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Quark-Gluon Plasma And Relativistic Ion Collisions

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November 1984

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U.S. Department of Energy

USDOE Office of Science (SC)

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RHIC-PH-6

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AND
RELATIVISTIC ION COLLISIONS

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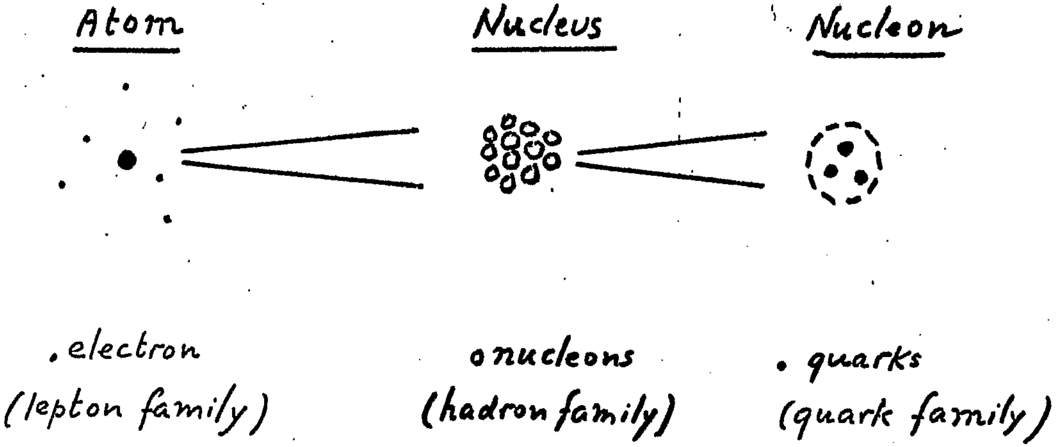
A labwide lecture and two seminars
at Brookhaven National Laboratory
(November 1984)



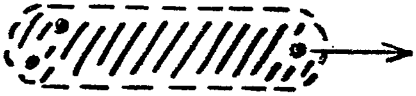
Strong interaction: [acts on quarks,
is mediated by gluons.

Electro-weak interactions: [act on quarks and leptons,
are mediated by photons and weak bosons. $(W^{\pm}, Z^{0})$

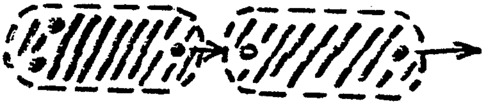
Leptons, photons, weak bosons, hadrons can exist as isolated particles.
Quarks and gluons don't (confinement property).

Confinement - Hadronization

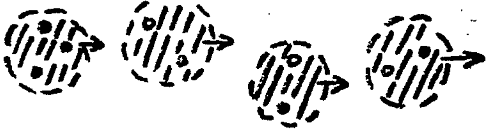
//////// Colour electric field



QCD flux tube (also called string).

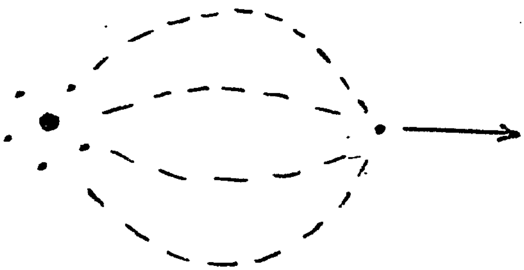


Hadronization by $q\bar{q}$ pair creation.



String tension ~ 1 GeV/fm

For comparison, "liberation" of electron:



Electric field

Theoretical prediction of a new state of matter, the "QUARK-GLUON PLASMA" (also called "quark matter").

- Constitution of hadronic matter according to QUANTUM CHROMODYNAMICS (QCD), a non-abelian gauge theory based on SU_3 (colour qu.nbs)

  [Spinor fields → QUARKS, SU_3 triplets, 5 (6?) "flavours"

  [gauge fields → GLUONS, SU_3 octets, no further int.^{e} qu.nb.

- CONFINEMENT property: hadronic systems in vacuum form SU_3 singlets ("colourless")

  Examples: baryon $= (qqq)_{singlet}$, meson $= (q\bar{q})_{singlet}$;

where $q, \bar{q}$ may be "dressed" by a "sea" of $q\bar{q}$ pairs and gluons.

- nucleus is also SU_3 singlet, containing 3A quarks and perhaps more ($q\bar{q}$ pairs).
- $q, \bar{q}$ distribution in nuclei is not the one in nucleons folded with Fermi distribution (EMC effect)

- At low density, hadronic matter forms HADRON GAS.

- Single hadrons occupy finite volume, $\gtrsim 1\,fm^3$.

- What about very dense hadronic matter as must occur

  i) when nuclear matter is highly compressed (dense stellar objects)

  ii) at high temperature, high density of hadrons being created by thermal agitation (early Universe).

Hadrons must then coalesce into a dense, continuous fluid of q's, $\bar{q}$'s and gluons, the QUARK-GLUON PLASMA.

i) Compress nuclear matter by factor 20:
Quark density $\sim 20 \times 3 \times 0.17 \text{ fm}^{-3} \sim 10 \text{ fm}^{-3}$

ii) Heat matter to $T \sim 500$ MeV $\sim 6 \times 10^{12}$ K:
An ideal pion gas would have ~ 6 pions / fm^3, i.e., a $q + \bar{q}$ density $\sim 12 \text{ fm}^{-3}$

Under such conditions, existence of Quark-Gluon Plasma seems inescapable.

- Can this new state of matter be produced on earth? Perhaps in ultrarelativistic nuclear collisions

- 3 classes of problems, all affected by large uncertainties:
  - i) Expected properties of QGP and of QGP → HG transition (HG = Hadron Gas).
  - ii) Compression and heating in nuclear collisions.
  - iii) Signals for QGP formation in " " .

- Much theoretical work, great quantitative uncertainties.
- Severe lack of data hampers work; experimental programmes to start soon at Brookhaven (15 GeV/nucleon up to ^{32}S) and CERN (225 GeV/nucleon up to ^{16}O).
- Impossibility to measure "colour conductivity".

RHIC: colliding beams up to gold (^{197}Au) up to 100 GeV/nucleon.
(RHIC = Relativistic Heavy Ion Collider)

. Quark-gluon plasma (QGP) and hadronic phase transition

One expects 2 phase transitions, but they may coincide:

[**Deconfinement transition**: QGP $\longleftrightarrow$ HG (hadron gas)
[**Chiral transition**: restoration of chiral symmetry (from $<\psi_q \bar{\psi}_q> \neq 0$ to $<\psi_q \bar{\psi}_q> = 0$)

Theoretical work follows 2 approaches:

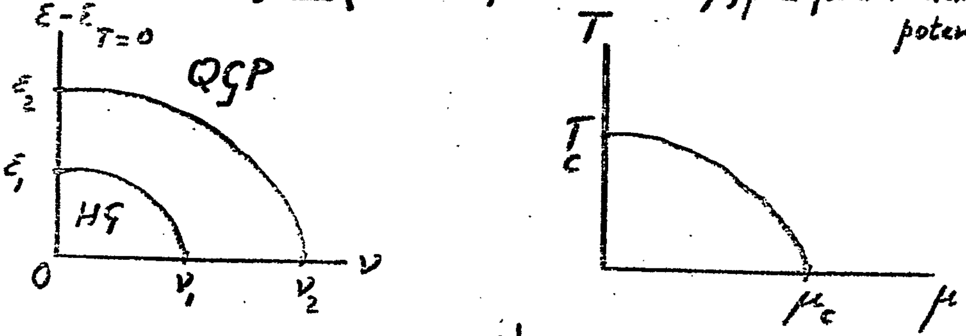
Continuum approach:

- describe HG from hadron phenomenology
- " QGP by ideal gas with perturbative and "plasmon corrections" based on QCD. (complexity of collective effects!)

Lattice approach: thermodynamics of QCD in lattice approximation by Monte Carlo integration.

- Pure SU_3 gauge field (self-interacting gluons): First order phase transition, large latent heat - ($\varepsilon_{QGP} \gg \varepsilon_{HG}$ at transition, ε = energy density)
- Full QCD with quarks $\Big\{$ nature of transition unclear, but large variation of ε for small variation of T, μ.

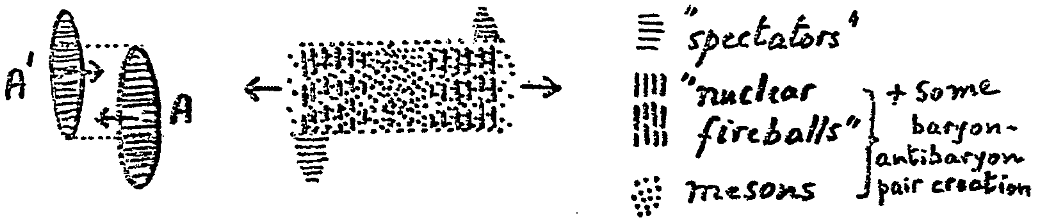
Possible phase diagram (ν = net quark density, μ = quark chemical potential)



perhaps $\begin{cases} \varepsilon_2 \sim 2\varepsilon_1 \sim \text{a few GeV fm}^{-3} \\ \nu_2 \sim 2\nu_1 \sim \text{a few fm}^{-3} \end{cases}$ | perhaps $\begin{cases} T_c \sim 150-300 \text{ MeV} \\ \mu_c \sim 400-800 \text{ MeV} \end{cases}$

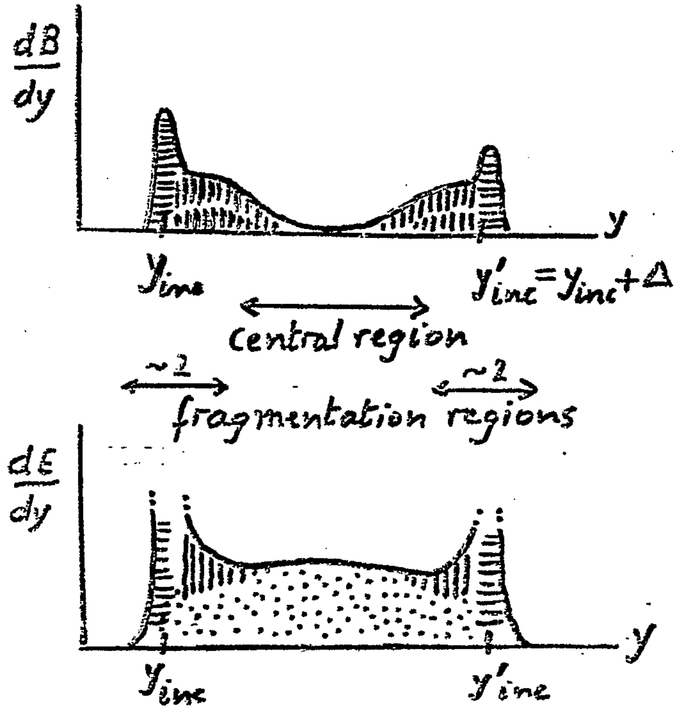
(1 MeV $= 1.16 \times 10^{10}$ K)

Ultrarelativistic nuclear collisions.



Longitudinal rapidity: $y = \mathrm{arcth}\, v_{long.}$

Net baryon number: B



$\left(\begin{array}{l} \Delta = 6 \text{ for} \\ E_{lab} = 200\, GeV/N \end{array} \right)$

dE: comoving energy of particles in $(y, y+\Delta y)$

Fragmentation regions: compression gives $\nu \sim 2\nu_0 \sim 1\, fm^{-3}$, $\varepsilon \sim 1\, GeV\, fm^{-3}$ (maximum at $E_{lab} \sim 15-20\, GeV/_N$?)

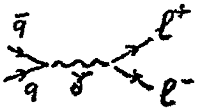
Central region: perhaps $\varepsilon \gtrsim 2\, GeV\, fm^{-3}$ at $E_{lab} \gtrsim 200\, GeV/_N$ (keeps growing with energy)

But: FLUCTUATIONS can help!

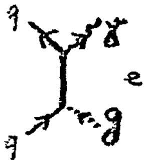
Signals for plasma formation.

"Traditional" signals:

- direct e^+e^- and $\mu^+\mu^-$ pair production

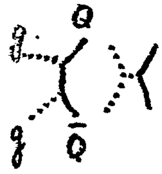


- direct photon production:



to be calculated in plasma as fct of T and ν, space-time distribution of T, ν needed, production in absence of plasma poorly known.

- production of heavy quark flavours (strange particles, charmed particles too heavy?):



not in equilibrium in plasma, mainly produced in hot plasma, probably more abundant than without plasma (production by gluons mainly).

Signals of phase transition with large latent heat:

If plasma formation is common

- $\langle p_t \rangle$-multiplicity correlation (observed in central region for pp at $E_{cm} \sim 50$-60 GeV, $\bar{p}p$ at $E_{cm} \sim 540$ GeV):

Characteristic of thermal behaviour:

[$\langle p_t \rangle$ grows with temperature T and pressure p,
multiplicity grows with entropy.

But phase transition with large latent heat gives large increase of entropy without increase of T, p.

This might show as an anomaly in $\langle p_t \rangle$-mult. curve.

If pl. form. is exceptional.

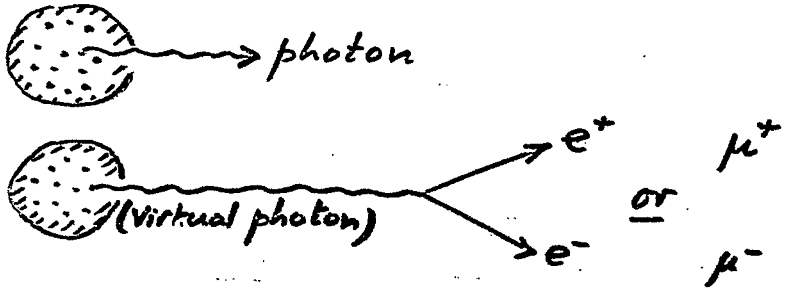
- multi-hadron fluctuations caused by instabilities in release of latent heat by plasma (plasma deflagration) QGP $\overset{+}{\underset{-}{\Big|}}$ HG $\rightarrow$

Shock front

Cosmic ray evidence?

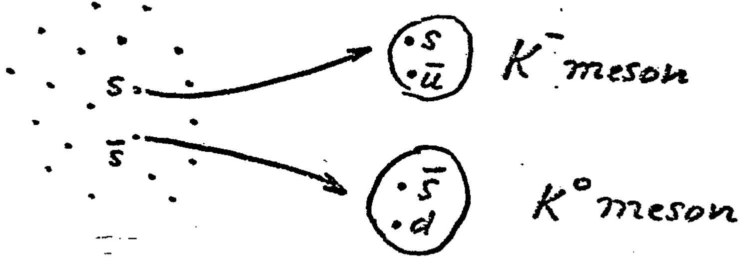
Signals for plasma formation (in pictures)

i) electromagnetic radiation emitted by plasma

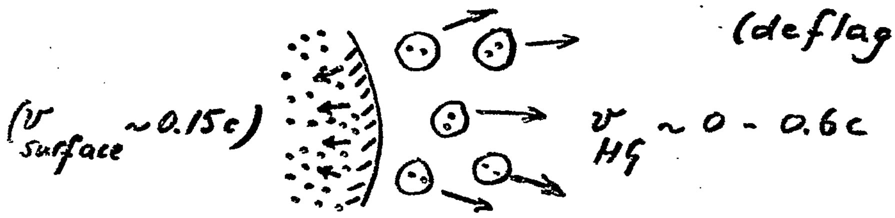


(escapes with negligible absorption)

ii) strange quark pairs formed in plasma, emitted as strange hadrons



iii) sudden liberation of latent heat at transition (deflagration)



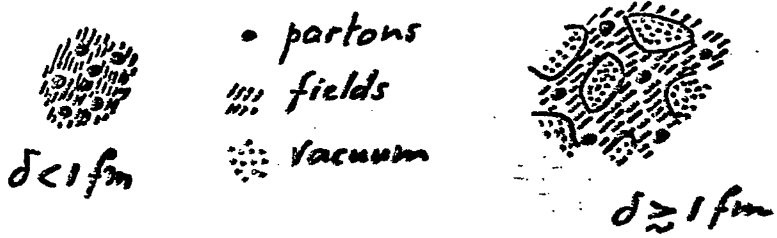
Plasma ⟶ Hadrons

high energy contents → high transverse motion

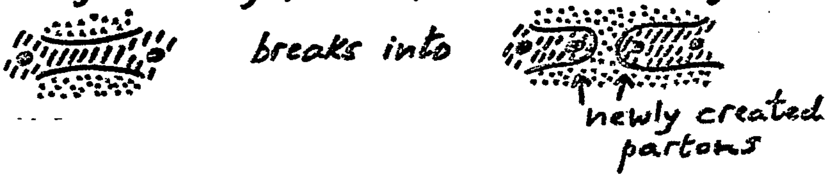
" entropy " → " multiplicity

Proposed Scenario for Hadronization of expanding droplet of QG Plasma

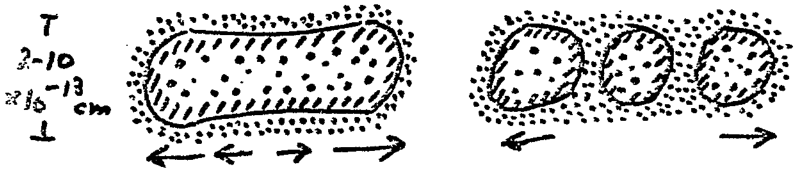
- δ : nearest neighbour distance between QCD "partons" (= quarks, antiquarks, gluons)
- For $\delta < 1$ fm colour confining fields (i.e. QCD gauge fields) cover all space in plasma.
- When $\delta \gtrsim 1$ fm the fields collapse into strings (= flux tubes) separated by vacuum (non-perturb. QCD vacuum)



- Some strings break by parton pair creation (light quarks)



- A small expanding droplet breaks into smaller ones, and string tension stops expansion of the pieces



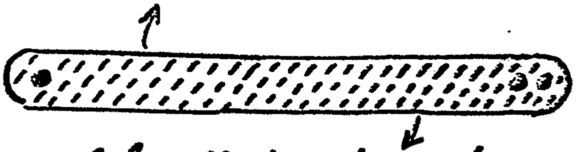
Time scale $10^{-22} - 10^{-20}$ s

- Non-expanding plasma droplet can "deflagrate" by emitting a flow of hadron gas into vacuum.

(In larger expanding droplets, bubbles of vacuum would form)

Heavy hadrons of high spin: $J = \alpha' m^2 + c^t$

$$\alpha' \simeq 1\ \mathrm{GeV}^{-2}$$



- String of length L, diameter $D \simeq 1\,\mathrm{fm} = \frac{1}{200\,\mathrm{MeV}}$
- Mass of non-rotating string $L\sigma$

$$\sigma = \frac{\pi}{4} D^2\, T_0 s_0$$

- Rotating string, endpoints velocity $c=1$

$$\text{mass: } \frac{\pi}{2} L\sigma = m$$

$$\text{spin: } \frac{\pi}{8} L^2 \sigma = J$$

$$J = \frac{m^2}{2\pi\sigma}\ , \quad \alpha' = \frac{1}{2\pi\sigma}$$

Using $D = 1\,\mathrm{fm}$, $\alpha' = 1\,\mathrm{GeV}^{-2}$ one finds

$$\sigma = 0.16\ \mathrm{GeV}^2\ , \quad T_0 s_0 = 10^{-2}\,\mathrm{GeV}^4 = 1.25\,\frac{\mathrm{GeV}}{\mathrm{fm}^3}$$

An ideal gas of gluons and light quarks (u,d) at $T_0 = 150\,\mathrm{MeV}$ would have $T_0 s_0 \simeq 1\,\mathrm{GeV}/\mathrm{fm}^3$.

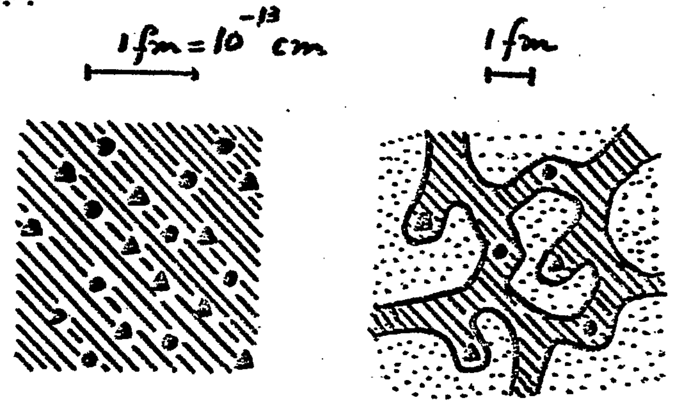
Colour fields in expanding plasma

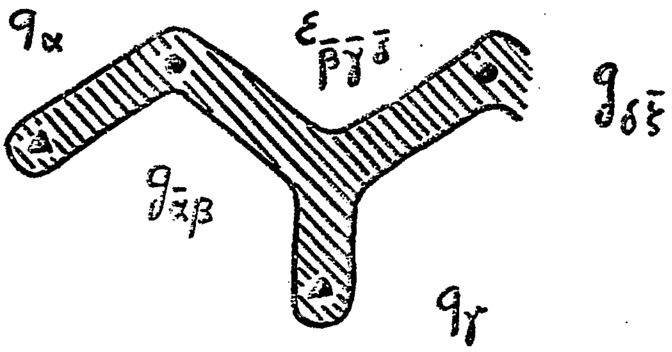
▲ quarks and antiquarks

● gluons

▨ colour fields

⁘ QCD vacuum

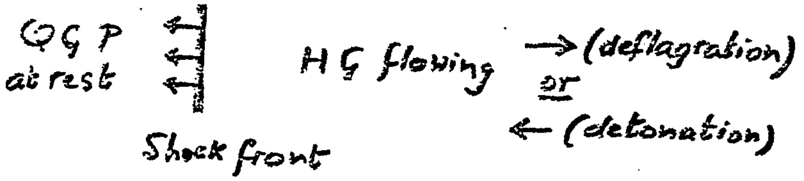




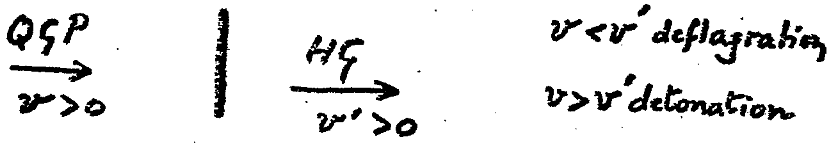
Can the Quark Gluon Plasma deflagrate?

Can it liberate its latent heat by emitting a flow of Hadron Gas?

Picture in QGP rest frame:



Picture in rest frame of shock front:



Question: is this possible with increase of entropy?
[If entropy would decrease, inverse process ($v<0$, $v'<0$) could take place: compression of HG into QGP]

Energy conservation: $\underset{(QGP)}{\dfrac{v(\varepsilon+p)}{1-v^2}} = \underset{(HG)}{\dfrac{v'(\varepsilon'+p')}{1-v'^2}} \rightarrow v v' \geq 0$

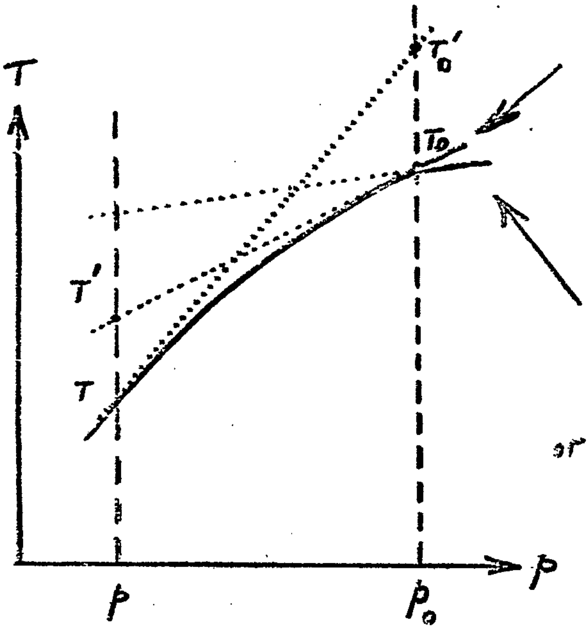
$\varepsilon+p > \varepsilon'+p' \rightarrow |v|<|v'|$ i.e. deflagration $(0<v<v')$
or compression $(0<-v<-v')$

+ Momentum cons.: $\dfrac{v^2}{1-v^2} = K\dfrac{\varepsilon'+p}{\varepsilon+p}$, $\dfrac{v'^2}{1-v'^2} = K\dfrac{\varepsilon+p'}{\varepsilon'+p'}$, $K = \dfrac{p-p'}{\varepsilon-p-\varepsilon'+p'}$

Baryon nb cons.: $\nu^2\dfrac{\varepsilon'+p}{\varepsilon+p} = \nu'^2\dfrac{\varepsilon+p'}{\varepsilon'+p'}$

Entropy increase: $\begin{cases} \nu \text{ and } \nu' \neq 0: & \sigma/\nu \leq \sigma'/\nu' \\ \nu=\nu'=0: & \dfrac{\sigma^2}{\sigma'^2} \leq \dfrac{(\varepsilon+p)(\varepsilon+p')}{(\varepsilon'+p)(\varepsilon'+p')} \leftrightarrow \dfrac{T'^2}{T^2} \leq \dfrac{\varepsilon+p'}{\varepsilon+p}\,\dfrac{\varepsilon'+p'}{\varepsilon'+p} \end{cases}$

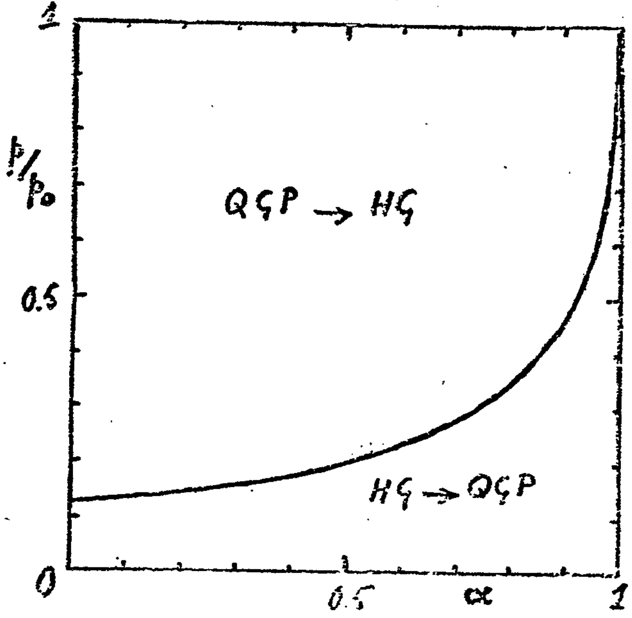
Graphical treatment of $\nu = \nu' = 0$ case: entropy increase $T T_0' \leq T' T_0$



Impossible if
$c_s^2 = \frac{dp}{d\varepsilon}$ constant ≤ 1
$(\varepsilon + p = T\sigma = T\,dp/dT)$
$\left(c_s^2 = -\frac{1}{T}\left(\frac{dT}{dp}\right)^2 \Big/ \frac{d^2T}{dp^2}\right)$

Easy in case of phase transition at or just below p_0

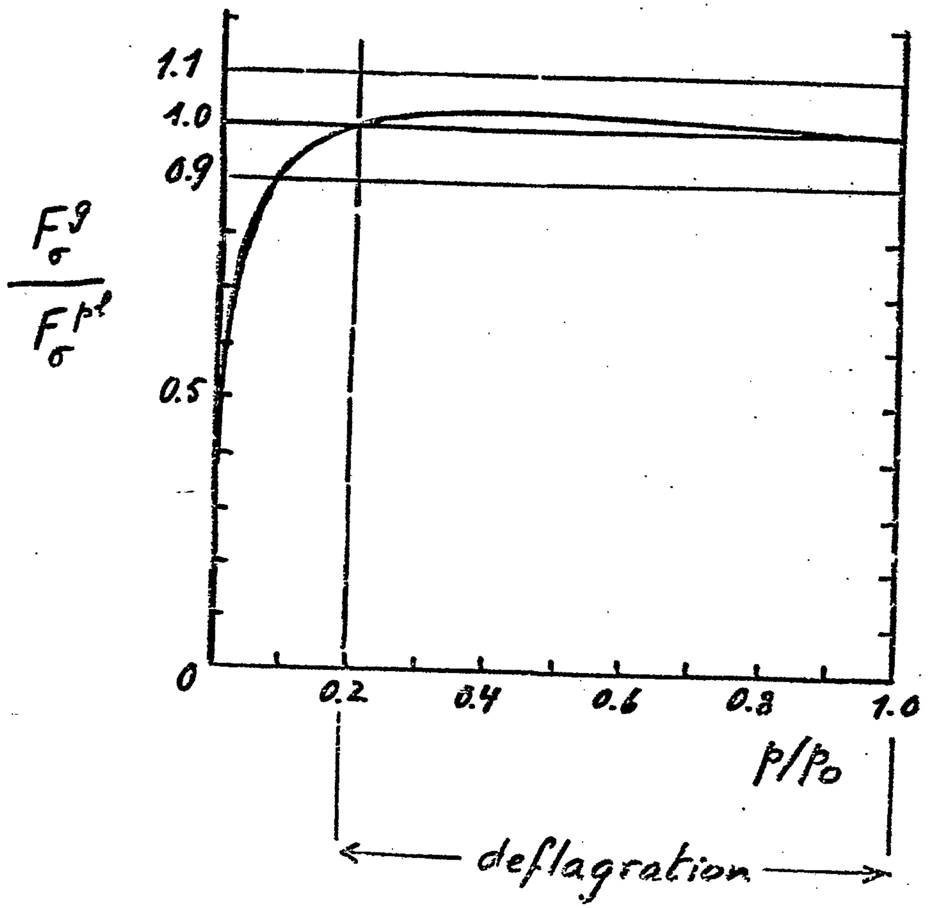
Example: $T \propto p^n$, $n = ct$ for $p \leq p < p_0$, $c_s^2 = n/_{1-n}$, $n \leq \frac{1}{2}$. Take $n = \frac{1}{4}$
Phase transition at p_0: $\left.\frac{dT}{dp}\right|_{p_0+0} = \alpha \left.\frac{dT}{dp}\right|_{p_0-0}$, $0<\alpha<1$. (ideal massless)

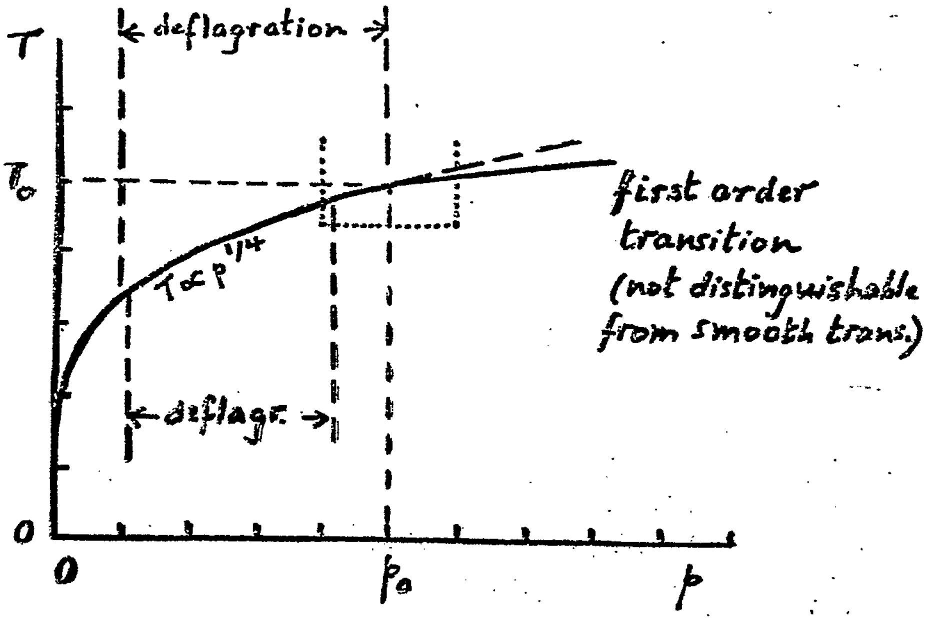


$\left(\alpha = \frac{\sigma_{gas}}{\sigma_{plasma}}\right.$ at transition$\left.\right)$

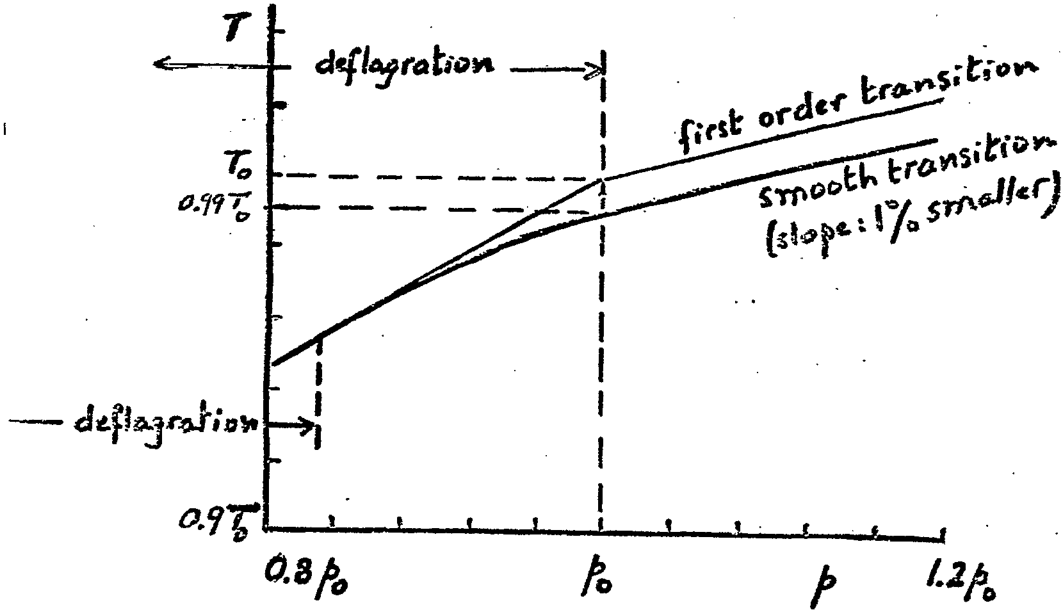
F^{g}_{σ} : entropy flux in gas
F^{pl}_{σ} : entropy flux in plasma
} in rest frame of front.

First order trans, $\alpha = \sigma_g / \sigma_{pl} = 0.5$ at transition.

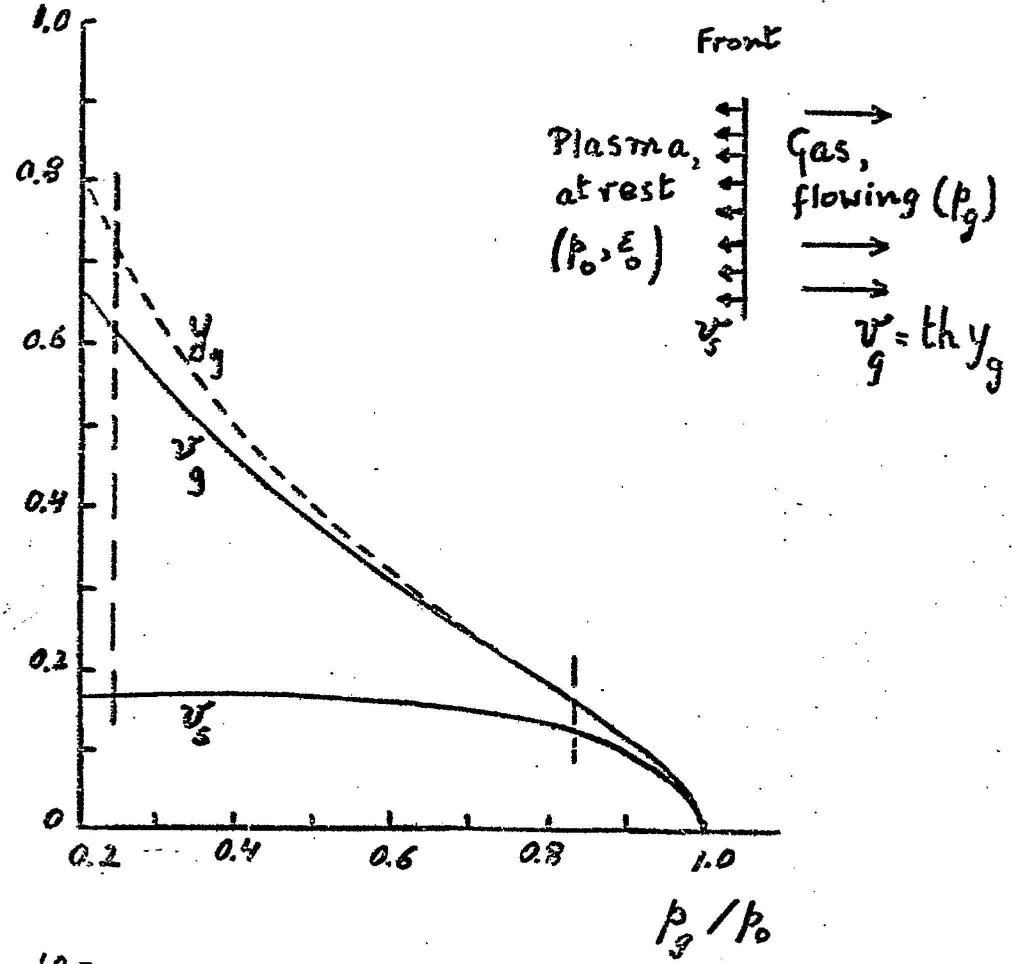


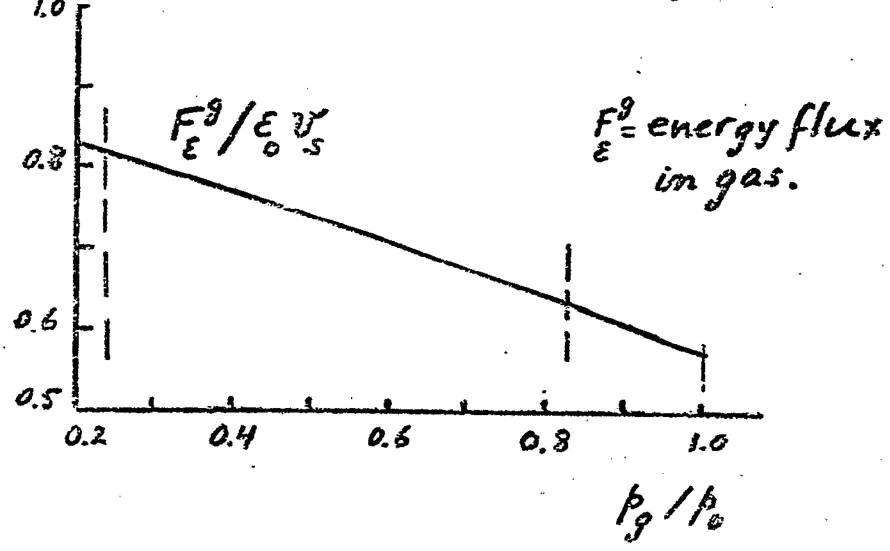


T
deflagration
T_0
$T \propto p^{1/4}$
deflagr.
first order transition (not distinguishable from smooth trans.)
0
0
p_0
p



T
deflagration
first order transition
T_0
$0.99T_0$
smooth transition (slope: 1% smaller)
deflagration
$0.9T_0$
$0.8p_0$
p_0
p
$1.2p_0$


1.0
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0
p_g/p_0
y_g
v_g
v_s
Front
Plasma, at rest (p_0, ε_0)
Gas, flowing (p_g)
v_s
$v_g = \text{th}\, y_g$


1.0
0.8
0.6
0.5
0.2
0.4
0.6
0.8
1.0
p_g/p_0
$F^g_\varepsilon/\varepsilon_0 v_s$
F^g_ε = energy flux in gas.

Discussion of energy flux $F_\varepsilon^g = (\varepsilon_g + p_g)\, v_g\, (1 - v_g^2)^{-1}$

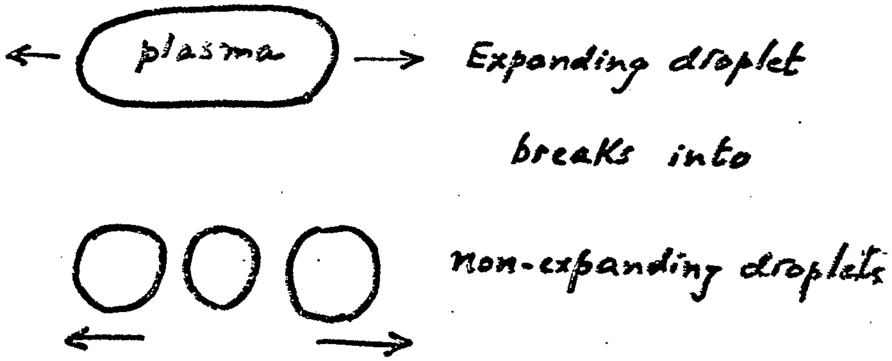
- Order of magnitude $$\underbrace{\frac{3}{4}}_{\dfrac{F_\varepsilon^g}{\varepsilon_0 v_s}} \times \underbrace{\frac{1}{6}}_{v_s} \times \varepsilon_0 = \frac{1}{8}\varepsilon_0$$

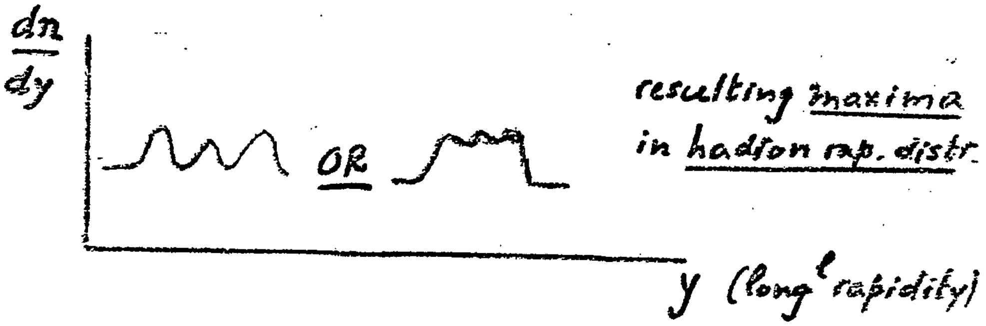
- What would it be if all quarks, antiquarks and gluons flying toward surface would cross it without energy loss?

$$\underbrace{\frac{1}{2}}_{\text{half of the quanta}} \times \underbrace{\frac{1}{2}}_{\overline{\cos\theta}} \times \varepsilon_0 = \frac{1}{4}\varepsilon_0$$

Experimental consequences.

If plasma droplet (possibly after breaking up) hadronizes by deflagration, resulting rapidity distribution of hadrons should show maxima at rapidities of droplets





Expected width of maxima $\sim 1 \div 1.5$

- The other signals for plasma formation (direct dileptons and photons, strange hadrons) should be concentrated in these maxima.
- Hadrons from plasma should have p_T somewhat larger than normal, with broad but fluctuating azimuthal distribution.

THE HADRONIC PHASE TRANSITION IN THE EARLY UNIVERSE.

L. VAN HOVE

A Colloquium Lecture at
Brookhaven National Laboratory
(November 1984)

I

"Age of Universe"	Temperature	Matter in the universe
~ 2×10^{10} y ($\simeq 6 \times 10^{17}$ s)	3°K ($\simeq 2.6 \times 10^{-4}$ eV)	[0.4 photon/mm^3, 0.1-1 nucleon/m^3, $\frac{n}{p} \simeq \frac{1}{8}$, $\frac{e}{p} = 1$, a few neutrinos/mm^3 (on average)] + "dark" matter?
~ 6×10^5 y	~ 3000 °K	↑ photons decoupled from other matter, atoms exist ↑ ↓ photons in equil. with plasma of nuclei and electrons ↓
~ 3 min (= 180 s)	~ 0.1 MeV	↑ neutrons bound in nuclei ↑ ↓ protons and neutrons form gas ↓
~ 15 s	~ 0.3 MeV	↑ no electron-positron pairs ↑ ↓ such pairs in equil. with photons and protons ↓
~ 1 s	~ 1 MeV	↑ neutrinos decoupled from other matter ↑ ↓ neutrinos in equil. with other matter ↓
~ 10^{-3} s	~ 30 MeV	↑ no <u>hadrons</u> except protons and neutrons ↑ ↓ unstable hadrons ↓

Limit of "conventional" physics.

10^9 photons/mm^3

Exergy formation

"The first three minutes" by S. Weinberg, Basic NY (1977)

"Known" matter is mostly leptonic but there is evidence for "dark" matter!

Picture based on "new" physics and increasingly speculative!!

~ 5×10^{-5} s	~ 150 MeV	↑ hadrons form gas ↑	
~ 2×10^{-5} s	~ 250 MeV	↓ hadronic matter coalesced in quark-gluon plasma ↓	Hadronic phase transition ① (large decrease of energy and entropy density) $\gg 10^{36}$ particles/mm^3 $= 1$ part./$fm^3 \propto T^3$.
~ 10^{-8} s	~ 10 GeV (= 10^4 MeV)	↑ electromagn., weak, strong } interactions, photons ↑	
~ 10^{-12} s	~ 10^3 GeV	↓ electro-weak interactions merge, photons mixed with massless Z^0, $W^\pm$ massless ↓	Electroweak phase transition ②
		? ? ? ? ?	
~ 10^{-32} s	~ 10^{13} GeV	↑ electroweak, strong } interactions, gluons ↑	
~ 10^{-36} s	~ 10^{15} GeV	↓ electro-nuclear interactions merge, gluons mixed with other particles ↓	Electronuclear phase transition ③ (origin of baryon asymmetry? - monopoles, strings, ...?)
		? ? ? ?	
~ 10^{-42} s	~ 10^{18} GeV		
		FRONTIER OF IGNORANCE (Quantum gravity?)	
~ 0 (by definition)	~ 10^{19} GeV (Planck energy)	**Experimental tests:** ① ultrarelativistic ion collisions, ② [$p\bar{p}$ and e^+e^- colliders], ③ {proton decay expts, heavy monopole searches	

"Known" "matter mostly hadronic"
Nature of "dark" "matter"?

- Other type of expansion?
- Creation of matter & entropy out of coherent field energy?

III

Basic equations for expanding Universe (homogeneous isotropic model)

- Metric: $ds^2 = dt^2 - d\ell^2$, $d\ell^2 = a^2(t)\left[\frac{dr^2}{1-Kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)\right]$

  r, θ, φ: space coordinates of co-moving observers

  t : proper time of co-moving observers

  $d\ell$: space distance, $a(t)$ scale parameter

  K: curvature constant ($K=0$ flat space , open
  $K<0$ hyperbolic space, open } if s^y-conn^d
  $K>0$ spherical space, closed)

- Einstein equations for gravitation give:

$$\left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{8\pi}{3} G\rho - \frac{K}{a^2} + \Lambda$$

Λ ← cosmological constant

$\frac{K}{a^2}$ ← curvature term

"kinetic energy term"

gravit. attraction term, G = Newton constant, ρ = non-gravitational energy density

$G^{1/2} = 1.6 \times 10^{-33}\,\text{cm}\ (= \ell_P) = 0.54 \times 10^{-43}\,\text{sec}\ (= t_P)$

$G^{-1/2} = 1.2 \times 10^{19}\,\text{GeV} = 2.2 \times 10^{-5}\,\text{g}\ (= M_P)$

(P for Planck, $\hbar = c = 1$)

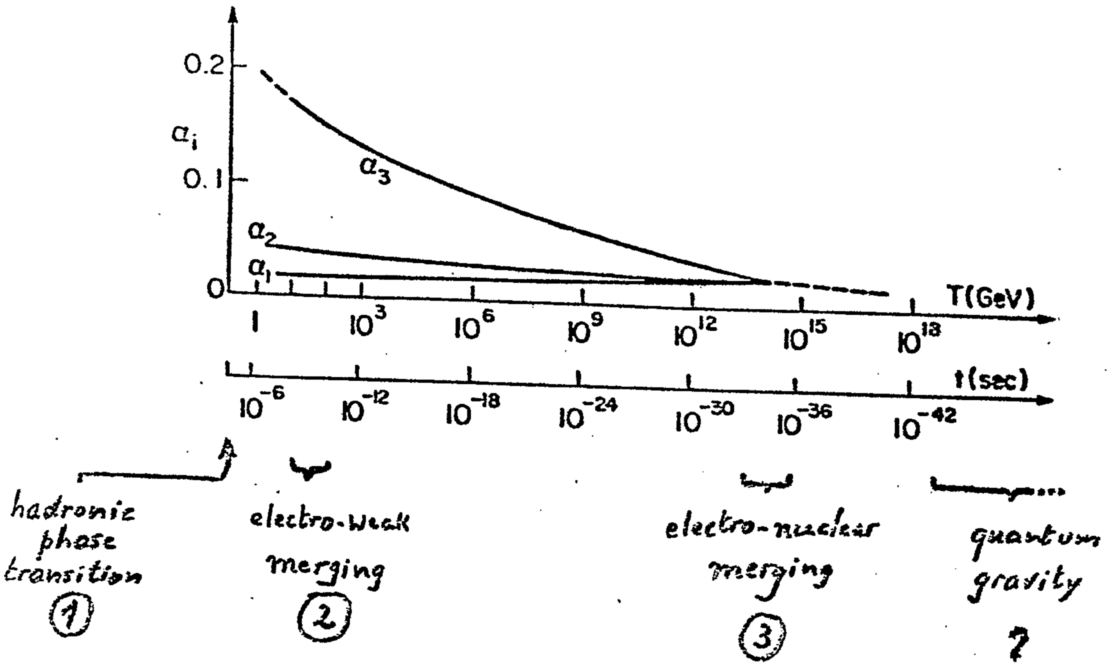
- Energy conservation for co-moving volume V

$$\frac{d}{dt}(\rho V) + p\frac{dV}{dt} = 0 \Rightarrow \frac{d}{dt}(\rho a^3) + p\frac{da^3}{dt} = 0$$

[If ρ dominated by non-relativistic matter, $p \ll \rho$, ρa^3 = constant
" " " " ultra- " " , $p = \rho/3$, ρa^4 = "

(non-relativistic : $5 \times 10^5\,y \lesssim t \lesssim 1.5 - 2 \times 10^{10}\,y$ = today ,
ultra- " before)

At every time, state of matter is characterized by the particle species present and their equation of state.



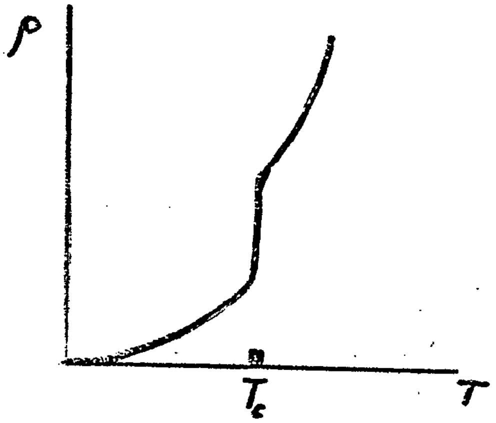
electro-weak = electromagnetic + weak interactions
electro-nuclear = electro-weak + strong interactions

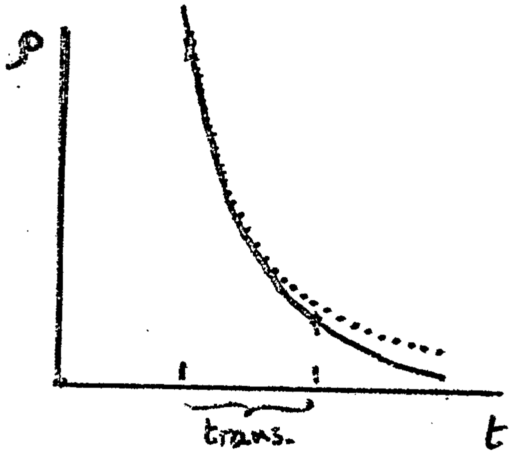
$\alpha_i = \frac{g_i^2}{4\pi}$, g_i coupling strength for energy-momentum transfers ~ T

α_1, α_2 : electro-weak interactions
α_3 : strong interaction.

Hadronic phase transition in the expansion of the Universe.

V





$$\left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{8\pi}{3} G\rho \qquad \frac{d}{dt}(\rho a^3) + p\,\frac{da^3}{dt} = 0$$

$p \simeq p_c$ constant during transition [1st order trans. assumed for simplicity]

$(\rho + p_c)\,a^3 \simeq$ " " "

$$\frac{d\rho}{dt} = -(24\pi G)^{1/2}\,\rho^{1/2}(\rho + p_c)$$

$$\rho \simeq p_c\left(\frac{\sqrt{\rho_1} - \sqrt{p_c}\,\tan\gamma(t-t_1)}{\sqrt{p_c} + \sqrt{\rho_1}\,\tan\gamma(t-t_1)}\right)^2$$

$\gamma = (6\pi G p_c)^{1/2}$, t_1 = beginning of transition, $t_1 \sim 10^{-5}$ s = 3 Km when $\rho(t_1) = \rho_1 = \rho\,[QGP + leptons + \gamma's]$ at T_c, p_c.

Transition ends at t_2 when $\rho(t_2) = \rho_2 = \rho\,[HG + lept. + \gamma.]$ at T_c, p_c.
$\rho_2 \sim 0.5 - 0.7\,\rho_1$, $t_2 \sim 1.2 - 1.5\,t_1$.

At $t = t_1 + \delta t$, HG bubbles separated by $t_1^{1/3}(1\,fm)^{2/3} \sim 10^{-7}$ cm.
After percolation space structure may reach $t_1^{2/3}(1\,fm)^{1/3} \sim 1$ cm

Most probably, no trace is left today of the hadronic phase transition in the early Universe

But one cannot exclude some exotic possibilities:

1) <u>Black hole formation</u> (Schramm et al.)

If QGP regions of size ~t, surrounded by larger HG regions would form, some of them could collapse into black holes of mass $\lesssim 10^{58}$ GeV and radius $\lesssim$ 10 km ($M_\odot \simeq 2\times10^{33}$ g $\simeq 10^{57}$ GeV)

The black holes could later contribute to galaxy formation. They would now form invisible matter

(M. Crawford & D.N. Schramm, Nature 298 (1982) 538; K. Freese, R. Price & D.N. Schramm, Ap. J. 275 (1983) 405)

For this to work, the ρ_{BH} in the black holes should now be ~(10-100) $\rho_{visible}$

2) <u>Formation</u> of "<u>strange quark matter</u>" (Witten):

a possible new form of stable matter containing u,d,s quarks, could also form invisible matter in the present Universe

(E. Witten, Phys. Rev. D 30 (1984) 272)

There is something fascinating about Science -
One gets wholesale returns of conjecture
out of such trifling investment of fact!
(Mark Twain)

VII

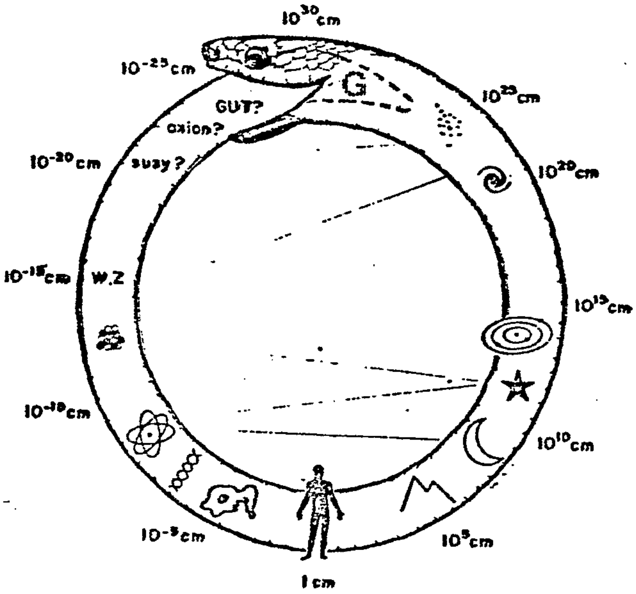


Fig. 7. New ideas in particle physics suggest further linkages between "micro" and "cosmic" scales (i.e. between left and right on this picture) in addition to the well-known ones between atomic and nuclear physics and the terrestrial and stellar scales. The ultimate unification will involve quantum gravity (the Planck scale) and cosmology. (from Primack and Blumenthal, Proc. 3rd Moriond Astrophysics Workshop (Reidel) p. 180 (1983)).