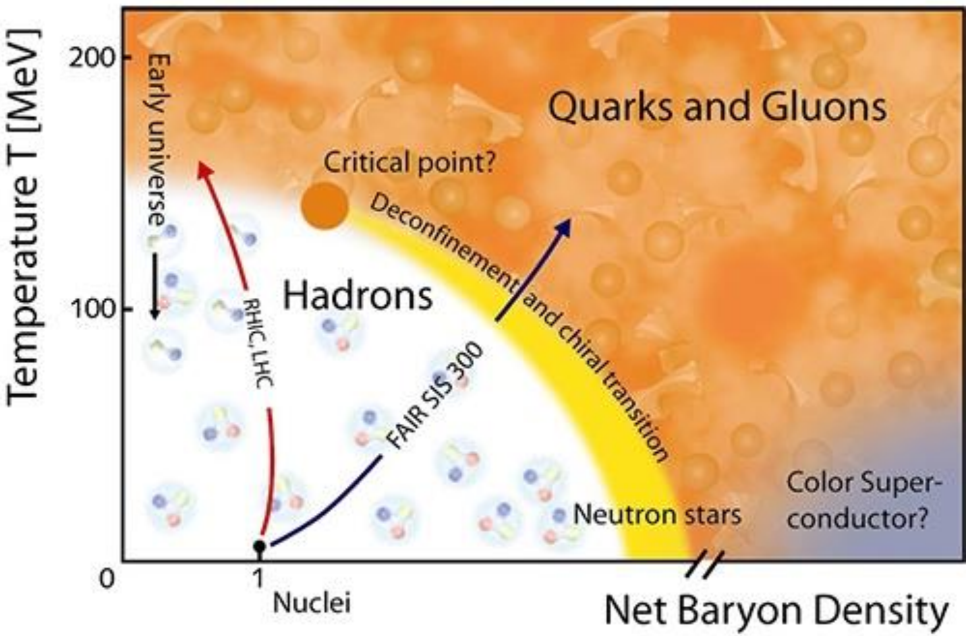


[A Bazavov et al. PRD 90 094503 (2014)]

- around critical temperature (T_C): rapid change of
  - energy density ε
  - entropy density s
  - pressure p
- due to activation of partonic degrees of freedom
- at zero baryon density → smooth crossover
- T_C = (156.5 ± 1.5) MeV [A Bazavov et al. Phys.Lett.B 795 (2019) 15]
- ε ~ O(GeV/fm^3)



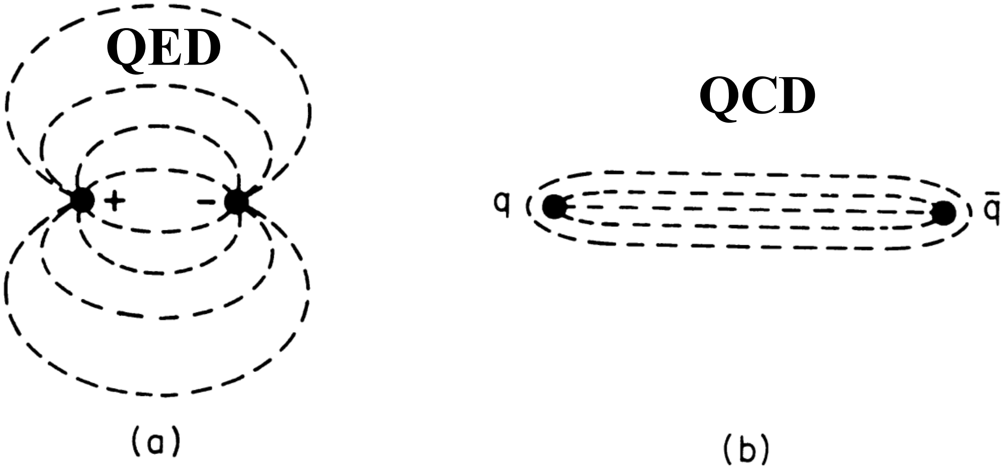
The QCD (de-)confinement phase transition



- origin of nucleon masses
  - $2\ m_u + m_d \sim 10$ MeV!
- phase transition in QFT
  - the only experimentally accessible one!
- Big Bang evolution
  - QGP ➔ hadrons at t ~ 10 μs
- structure of compact stars

- ... what about the physical mechanisms behind confinement?
- can we get an intuitive view of what happens in a confined system?
- can we get a feeling about the physical conditions for deconfinement?
- ... let’s try...
  (mostly following K Gottfried and V Weisskopf, “Concepts of Particle Physics”, Vol. II, Oxford University Press, 1986)

Confining potential in QCD



- unlike in QED, the QCD field lines are compressed into a “flux tube” (or “string”)
    - cross-section (~fm^2)
    - → long-distance potential which grows linearly with *r:*

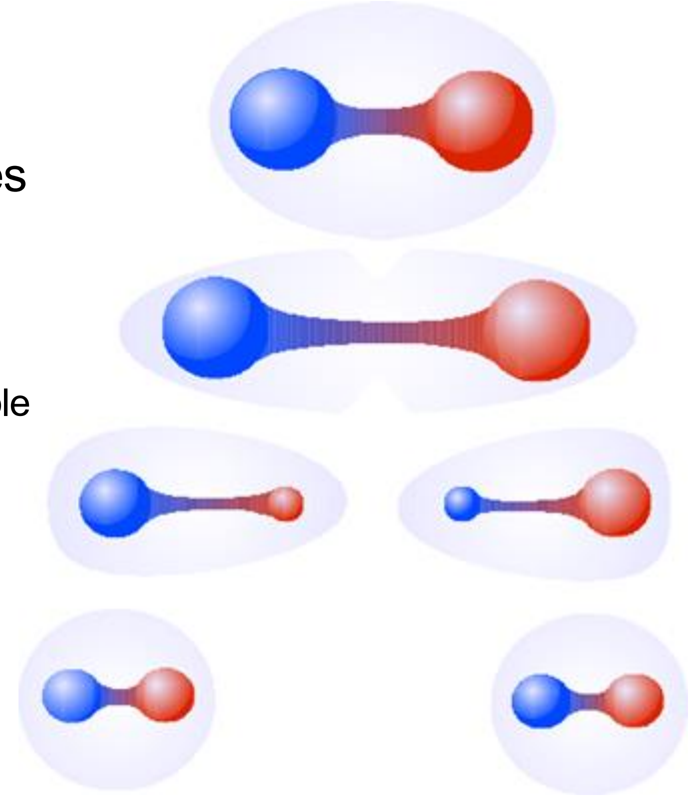
$$V \sim \kappa r \text{ with } \kappa \sim \text{GeV/fm}$$

    - → this leads to confinement

String potential

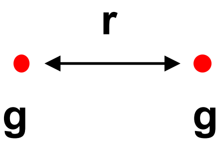
- pulling string apart → energy in string increases
  - V ~ κr
- string breaking point
  - creating a q-qbar pair becomes energetically favourable
  - → colour charge neutralised

→ one ends up with two colour neutral strings
  - ... and eventually hadrons



The QCD vacuum is far from trivial...

- e.g.: 2 gluons in singlet state at a distance r



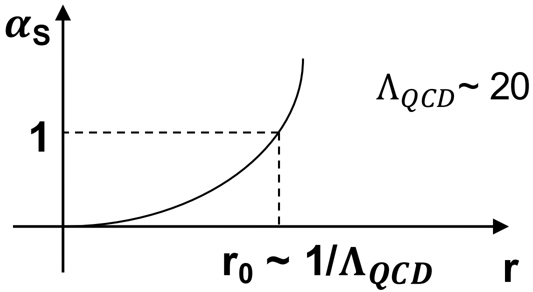
$$\Delta p \Delta r \sim \hbar = 1$$

$$r \sim \frac{1}{p} \sim \frac{1}{E_{KIN}} \quad \rightarrow \quad E_{KIN} \sim \frac{1}{r}$$

$$r \rightarrow 0 \qquad E \sim \frac{1}{r}$$

$$r \sim r_0 \qquad E <\sim 0$$

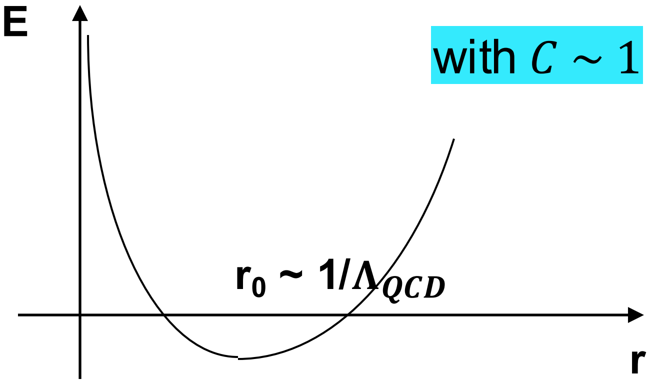
$$r \rightarrow \infty \qquad E \sim kr$$



Λ_{QCD}~ 200 MeV ~ 1 fm^{-1}

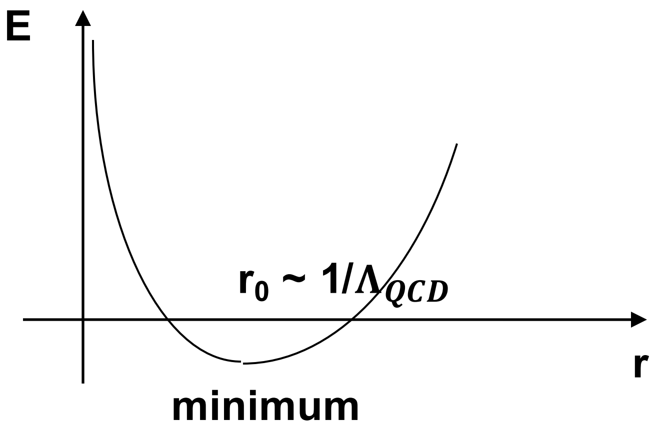
$$E = \frac{1}{r} - C\frac{\alpha_S}{r} = \frac{1 - C\alpha_S}{r}$$

with $C \sim 1$



minimum < 0 !

What just happened?



or, as Gottfried and Weisskopf put it:

"The 'empty' vacuum is unstable.
There is a state of lower energy that consists of cells, each containing a gluon pair in colour- and spin- singlet state.
The size of these cells is of order r_0.
We may speak of a "liquid" vacuum."

a state with

- two gluons in singlet configuration
- at a distance $r_0 \sim 1/\Lambda$

... is actually energetically favoured!

- over the "empty" vacuum

We can picture confinement as an effect of the pressure exerted by this liquid...

The MIT Bag Model

- the essential phenomenology of confinement is described as follows:
  - assume quarks are confined within bubbles (bags) of perturbative (=empty) vacuum
  - on which the QCD vacuum ("liquid") exerts a confining pressure *B (*= bag constant*)*
  - B ~ Λ_{QCD}^4 → hadron size ~ 1/ $\boldsymbol{\Lambda_{QCD}}$

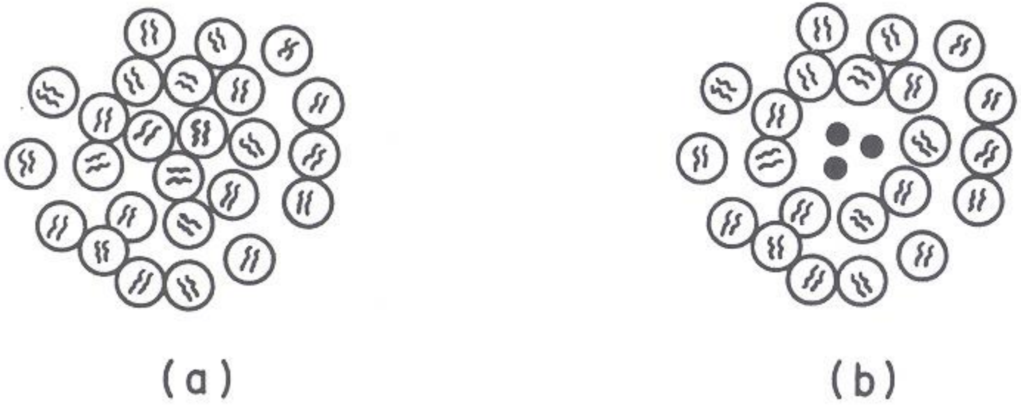
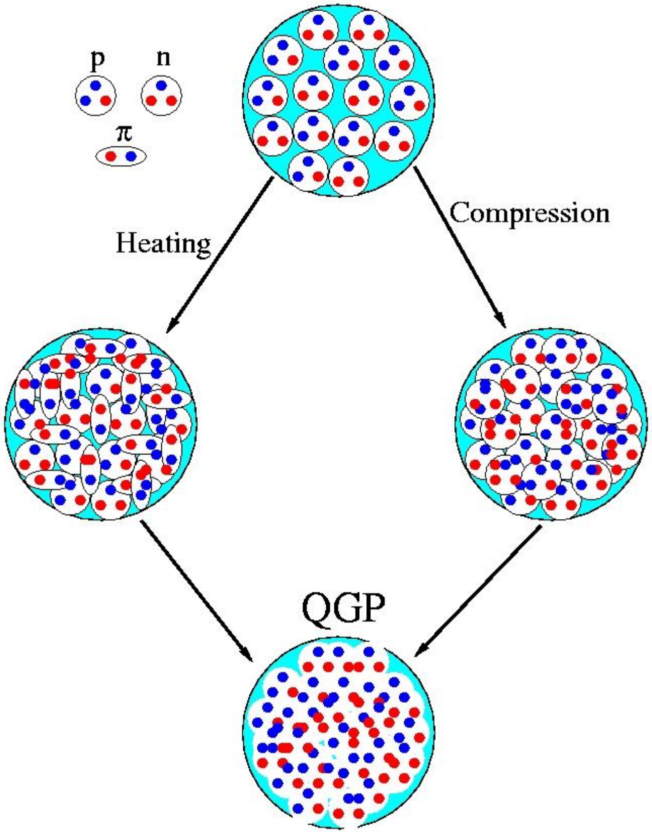


FIG. 9. The QCD vacuum state is depicted in (a). It is a random distribution of cells that contain a gluon pair in a color and spin singlet state. Quarks (in a color singlet configuration) displace these cells, creating a region (or "bag") of "empty" vacuum, as shown in (b).

(from: K Gottfried and V Weisskopf, "Concepts of Particle Physics", Vol. II, Oxford University Press, 1986)

Deconfinement: the bag viewpoint



- if a system of hadrons is brought to sufficiently large density and/or large temperature

→ deconfinement phase transition

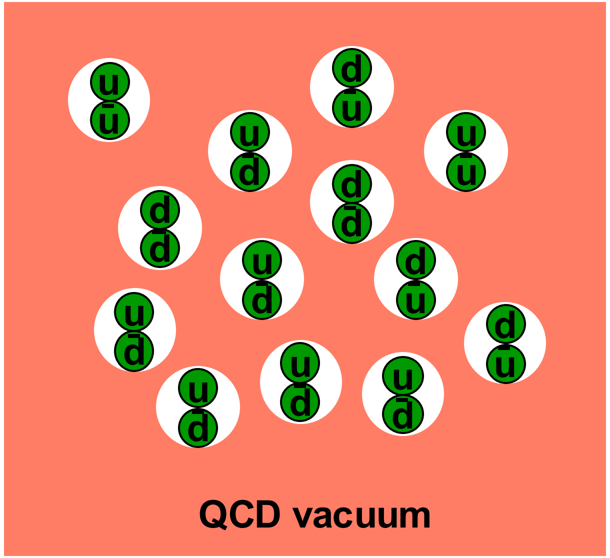
- in the deconfined phase the individual bags have coalesced into a single large bag of Quark-Gluon Plasma (QGP)

- quarks and gluons are now free to move around over a larger volume

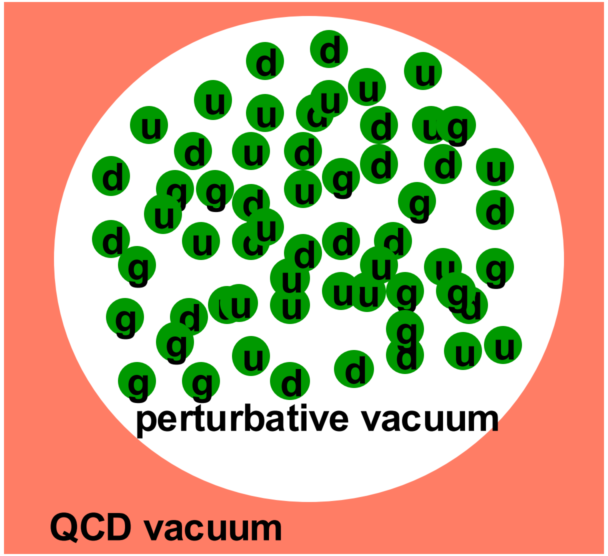
- can one get a quantitative estimate of T?

Deconfinement: a “toy model”

Hadron (pion) Gas



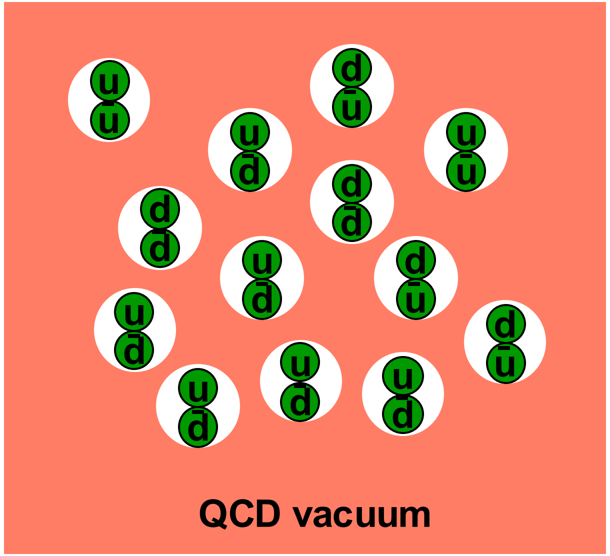
Quark-Gluon Plasma



- Gibbs’ criterion: the stable phase is the one with the largest pressure
- from statistical mechanics:
  (for an ideal gas)

$$p = \frac{\varepsilon}{3} = \left(g_B + \frac{7}{8} g_F \right) \frac{\pi^2 T^4}{90}$$

Hadron (pion) Gas



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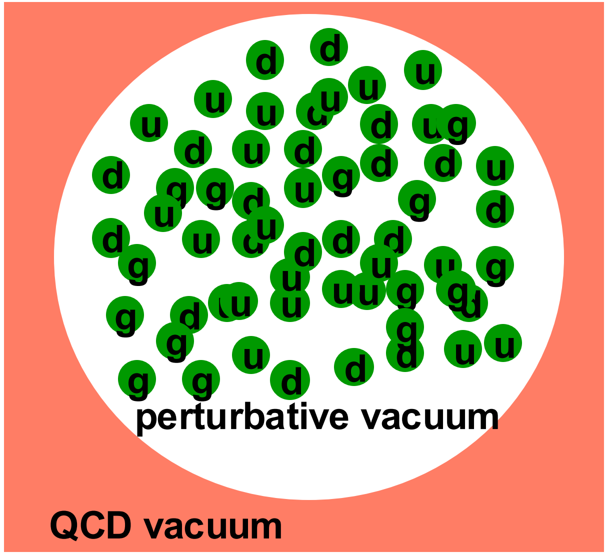


$$g_B = 3 \qquad g_F = 0$$

$$p = \frac{\varepsilon}{3} = \left(g_B + \frac{7}{8} g_F \right) \frac{\pi^2 T^4}{90}$$

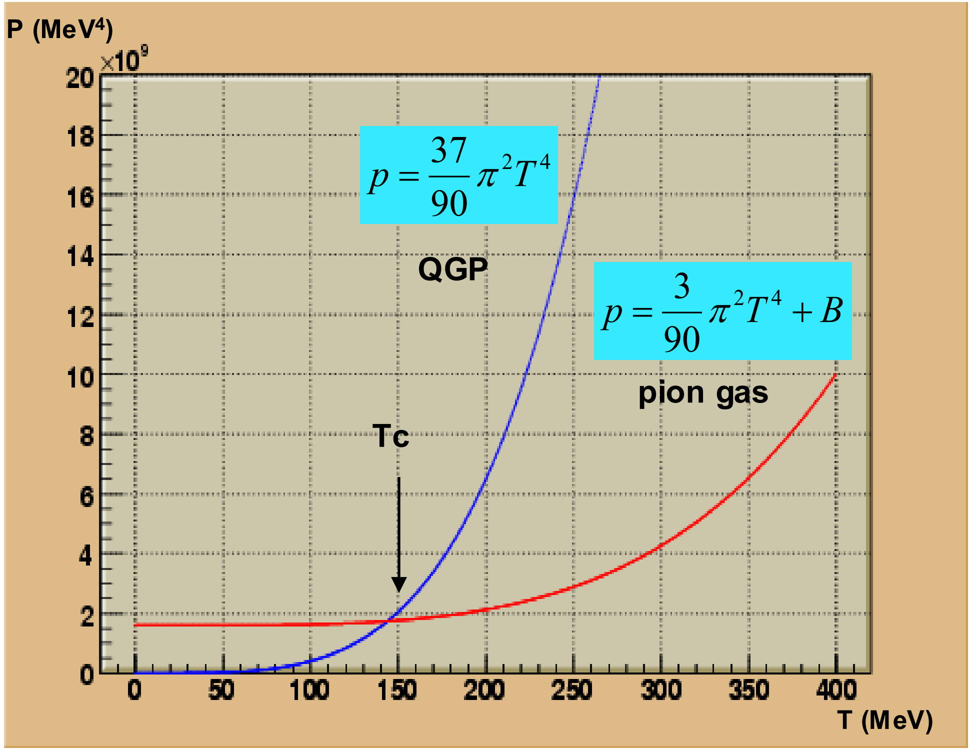
$$g_B = 16 \qquad g_F = 24$$

$$p = \frac{3}{90} \pi^2 T^4 + B$$

from hadron spectra:
$B \sim (200\ \mathrm{MeV})^4$

$$p = \frac{37}{90} \pi^2 T^4$$

- at low temperature the hadron gas is the stable phase
- but there is a temperature (T_C) above which the QGP "wins"
  - thanks to the larger number of degrees of freedom



one can easily derive:

$$T_C = \left[\frac{90}{34\pi^2}\right]^{1/4} B^{1/4}$$

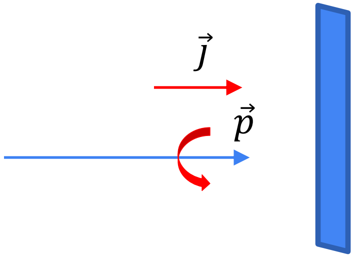
and plugging in $B^{1/4} \sim 200$ MeV
one gets:

$$T_C \sim 150 \text{ MeV}$$

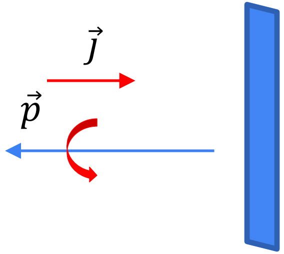
not too bad...
(latest lattice estimate: 156.5 $\pm$ 1.5 MeV)
[A Bazavov et al. Phys.Lett.B 795 (2019) 15]

Confinement, chiral symmetry and mass (an intuitive example)

- “chiral symmetry”: fermions and antifermions have opposite helicity
- exact only for massless fermions
    - travel at light speed → cannot be overtaken (overtaking would flip helicity...)
- now, take e.g. a left-handed, confined fermion
    - propagation is limited → at some point it will “hit a wall”...



    - ... and bounce back... reflection flips $\vec{p}$, but not $\vec{j}$!



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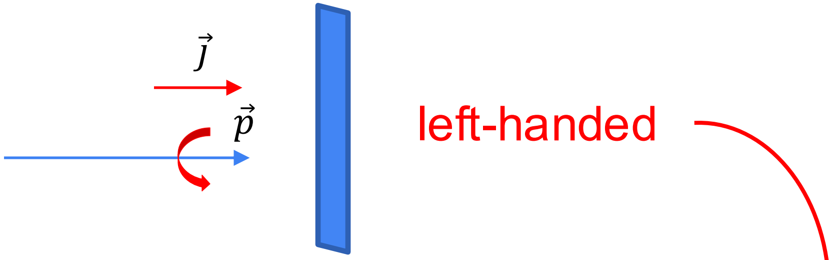

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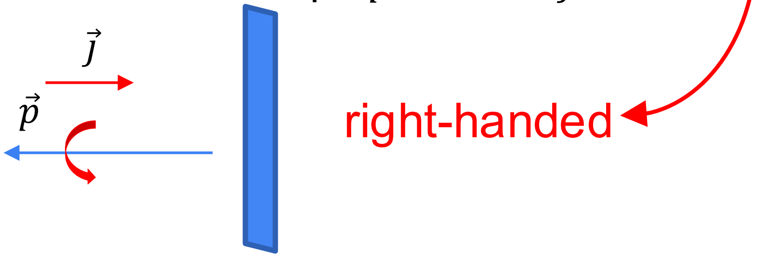

→ even (quasi-)massless fermions acquire an additional mass term when confined!

(Partial) chiral symmetry restoration

- confined quarks acquire additional mass (~ 350 MeV) dynamically
  - through the confining effect of strong interactions
  - e.g.: M(proton) $\approx$ 938 MeV; m(u)+m(u)+m(d) ~ 10 MeV
  - → ~ 99% of the mass of standard matter is generated by confinement!
    - only ~ 1% by Higgs mechanism!

- deconfinement expected to be accompanied by restoration of masses
  - → to the “bare” values of the Lagrangian
  - e.g.: m(s): ~ 500 MeV $\rightarrow$ ~ 150 MeV

- as we saw, symmetry can be exact only for massless particles:
  - → “partial” restoration of chiral (χ) symmetry