Quark-Gluon Plasma and Relativistic Heavy Ion Collisions

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High energy density physics
E.Teller, Ya.Zeldovich

REMINDER: WHAT'S A PLASMA?

- 4th state of matter (after solid, liquid and gas)
- a plasma is:
  - ionized gas which is macroscopically neutral
  - exhibits collective effects

- interactions among charges of multiple particles
  - spreads charge out into characteristic (Debye) length, l_D
  - multiple particles inside this length
  - "normal" plasmas are electromagnetic
  - quark-gluon plasma interacts via strong interaction
    - color forces rather than EM
    - exchanged particles: gluon instead of photon

classical electromagnetic plasma can be a good liquid too if sufficiently strongly coupled

$$\Gamma = Q^2 / dT$$

Coulomb coupling parameter

(T – plasma temperature, d – interparticle distance, Q – charge of plasma particles)

one-component plasma with pure Coulomb interaction this parameter corresponds to ratio of interaction energy to thermal energy per particle

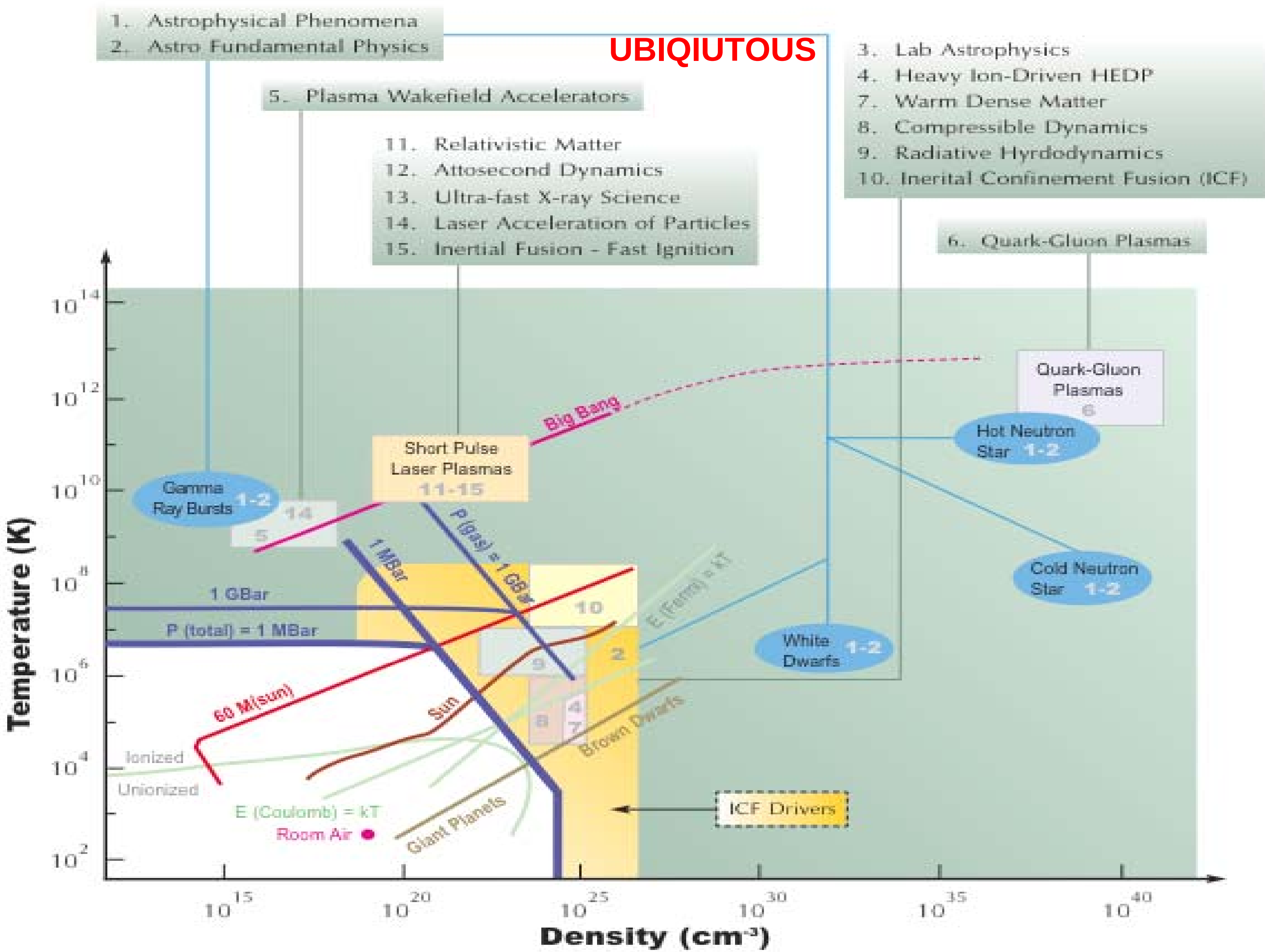
most plasmas in nature and laboratory are weakly coupled (could be a gas, liquid, and even solid phase)

$\Gamma > 1$ behaves like a liquid

$\Gamma > 172$ plasma particles are predicted to arrange in ordered structures (the plasma crystal) was discovered in dusty plasmas

in real plasmas
Coulomb interactions modified to Yukawa because of screening

Γ is not above ratio
additional parameter is of importance $\kappa = d / \lambda_D$
λ_D – Debye screening length, $\kappa \gg 1$ means plasma is weakly coupled
(Γ- κ)-plane defines the phase structure


UBIQIUTOUS
1. Astrophysical Phenomena
2. Astro Fundamental Physics
5. Plasma Wakefield Accelerators
11. Relativistic Matter
12. Attosecond Dynamics
13. Ultra-fast X-ray Science
14. Laser Acceleration of Particles
15. Inertial Fusion - Fast Ignition
3. Lab Astrophysics
4. Heavy Ion-Driven HEDP
7. Warm Dense Matter
8. Compressible Dynamics
9. Radiative Hyrdodynamics
10. Inerital Confinement Fusion (ICF)
6. Quark-Gluon Plasmas
Quark-Gluon Plasmas 6
Hot Neutron Star 1-2
Cold Neutron Star 1-2
White Dwarfs 1-2
Gamma Ray Bursts 1-2
Short Pulse Laser Plasmas 11-15
Big Bang
P (gas) = 1 GBar
1 MBar
1 GBar
P (total) = 1 MBar
E (Fermi) = kT
60 M(sun)
Sun
Brown Dwarfs
Giant Planets
Ionized
Unionized
E (Coulomb) = kT
Room Air
ICF Drivers
Temperature (K)
Density (cm⁻³)

Multiparticle Production at High Energies
Statistical approach

E. Fermi, 1950

$V_n = (\gamma V_0)^{n-1}$, $V_0 = (4/3)\pi(1/m_\pi)^3$

γ - Lorentz factor, m_π – π-meson mass

proposed strong interaction leading to equilibration: <n>~ $s^{1/4}$

I. Pomeranchuk, 1951

$V_n = (n\gamma V_0)^{n-1}$ introduced freezeout

L. Landau, 1953

explained that one should use hydro
in between, saving the Fermi's prediction
via entropy conservation

R. Hagedorn, 1965

$\rho(m) \sim m^{-a} \exp(bm)$, $b=1/T_0$, $T_0 \sim m\pi$

T_0 - ultimate temperature

K. Huang, S. Weinberg, 1971

Fourth law of thermodynamics,
ultimate temperature

Space-Time Picture:

Early work on energy densities:

Shuryak 1974

Zinovjev et al 1974

Ansiehtty et. al. 1980

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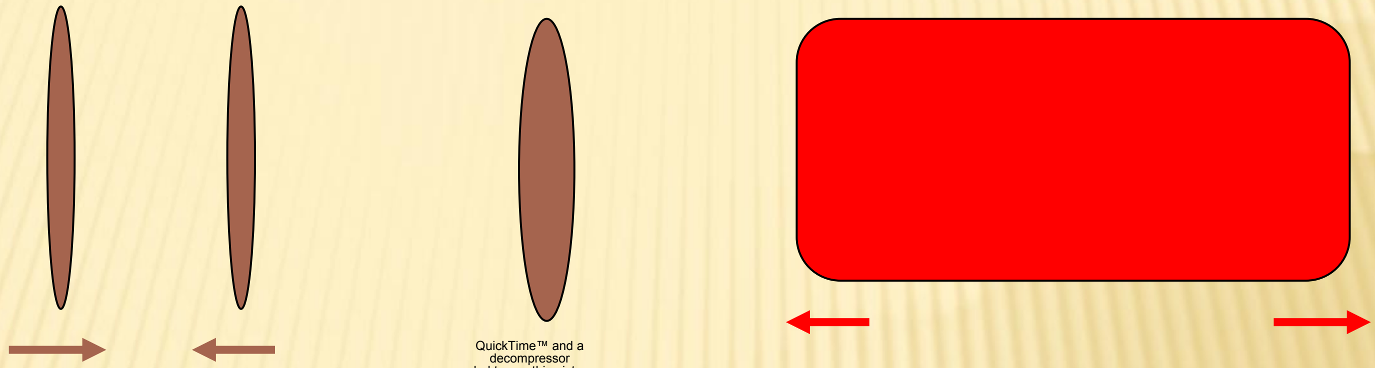

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Landau Hydrodynamics

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Colliding Nuclei

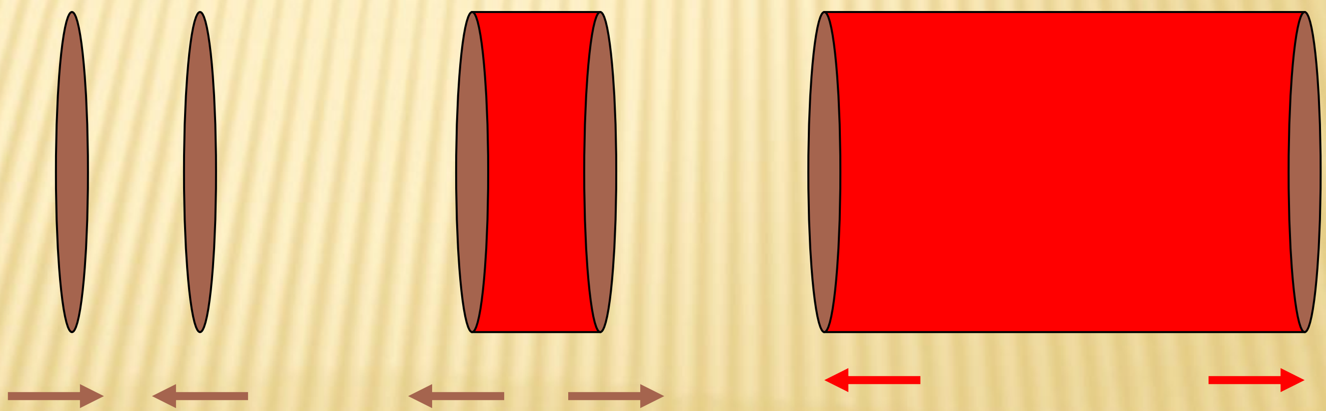
Collision

Expanding Fireball

Landau

Feynman

Bjorken



Longitudinal flow

Bjorken Hydrodynamics

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- hadrons have an intrinsic size with a radius $r_h \simeq 1\,\mathrm{fm}$ and hence a hadron needs a space of volume $V_h \simeq (4\pi/3) r_h^3$ in order to exist, it suggests a limiting density $n_c = 1/V_h \simeq 24\,\mathrm{fm}^{-3}$ of hadronic matter , beyond this point hadrons overlap more and more, so that eventually they cannot be identified any more.

- hadronic interactions provide abundant resonance production, and the resulting number $\rho(m)$ of hadron species increases exponentially as function of the resonance mass *m*, $\rho(m) \simeq \exp(b\,m)$ such a form for $\rho(m)$ appeared first in statistical bootstrap model based on self-similar resonance formation or decay , then also obtained in more dynamical dual resonance approach which specifies the scattering matrix through its pole structure . In hadron thermodynamics the exponential increase of the resonance degeneracy is found to result in an upper limit for the temperature of hadronic matter,

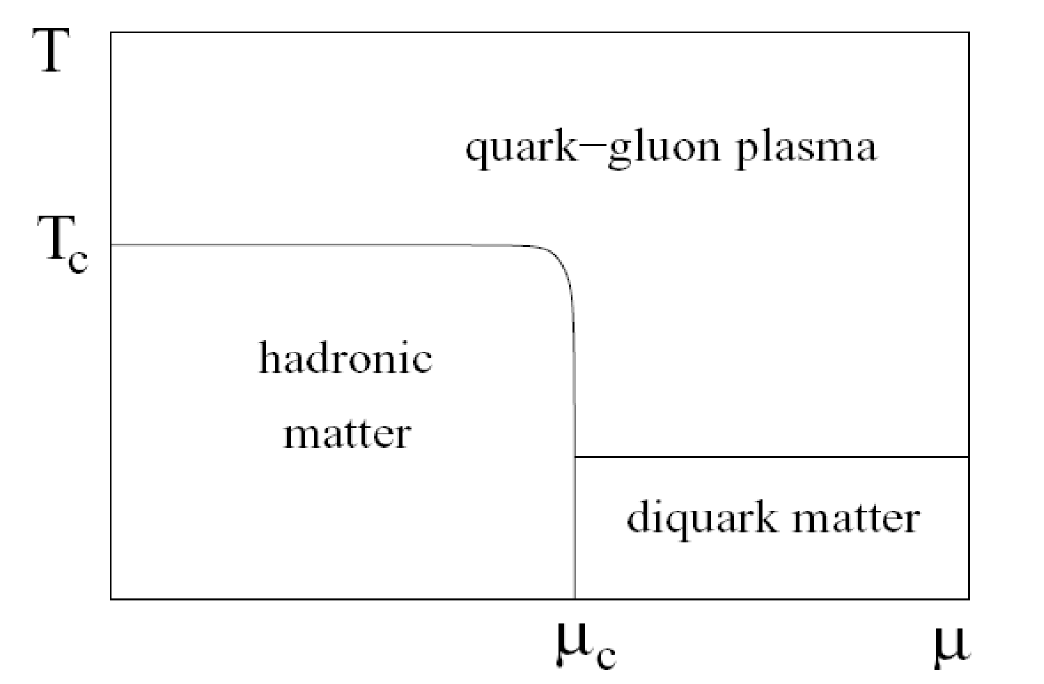
$$T_c = 1/b \simeq 150 - 200\,\mathrm{MeV}\,.$$

- What happens beyond T_c ? If hadrons are dimensionful bound states of more basic point-like entities hadronic matter consisting of these point-like constituents can therefore turn at high temperatures and/or densities into a plasma of the point-like constituents. This deconfining transition leads to a conducting (colour, for example) state and thus is the counterpart similar to the insulator-conductor transition in atomic matter.

Further transition phenomenon also expected from the behavior of atomic matter is a shift in the effective constituent mass. At T=0 in vacuum quarks dress themselves with gluons to form the constituent quarks that make up hadrons. As a result, the bare quark mass is replaced by a constituent quark mass M_q~300 MeV and in a hot medium this dressing melts and $M_q \neq m_q$. Since the QCD Lagrangian for m_q=0 is chirally symmetric $M_q \neq 0$ should imply spontaneous chiral symmetry breaking. The melting $M_q \to 0$ thus corresponds to chiral symmetry restoration. We shall see later on that in QCD, as in atomic physics, the shift of the constituent mass coincides with the onset of conductivity.

- **So far, the "heating" of systems of low or vanishing baryon number density. The compression of baryonic matter at low temperature could result in another type of transition. This would set in if an attractive interaction between quarks in the deconfined baryon-rich phase results in the formation of colored bosonic diquark pairs, the counterpart of Cooper pairs in QCD. At sufficiently low temperature, these diquarks can then condense to form a color superconductor. Heating will dissociate the diquark pairs and turn the color superconductor into a normal color conductor.**
- **For a medium of quarks with color and flavor degrees of freedom, the diquark state can in fact consist of phases of different quantum number structures. It should be also noticed that for increasing baryon density the transition at low *T* could lead to an intermediate "quarkyonic" state in which baryons dissolve into quarks but mesons remain as confined states what is another interesting aspect of possible consistent theory.**

Using baryochemical potential μ as a measure for baryon density of system (i.e. for total number of baryons minus that of antibaryons per unit volume) we then expect the phase diagram of theory to have the general schematic form as shown. Given QCD as the fundamental theory of strong interactions we could use the QCD Lagrangian as dynamics input to derive the resulting thermodynamics of strongly interacting matter. For vanishing baryochemical potential μ=0 this can be evaluated with the lattice regularization.



Before turning to study QCD let us illustrate the transition from hadronic matter to quark-gluon plasma by very simple model. For ideal gas of massless pions, the pressure as function of the temperature is given by the Stefan-Boltzmann form

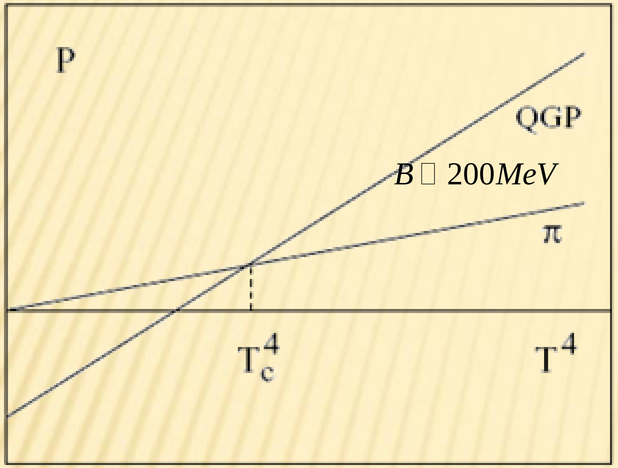
$$P_\pi = 3\frac{\pi^2}{90}T^4$$

where factor 3 accounts for three charge states of the pion. The corresponding form for an ideal quark-gluon plasma with two flavors and three colors is

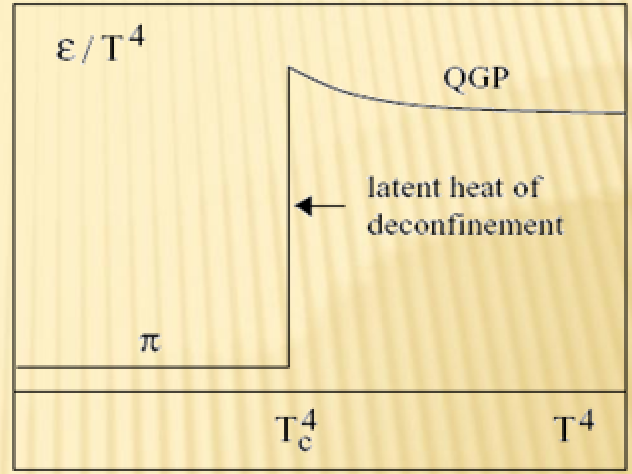
$$P_{qg} = \{2\times 8 + \frac{7}{8}(3\times 2\times 2\times 2)\}\frac{\pi^2}{90}T^4 - B = 37\frac{\pi^2}{90}T^4 - B.$$

First term in curly brackets accounts for two spin and eight color degrees of freedom of gluons, the second for three color, two flavor, two spin and two particle-antiparticle degrees of freedom of quarks with 7/8 to obtain the correct statistics. Bag pressure *B* takes into account the (non-perturbative) difference between physical vacuum and ground state for colored quarks and gluons.

Since in thermodynamics a system chooses state of the lowest free energy and hence highest pressure compare the temperature behavior of both definitions.



(a)



(b)

This simple model thus leads to two-phase picture of strongly interacting matter with a hadronic phase up to the temperature

$$T_c = \left(\frac{45}{17\pi^2} \right)^{1/4} B^{1/4} \simeq 0.72\, B^{1/4}$$

and a quark- gluon plasma above this critical temperature. From hadron spectroscopy the bag pressure is given by $B \simeq 200 MeV$ **so that** $T_c \simeq 150$ MeV **as the deconfinement temperature.**

simple estimate remarkably close to the value obtained in lattice

QCD

The energy densities of two phases of this model are given by

$$\varepsilon_\pi = \frac{\pi^2}{10} T^4 \quad \text{and} \quad \varepsilon_{qg} = 37\frac{\pi^2}{30} T^4 + B.$$

By construction the transition is first order and the resulting temperature dependence is as shown . At T_c the energy density increases abruptly by the latent heat of deconfinement $\Delta\varepsilon$, its value is found to be

$$\Delta\varepsilon = \varepsilon_{qg}(T_c) - \varepsilon_\pi(T_c) = 4B,$$

so that it is determined completely by bag pressure measuring level difference between physical and colored vacua.

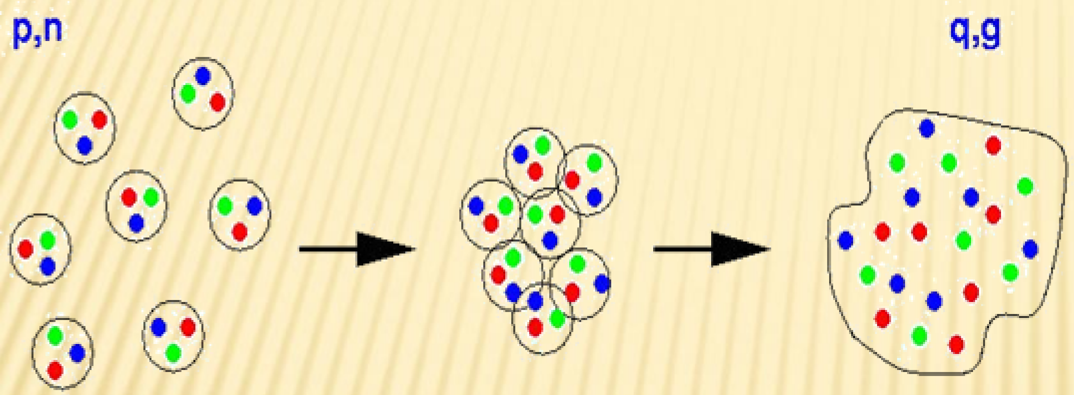
For an ideal gas of massless constituents the trace of energy-momentum tensor quite generally vanishes. Nevertheless, in this model of ideal plasma of massless quarks and gluons for $T \geq T_c$ have

$$\varepsilon - 3P = 4B,$$

again specified by bag pressure and not zero. It is related to the so-called trace anomaly and indicates the dynamical generation of a dimensional scale; shall return to it and will find that this scale is set by vacuum expectation value of the gluon condensate.

TAKE A DEEP BREATH ....

- What did we expect for QGP?



weakly interacting gas of quarks & gluons

- What SHOULD we expect?

quarks & gluons retain correlations,
medium exhibits liquid properties

NB: the (quasi-)bound states are not your mother's hadrons!

- A skier (quark?) is confined inside snow patches (hadrons?)

Temperature

- the skier can move further…a new phase develops

.. goes up

- a skier (quark?) can move freely over long distances...

.. this way

in QGP the coupling parameter could be

Γ=2Cg^2/4π dT , C – Casimir invariant (C=4/3 for quarks, C=3 for gluons),
d~0.5 fm, T~200 MeV

take the coupling constant g~2 and 2 in the numerator comes from taking into account the magnetic interaction to addition to the static electric (Coulomb) interaction (the same magnitude supposed)
Γ~1,5÷5

QGP in heavy ion collisions is a liquid rather than a gas

RHIC supports this crude estimate

Does QCD show smthg similar?

microscopic picture of phase transitions and QCD vacuum structure
estimate of possible phenomena basing on instanton liquid model

A. Polyakov, G ’t Hooft
C. Callan, D. Dashen, D. Gross

collective phenomena observed at RHIC
described by hydro allows to view QGP as a near perfect liquid

new idea: QGP at RHIC temperatures

$$T = (1 \div 2) T_c$$

seems to be in a strongly coupled regime
sQGP

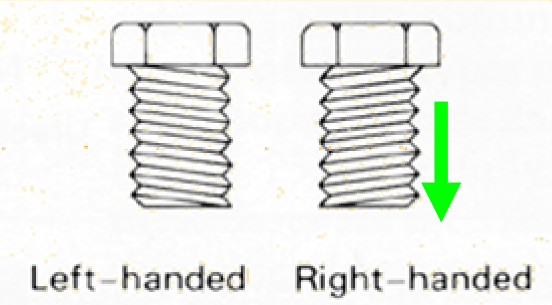
lattice QCD teaches: albeit quarks are deconfined at $T > T_c$ they can't get
separated, J/Ψ remains bound till $T \sim 1{,}2 T_c$

there are a lot of bound states and resonance
energy for separation of quarks close T_c is huge

**colour charges can't get separated until very high T and
perturbative methods are hopeless**

What is QCD?

It is a field theory describing an interaction of quarks and gluons with Lagrangian



$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_f \bar{q}^a_f (i\gamma_\mu D_\mu - m_f) q^a_f;$$

$$D_\mu = \partial_\mu - igA^a_\mu t^a$$

gluons

quarks

invariant at scale ($x \to \lambda x$) and chiral left $\leftrightarrow$ right transformations in limit of massless quarks

both symmetries are broken by quantum effects

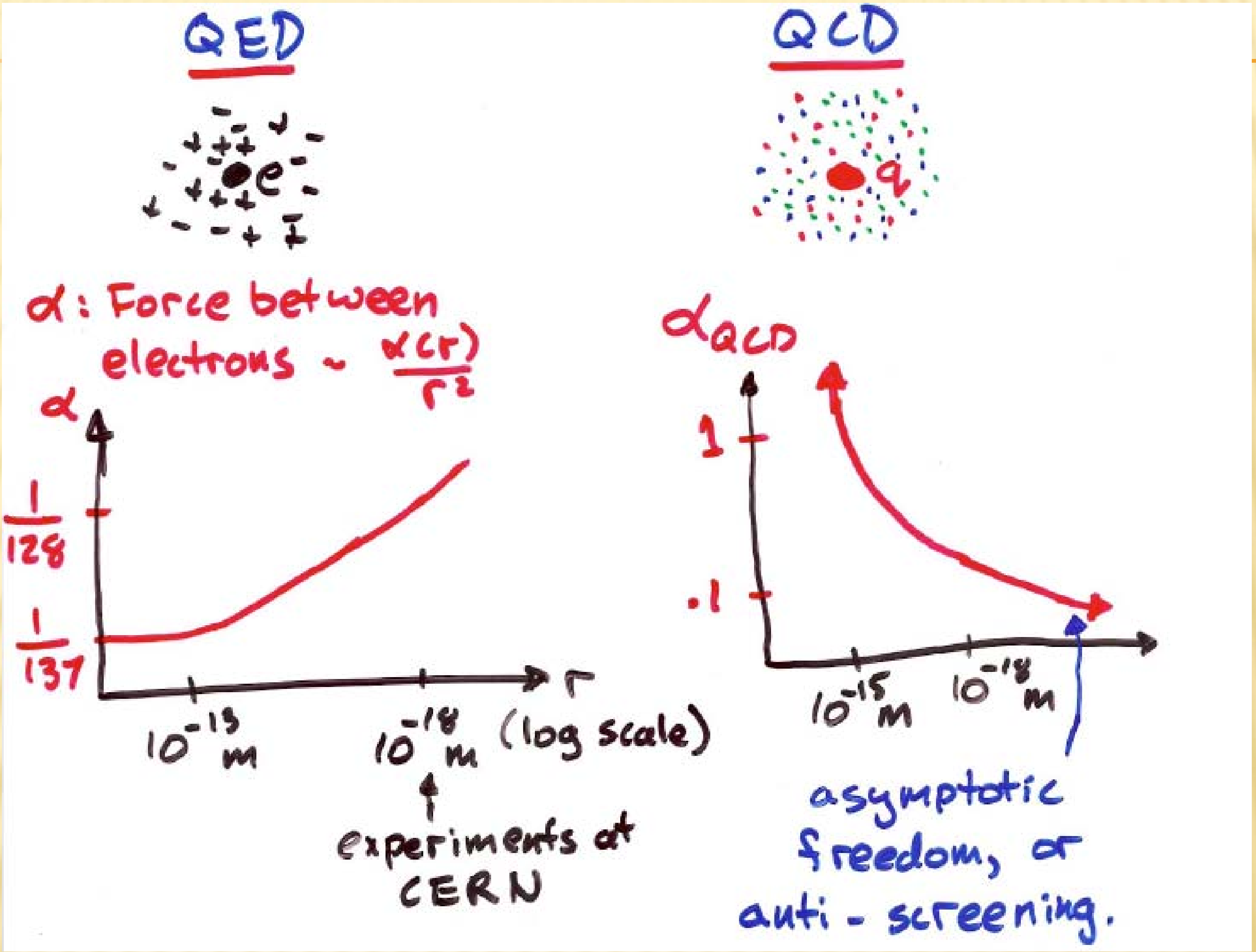
$$\partial^\mu s_\mu = \theta^\mu_\mu = m_f \bar{\psi}\psi_f + \boxed{\frac{\beta(g)}{2g} G^{\mu\nu a} G^a_{\mu\nu};}$$

$$\partial^\mu J_{\mu 5} = 2m_f i\bar{\psi}\gamma_5\psi_f - \boxed{\frac{N_f g^2}{16\pi^2} G^{\mu\nu a} \tilde{G}^a_{\mu\nu}}$$

not much different Lagrangians of QCD and QED which describes the electron-photon interactions

.i

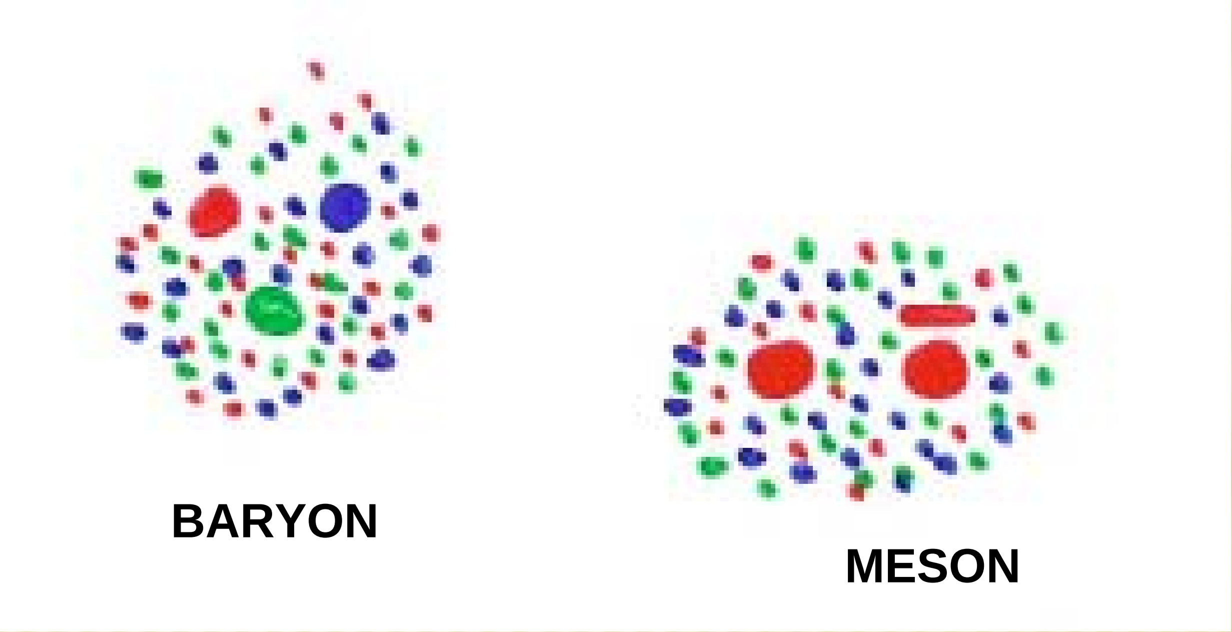
In quantum field theory the vacuum is a medium which can screen a charge



Coupling "constants" are not constant and depend on scale at which we probe quantum chromodynamics is different from quantum electrodynamics which is a theory of electrons and photons in presence of anti-screening and asymptotic freedom (Friedman,Kendall,and Taylor were able to see weakly interacting quarks because of this feature)

What does QCD describes?

Today it is an experimental fact that in the world around us quarks and gluons appear only in colorless heavy aggregates protons, neutrons, pions, kaons, ...



These hadrons are the quasi-particles of the QCD vacuum
They make up everything from nuclei to neutron stars and thus most of the mass of us

Why study QCD?

The only example we know of a strongly interacting gauge theory with quite understandable behavior at short distances (asymptotic freedom) at least .

Quasi-particles (vacuum excitations) which are hadrons do not look at all like the short distance quark and gluon degrees of freedom (deconfinement problem) and to study their properties and structure seems practical to get away from vacuum and understand other phase s of QCD and their quasi-particles.

At very high temperatures the QCD entropy wins over order and the symmetries of this phase should be those of the QCD Lagrangian and asymptotic freedom tells that we must have weakly coupled quark and gluon quasi-particles.

We knew always that at 1.5 -2 T_c quantum chromodynamics is not yet weakly coupled (there are strong long distance magnetic interactions).

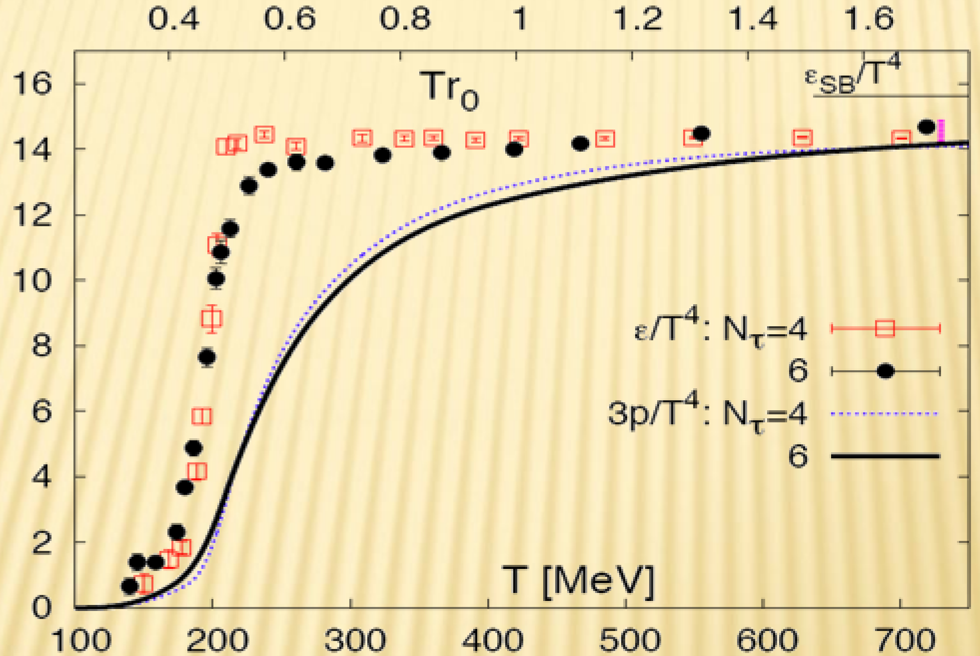
But lattice calculations demonstrated that above $2T_c$ thermodynamic quantities do not change more than 20%, there is a smooth crossover like ionization of a gas at T_c where hadrons “ionize” and the order characterizing the QCD vacuum melts.

It allows us to believe a quasi-particle picture everywhere above the critical temperature

Lattice Gauge Theory and Deconfinement:

L is similar to a spin variable
=> Confinement-
Deconfinement transition

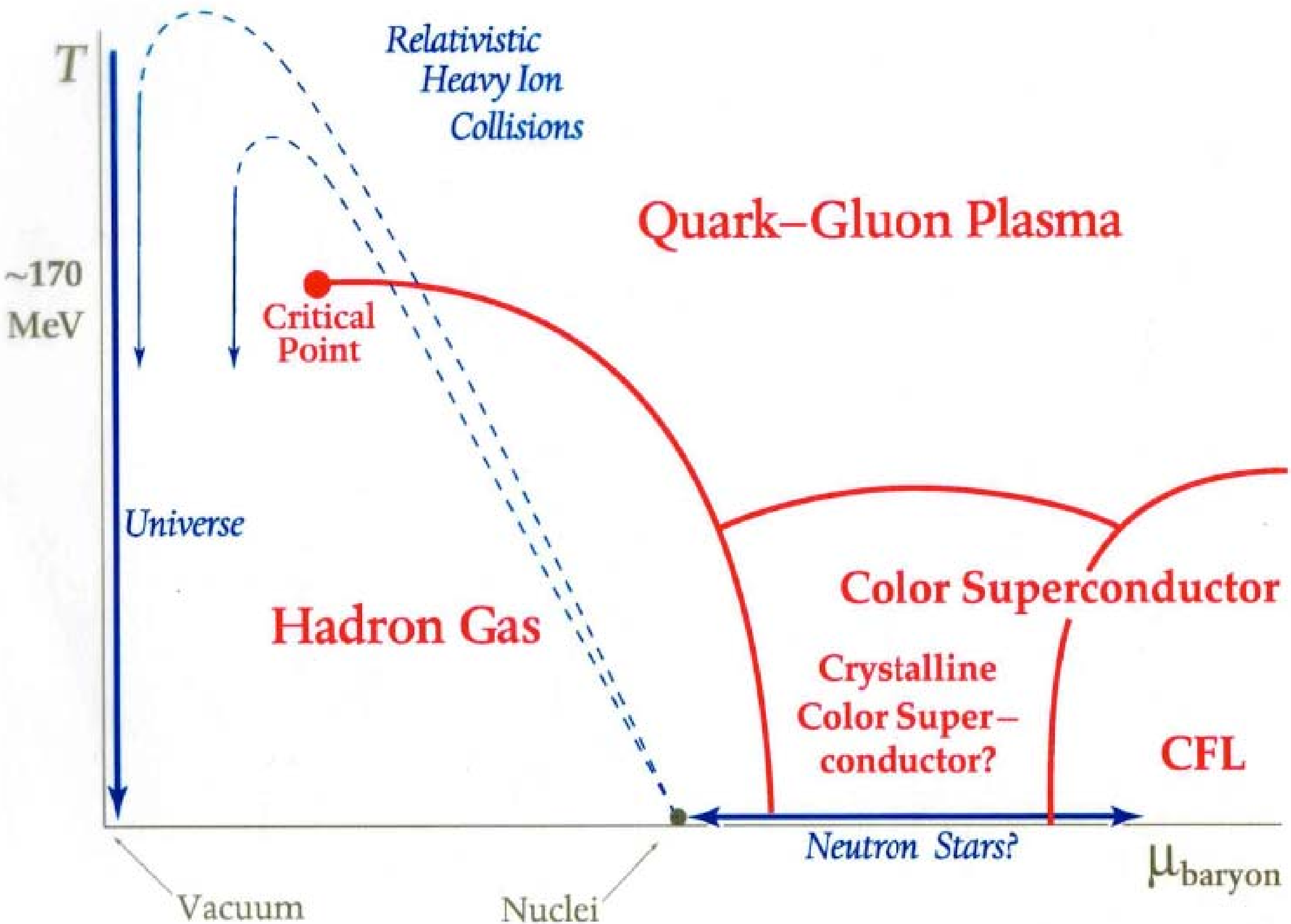
Polyakov 1978 Susskind 1979



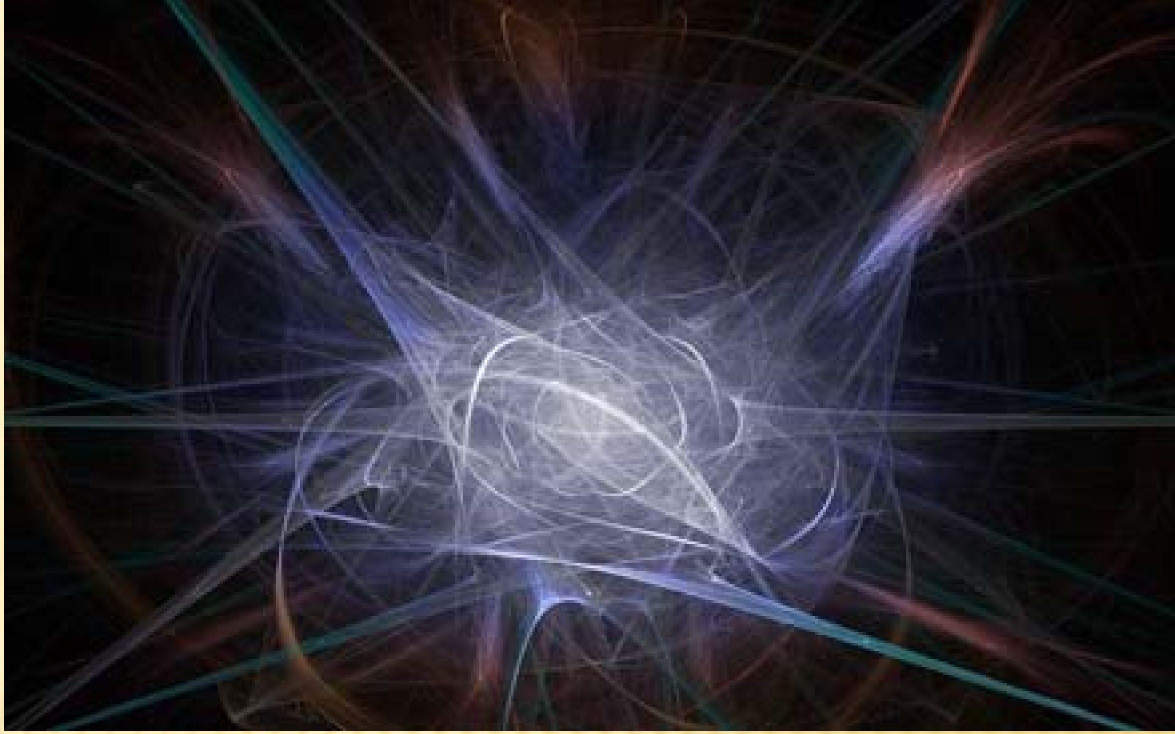
Wuppertal, Bielefeld,BNL, MILC, Mumbai …

First lattice computations at finite T; Kuti, Polonyi and Szlachanyi; McLerran and Svetitsky

EXPLORING *the* PHASES *of* QCD



T.D. Lee
Is our vacuum stable?



Vacuum is not true ground state: Tunneling

Could hadronic collisions make such a transition?

In this way one could temporarily restore broken symmetries of the physical vacuum and possibly create novel abnormal dense states of nuclear matter

T. D. Lee and G. C. Wick

Inflation of the universe from such transitions

Origins of Ultrarelativstic Heavy Ion Colisions:

Workshop on BeV Collisions of Heavy Ions: How and Why

Nov 29 - Dec 1 1974

Bear Mountain New York

Introduction and Summary:

The history of physics teaches us that profound revolutions arise from a gradual perception that certain observations can be accommodated only by radical departures from current thinking. The workshop addressed itself to the intriguing question of the possible existence of a nuclear world quite different from the one we have learned to accept as familiar and stable.

Leon Lederman and Joseph Weneser

It would be interesting to explore new phenomena by distributing high energy or high nuclear density over a relatively large volume.

T. D. Lee

Herodotus says,

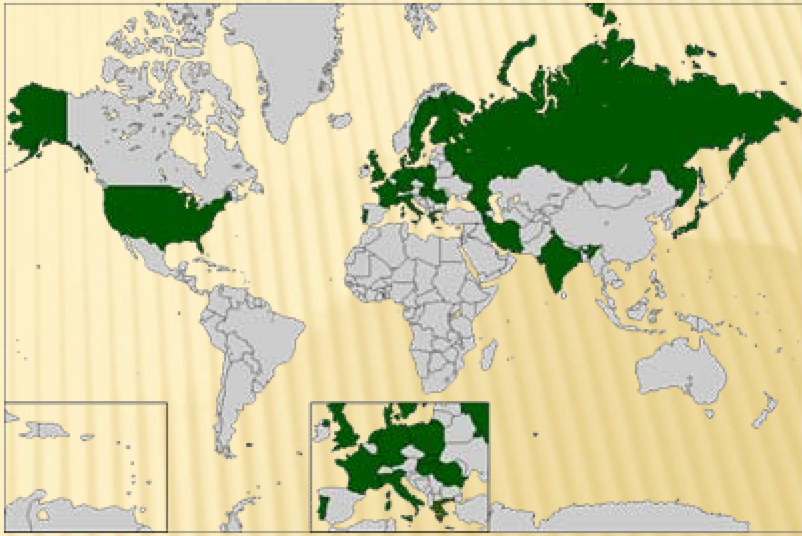
“Very few things happen at the right time...”

AGS-RHIC

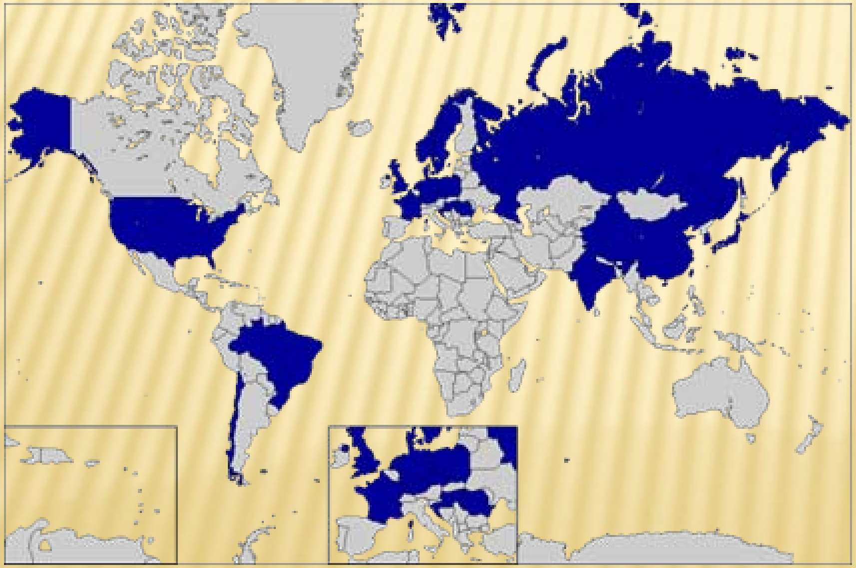
SPS-LHC

From the Bevelac to the LHC:

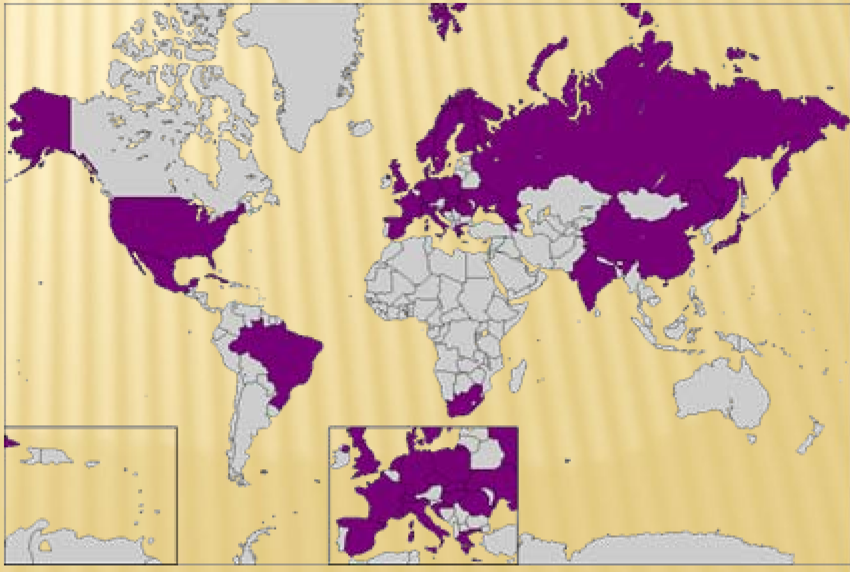
AGS



SPS



RHIC



Heavy Ions at LHC

Even a fully successful and quantitative model of heavy ion collisions will be of limited value to the broad scientific community if it does not bring us closer to answering the fundamental physics questions, such as:

What is the mechanism of confinement?
What is the origin of chiral symmetry breaking?
What is the origin of mass?