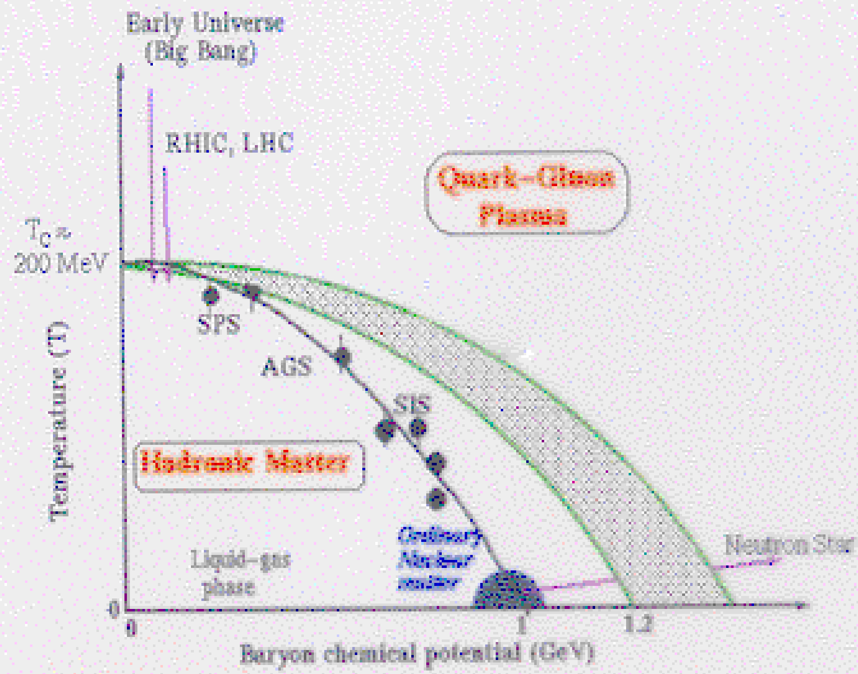
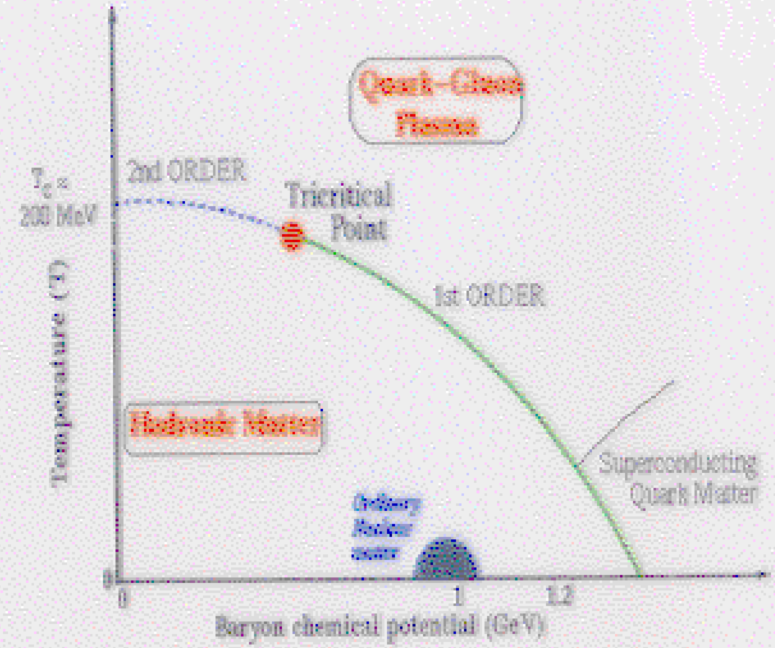
QCD PHASE DIAGRAM



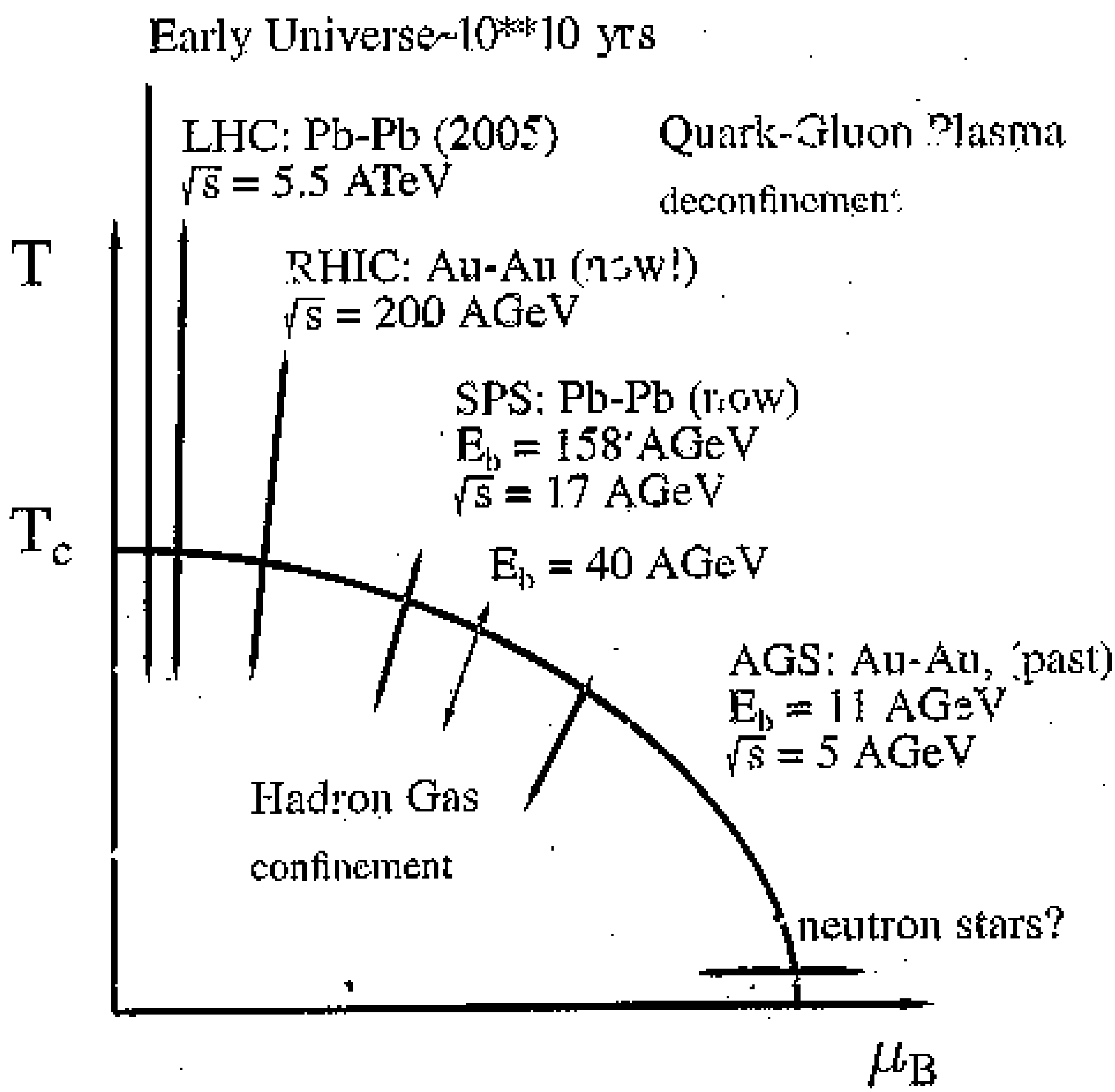
Deconfinement
Chiral symmetry restoration



Similar to behavior of M_s-T in m-T plane

HOW TO FIND THE TRICRITICAL POINT ?

LARGE EVENT-BY-EVENT FLUCTUATIONS



Early Universe~10**10 yrs
LHC: Pb-Pb (2005)
$\sqrt{s}$ = 5.5 ATeV
Quark-Gluon Plasma
deconfinement
T
RHIC: Au-Au (now!)
$\sqrt{s}$ = 200 AGeV
SPS: Pb-Pb (now)
E_b = 158 AGeV
$\sqrt{s}$ = 17 AGeV
T_c
E_b = 40 AGeV
AGS: Au-Au, (past)
E_b = 11 AGeV
$\sqrt{s}$ = 5 AGeV
Hadron Gas
confinement
neutron stars?
μ_B

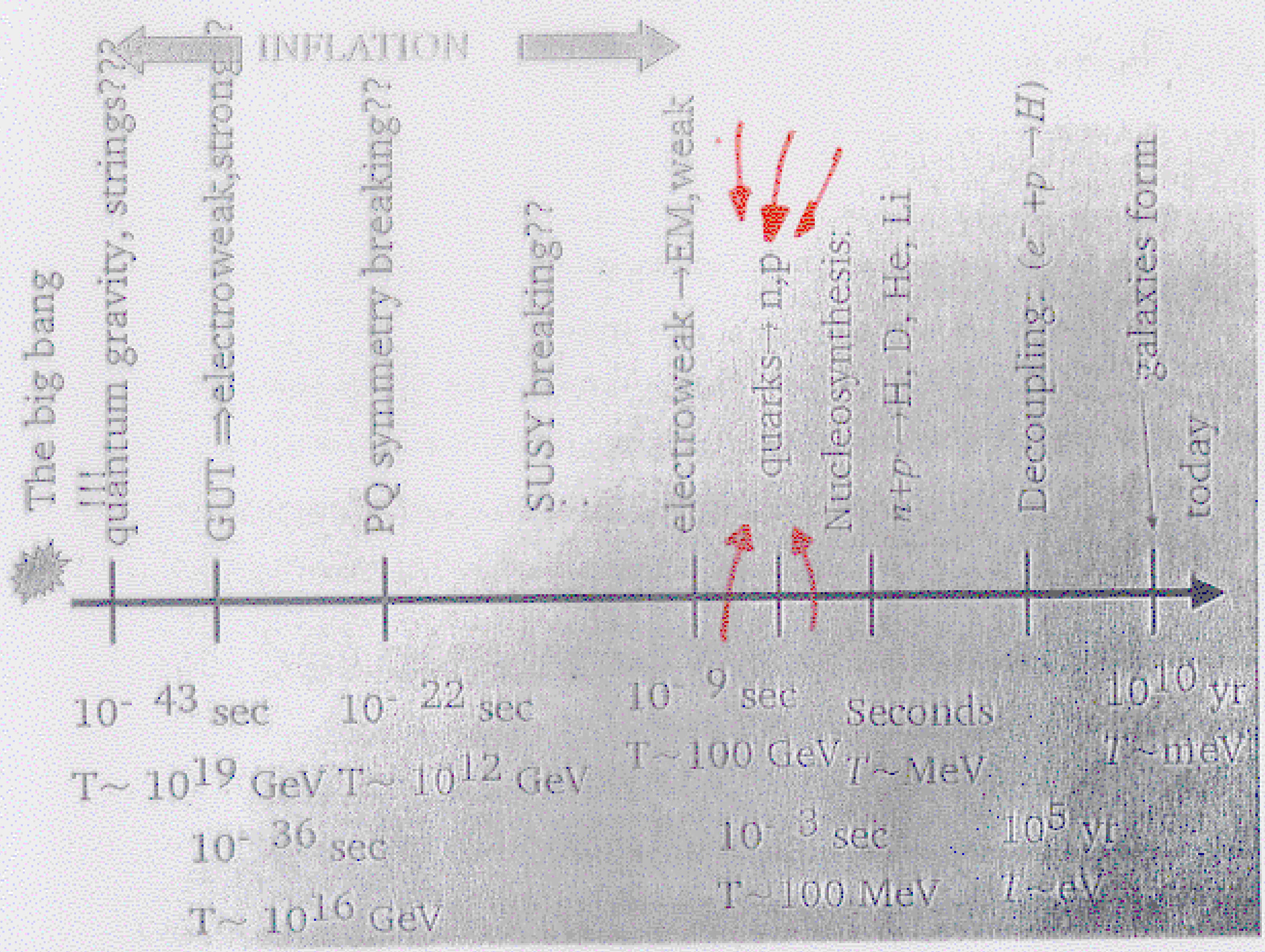


FIG. 6: Logarithmic history of the Universe. Inflation may have taken place at any time from the Planck time until the time of electroweak-symmetry breaking. Given the CMB confirmation of the inflationary predictions of a flat Universe and primordial adiabatic perturbations, an obvious goal of early-Universe cosmology should be to determine the time, or equivalently, the energy scale of inflation (defined more precisely to be the fourth root of the vacuum-energy density during inflation). This can be accomplished by searching for the unique CMB polarization pattern produced by the inflationary gravitational-wave background, the amplitude of which scales on the inflationary energy scale.

Quark Nuggets & Dark Matter :

Evolution of the universe, Einstein eqn. in

Robertson - Walker space time

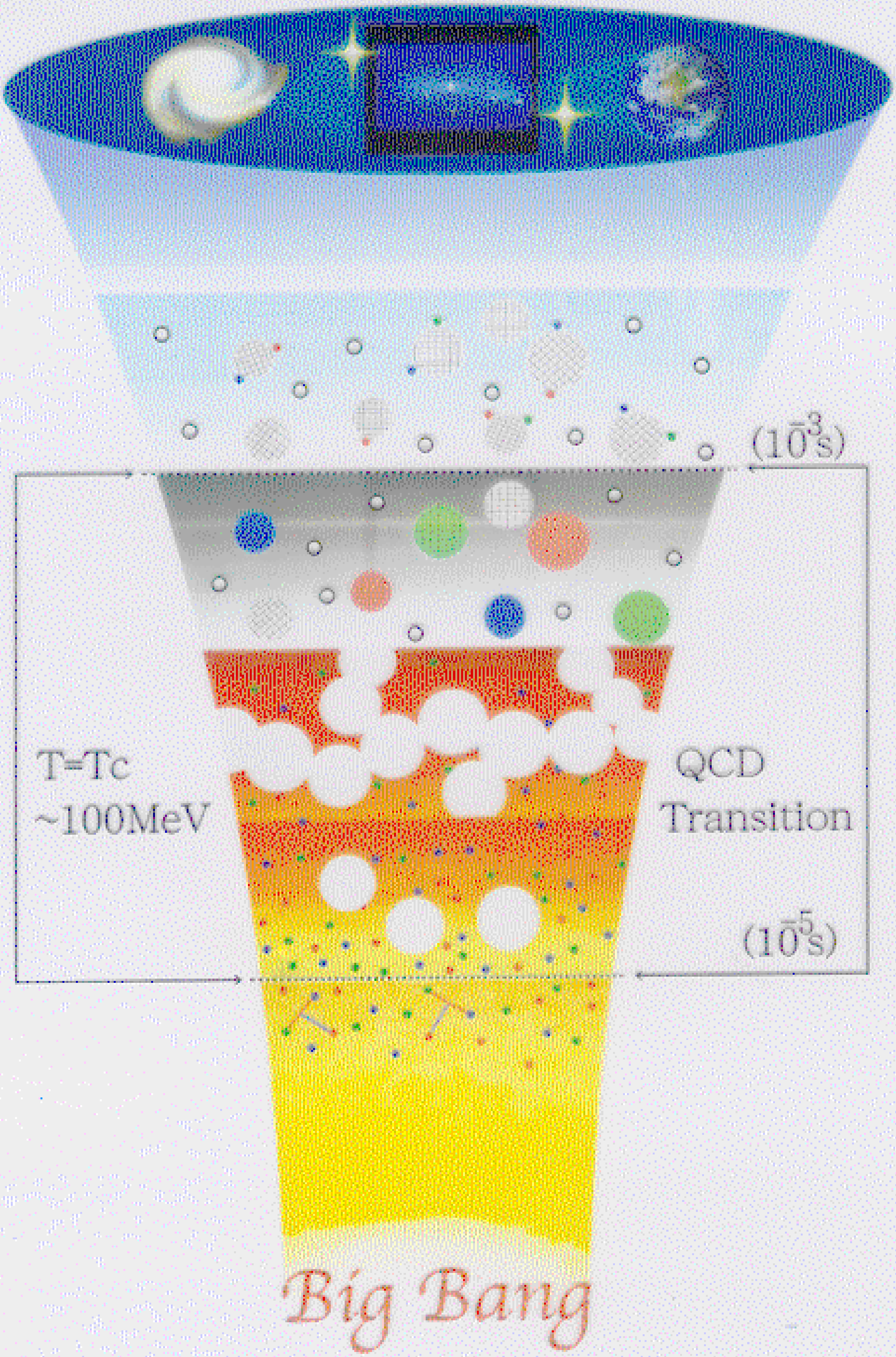
$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi\epsilon}{3M_{Pl}^2} \quad : \quad \frac{d(\epsilon R^3)}{dt} + P\frac{dR^3}{dt} = 0$$

in QGP

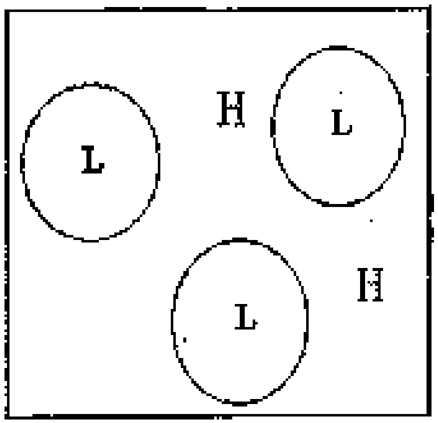
$$\epsilon = 3aT^4 + B$$

$$P = aT^4 - B$$

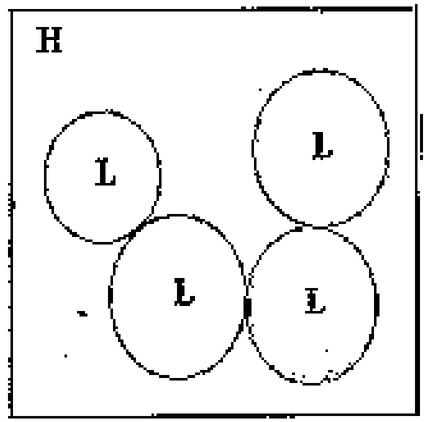
$$\boxed{t \simeq \frac{0.74}{T^2}}$$


(10⁻³s)
T=Tc
~100MeV
QCD
Transition
(10⁻⁵s)
Big Bang

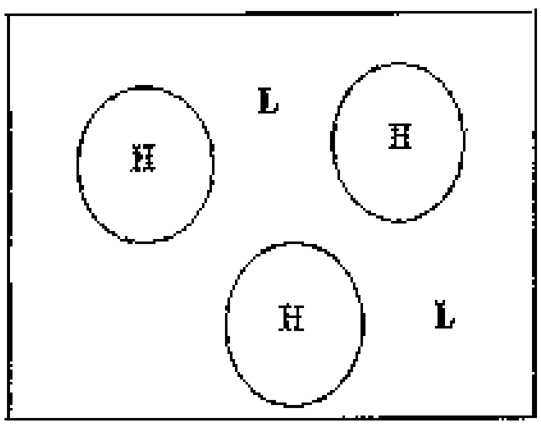
Strange quark nuggets (SQN)



Isolated expanding bubbles of low temp in high temp. phase



Expanding bubbles meet



Isolated shrinking bubbles of High temp. phase

$T \propto t^{-1/2}$

t_i (on set of the phase transition)

$T_c \sim (200 - 150)$ MeV : $t_i \sim \mu$sec.

$t_c \sim$ characteristic time scale

$$= \left(\frac{3 M_{Pl}^2}{8 \pi B} \right)^{1/2} \sim 40\,\mu\text{sec}$$

- $\frac{n_b}{n_\gamma} \sim 10^{-10}$

- Expansion time scale $\sim 10^{-5}$ sec

Mini Bang $\overset{?}{=}$ Big Bang

↓

Turbulence

Inflation

Gravitation

Horizon

Chromoelectric Flux-tube fission

P. Bhattacharya
J. Alam
S. Raha
B. S. (PR D '93)

$$\frac{dN_B}{dt} = \left[\frac{dN_B}{dt}\right]_{ev} + \left[\frac{dN_B}{dt}\right]_{abs.}$$

$$\left.\frac{dN_B}{dt}\right]_{abs} = -2\pi^2 \left[\frac{n_N v_N}{m_N T^2}\right] \exp\left[\frac{m_N - \mu_N^q}{T}\right] \left[\frac{dN_B}{dt}\right]_{ev}$$

QN's with baryon number N_B at time t will stop evaporating (survive) if the time scale of evaporation

$$\tau_{ev}(N_B, t) \equiv \frac{N_B}{dN_B/dt}$$

$$\gtrsim H^{-1}(t) = 2t \text{ of the}$$

universe

CEFT Model

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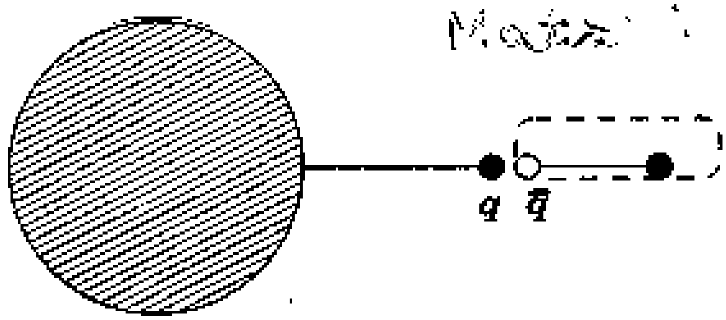
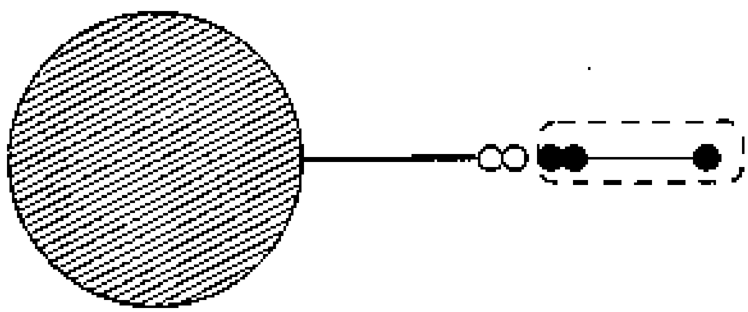


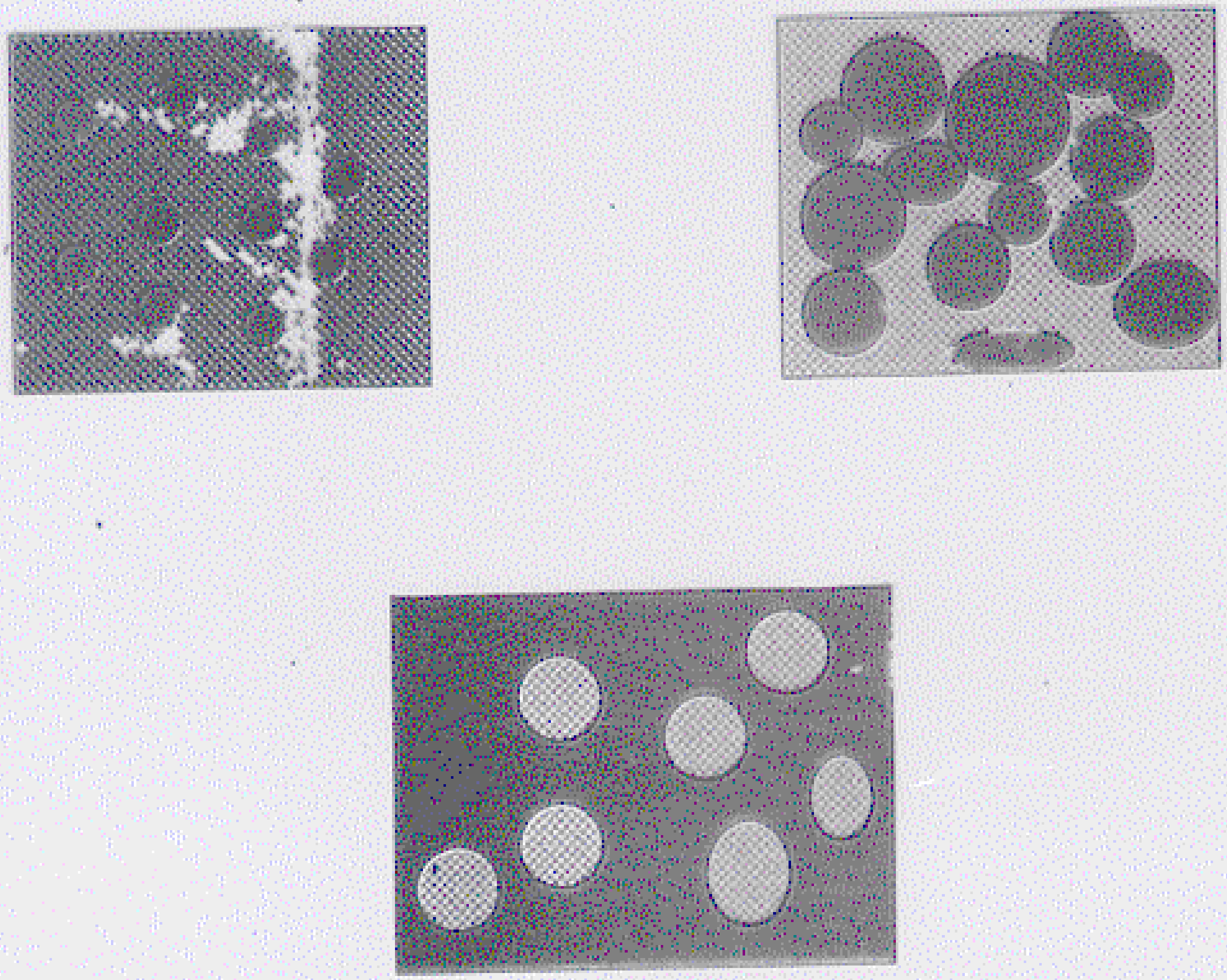
meson evaporation



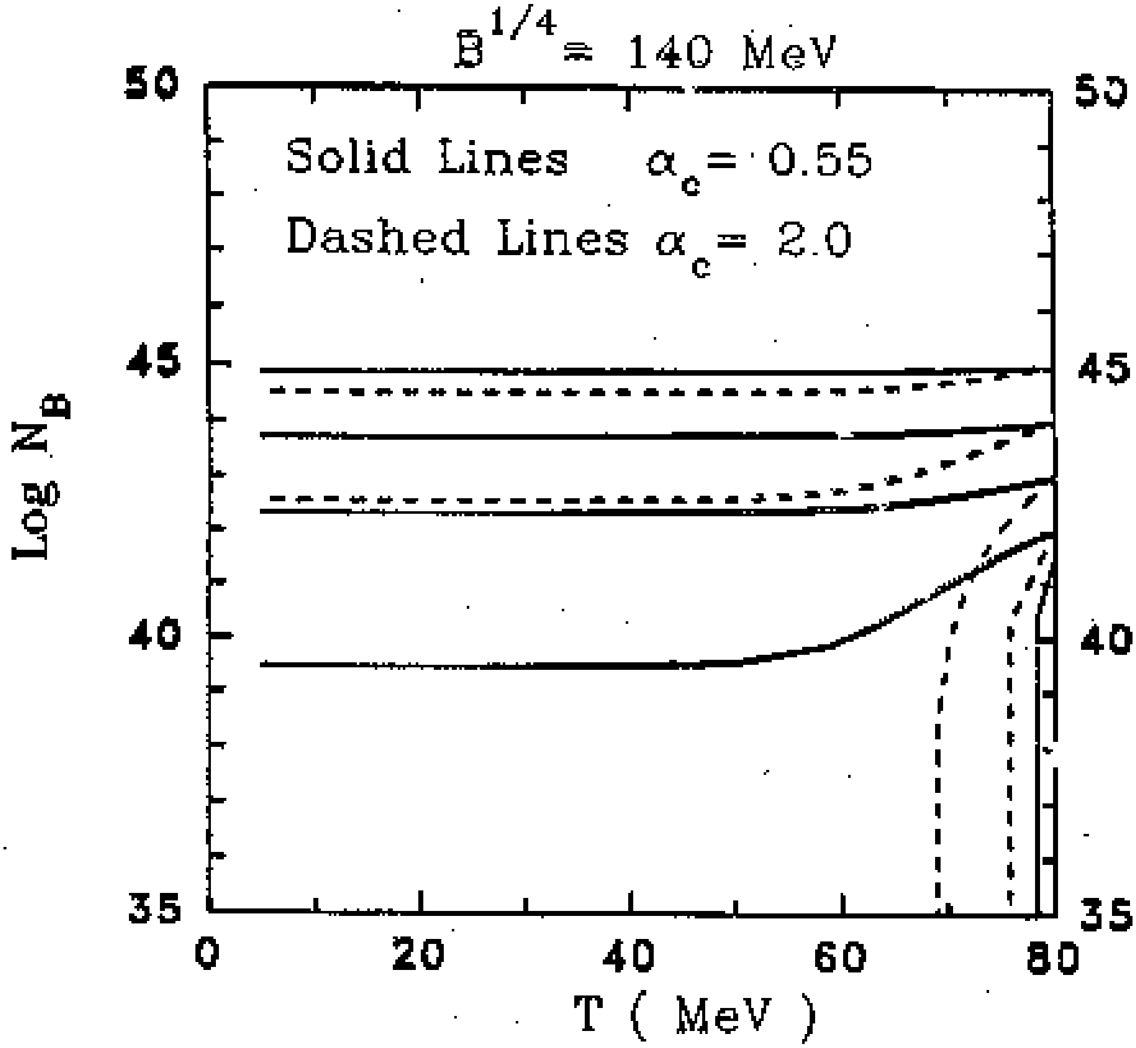
baryon evaporation

(Sumiyoshi et al 1990)

QCD PHASE TRANSITION IN THE EARLY UNIVERSE



(Witten - 1984)



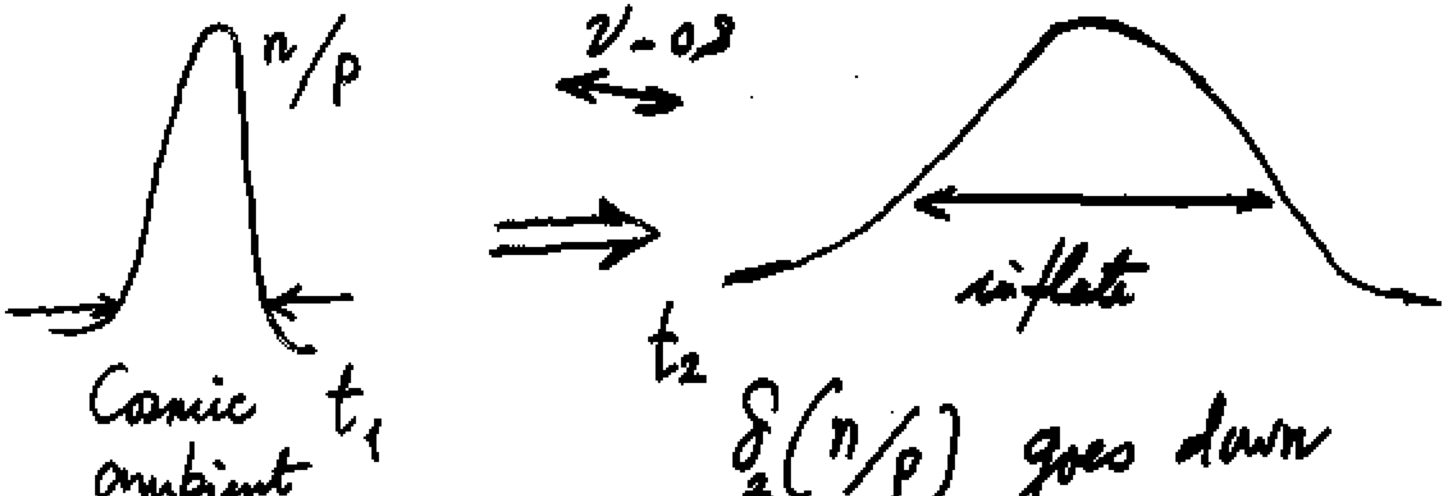
$$K_{c,B} \sim \frac{1}{\sqrt{\alpha_c}}$$

What is the future of a Quark Nugget formed during QCD phase transition?

These large objects may be candidates for MACHO.

radiate out

V -05 Come and [redacted] heat



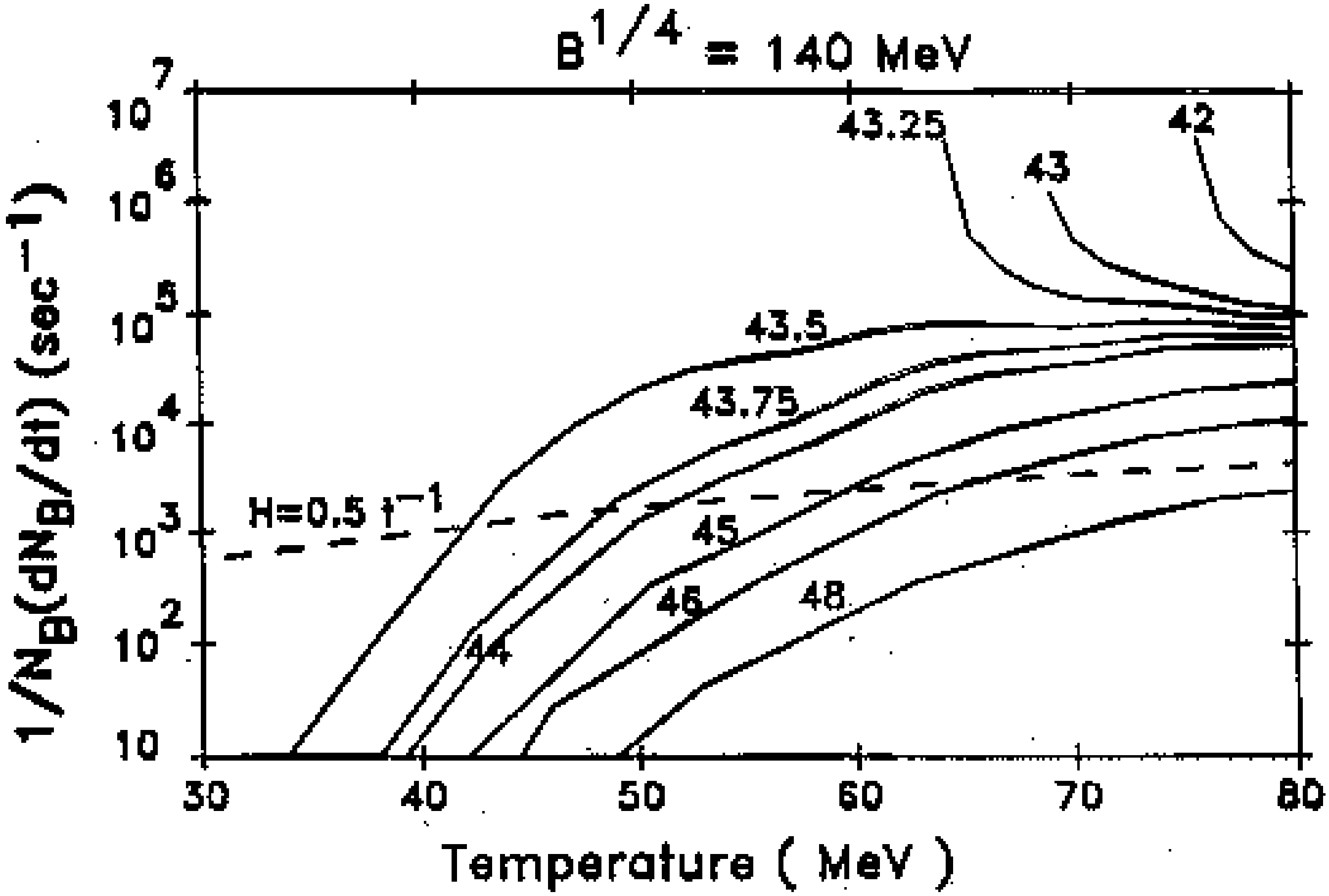
$\delta_1(n/p) \sim 10^{12}$

$\delta_2(n/p)$ goes down $\rightarrow 10^4$

But evaporating QN's keep sending neutrons to the Patches

Inhomogeneity

Big Bang NucleoSynthesis Survive!



(Bhattacharjee, Alam, Sinha & Raha
– 1993)

Cosmological Quark-Hadron Transition

&

Massive Compact Halo Objects

(MACHO)

DARK MATTER :

: Universe is flat $\Omega = \rho/\rho_c \simeq 1$

Baryons contribute 10% : $\Omega_B \simeq 0.1$

cold dark matter (CDM) [Non relativistic]

Clumping on small galactic/supergalactic scales

$\Omega_{CDM} \sim 0.35$

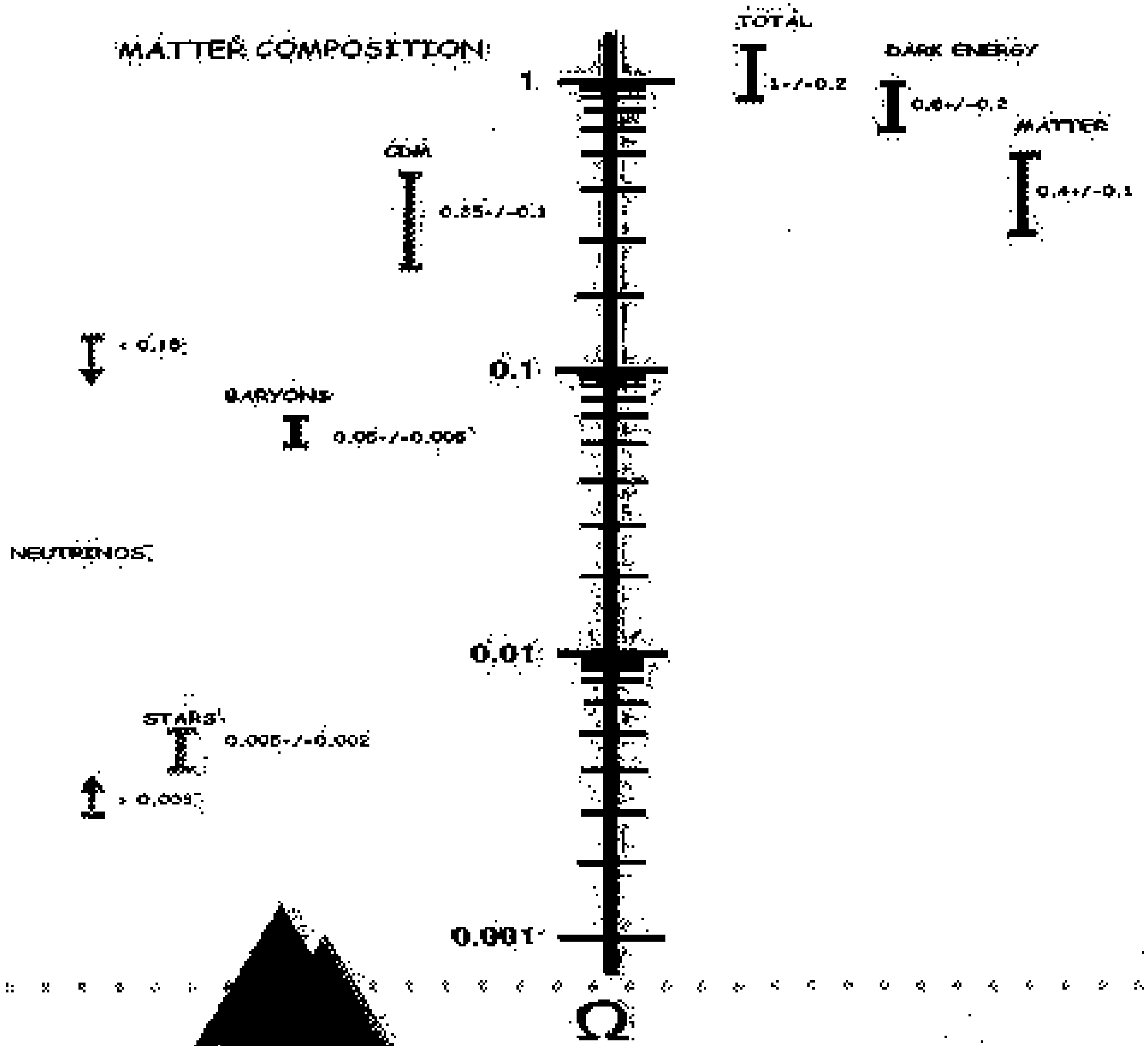
not understood or poorly " [The rest of the closure density arises (vacum energy)

⇓

accelerated expansion of the universe

SQN and Dark Matter

MATTER / ENERGY in the UNIVERSE



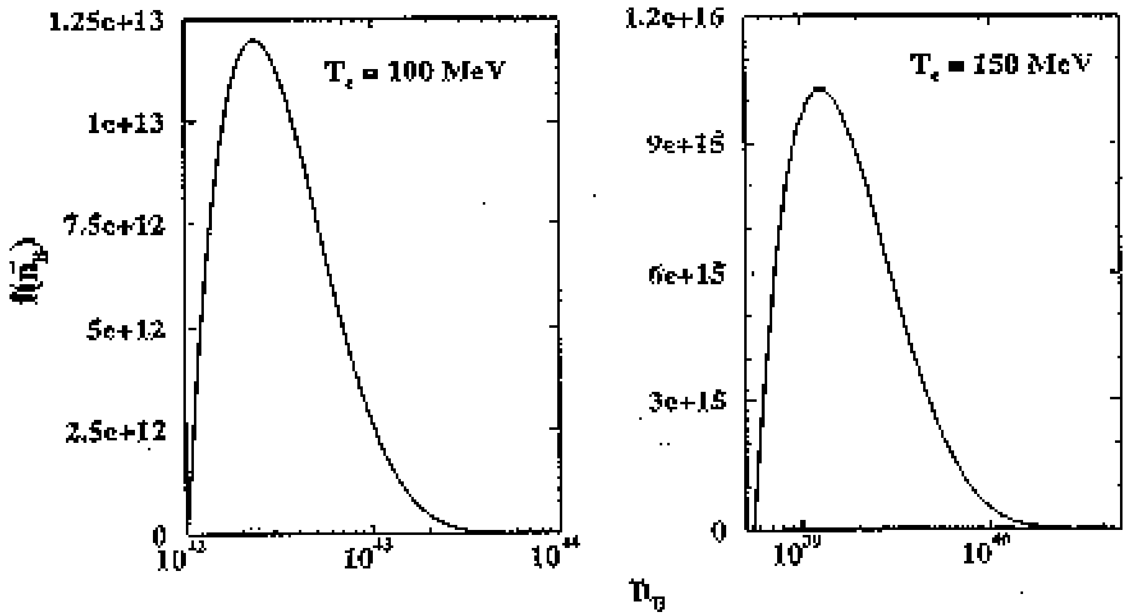


Figure 2: Same as fig. 1, using nucleation rate proposed by Csernai and Kapusta. The value of σ is $10 MeV fm^{-2}$.

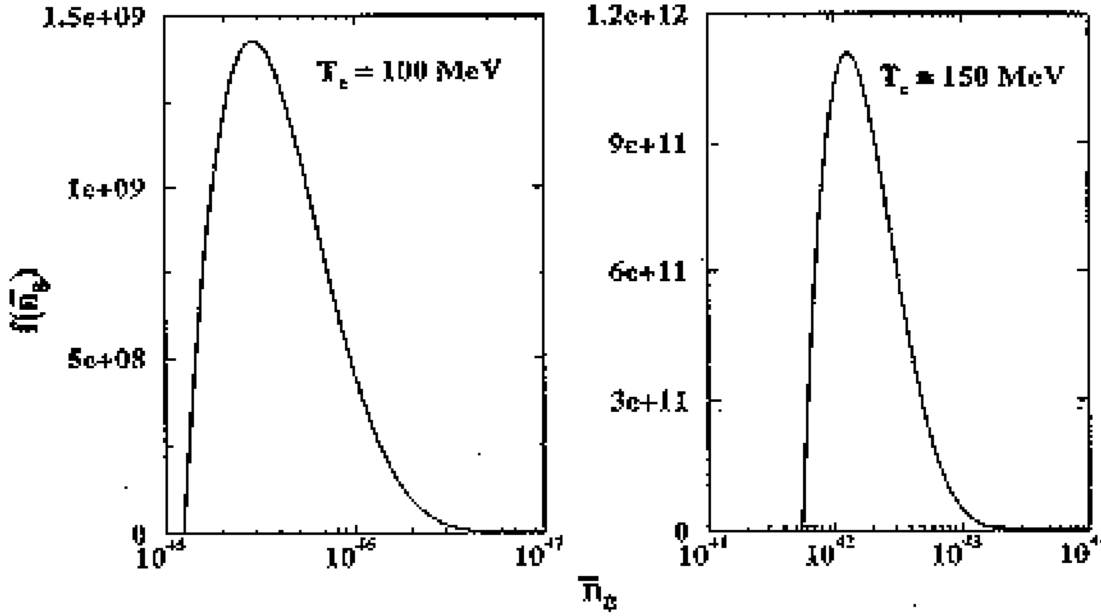


Figure 3: Same as fig. 2 with $\sigma = 50$ MeV fm^{-2}.

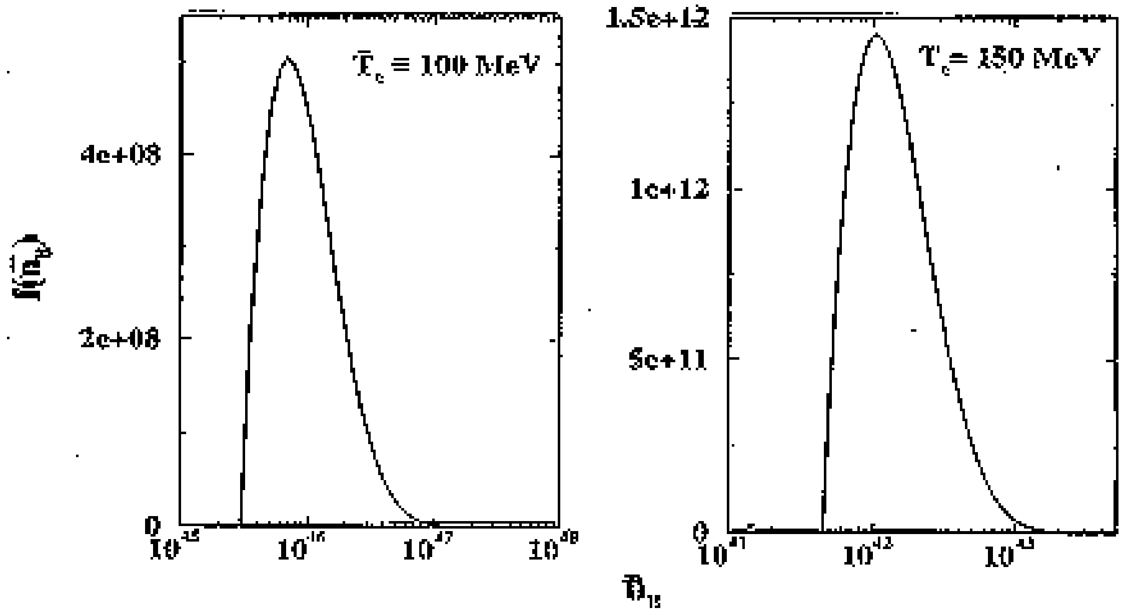


Figure 1: Distribution of QN, $f(\bar{n}_B)$, as a function of $\bar{n}_B$ using nucleation rate proposed by Cottingham *et. al.*

- $N_B^{in} \gtrsim 10^{42}$ are stable against baryon evaporation

$$10^{42} \lesssim N_B^{in} \lesssim 10^{49}$$

- Stable QN's could be a viable candidates for dark matter.

- ν-heat conduction is an important mechanism for the dissipation of baryon inhomogeneities in the early Universe about $T \sim 1$ MeV.

MACHOS <u>are</u> left over relics

from the putative first order

cosmic quark hadron phase transition.

BBN (Limits on baryon numbers)

⇓

MACHOS are white dwarfs?

Absence of sufficient active progenitors of appropriate masses in the galactic halo

⇓ Unlikely candidates for white dwarfs, even if they are as <u>faint as blue dwarfs</u>? [BLUE DWARF?]?

⇓ That will violate some of the very well known results of BBN (Freeze et. al. 2000)

- Not even primordial black holes

MACHO: What are they: Different opinion

- White Dwarfs ?? → absence of active progenitors of appropriate masses (Fields *et al.* 1998)
- May be faint blue dwarfs ?? → violate well known results of BBN (Freese *et al.* 2000)
- Primordial black holes ??? (Schramm 1998, Jedamzik 1998) → Density contrast necessary is not present
  → Too many fine tuning necessary to get PBH

Macho (Gravitational Micro Lensing)

based on 13-17 Milky Way halo

in the direction of LMC (Large Magellanic Cloud)

Galactic halo ⇗ $(0.15 - 0.95)\, M_\odot \approx 0.5\, M_\odot$

$\gg$ fusion threshold $0.08\, M_\odot$

Too many $\neq$ BBN limit of Ω_B

Machos are <u>not</u> normal baryonic matter

Trapped false vacuum domains (TFVD) : n_B (substantial)

$SQN \geq (n_B)\, 10^{42}$

not usual baryons : yet account for the baryonic number

Quasibaryonic dark matter

distinct from non baryonic or baryonic dark matter

(CDM)

- SQN's in collapsed structure?

- Net gravitational attraction

- Prevented by radiation pressure

But

With drop in temperature in the ambient universe

Gravity wins over radiation

⇓ SO,

SQN's are suspended in the radiation fluid.

$$F_{grav} = \frac{G\, b_N^2\, m_N^2}{\bar{r}_{nn}\, T^2}$$

$b_N \sim$ baryon no. SQN

$m_N \rightarrow$ " mass

$\bar{r}_{NN} \rightarrow$ mean seperation between two nuggets

$\Downarrow$

$$F_{rad} = \frac{1}{3} \rho_{rad}\, c\, v_{fall} \left(\pi R_N^2\right) \beta \gamma$$

$\rho_{rad} \rightarrow$ energy density

$v_{fall} \equiv \beta c$ velocity of SQN's

Banerjee et. al.

Mon. Not. R. Astron. Soc. 340

$$N_N^{SQN}(T) \cong \frac{10^{51}}{b_N}\left(\frac{100\,MeV}{T}\right)^3$$

density

$$n_N(T) = \frac{N_N}{V_N} = \frac{3N_N}{4\pi(2t)^3}$$

$$t = 0.3\, g_*^{-1/2} \frac{m_{pl}}{T^2} \quad : g_* \sim 17.25 \text{ (Alam et. al 1999)}$$

SQN(density) decreases $\sim t^{-3/2}$

Seperation <u>increases</u> $\sim t^{1/2}$

∴ gravitational pull decreases $\sim t^{-1}$

Radiation press decreases $\sim t^{-2}$

⇓ ⇓ ⇓

F_{grav} / F_{rad} is very small initially

↓

Nuggets will remain seperated due to radiation pressure

for $T < T_{ce}$: F_{grav} dominates

⇓

<u>Coalescence starts</u>

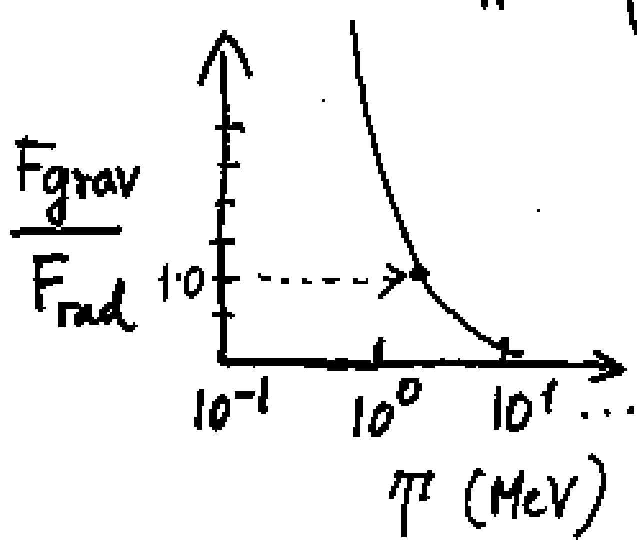
Banerjee, Bhattacharya, Ghosh, Raha, Toki, B.S.
Mon. Not. Astron. Soc. 340, 2003

The number at any late temp. (T)

$$N_N^{SQN}(T) = 10^9 \left(\frac{100\ \text{MeV}}{T}\right)^3$$

⇓

$$n_N(T) \equiv \frac{N_N}{V_H} = \frac{N_N}{\left(\frac{4\pi}{3}\right)(2t)^3}$$ ⟸ horizon length 2t rad. dom.



for $\Omega_{CDM} \sim 0.35 \Rightarrow 10^{23-24}$ such objects within the horizon today $\Rightarrow (2-3)10^{13}$ within the Milky Way halo

⇓ Consistent with Observation

(say) all the CDM arise from SQN's

Size distrib. peaks (reasonable nucleation rate)

$n_B \sim 10^{42-44}$ baryons

↙ (BBN)

Recalling $\Omega_B \sim 0.04$: 10^{49-50} baryons within the horizon at the around microsecond epoch.

for $\Omega_{CDM} \sim 0.35$: ⇒ 10^{7-9} SQN's $\sim 10^{51}$ baryons

1m ~ (100–300 m)

Clearly any deviation from a uniform distribution of SQN

in a large attractive force ⇒ coalesce ⇒ Larger and larger sizes

⇒ Radiation pressure acting on the moving SQN's inhibit such attractive tendencies

⇓ till such time, gravitational force dominates

⇓ SQN's formed at QCD phase transition epoch

$\sim 10^{44}$ GeV (mass) & sizes $R_N \sim 1$ metre

Compared to other particles like the usual baryons or leptons

Lumps of strange quark matter
(strangelets)

⇓

COSMIC ray flux

$A \sim 350-500$
$Z \sim 10-20$ } Kasuya et. al.
Phys Rev. D47

propagation of strangelets through earth's atmosphere:

$$\frac{d\vec{v}}{dt} = -\vec{g} + \frac{q}{m_s}(\vec{v}\times\vec{B}) - \frac{\vec{v}}{m_s}\frac{dm_s}{dt}$$

$A = 64$ a.m.u. ⇒ $A \sim 340$ amu
at 3.5 kms

$(5-10)/100\,m^2$ per yr.

→ Universe is flat $\Omega = \rho/\rho_c$
$= 1$

→ Baryons contributing only 10%
$\Omega_B = 0{\cdot}1$

Other matter, cold dark matter
(CDM)
clumping on small on galactic/supergalactic
scales

→ $\Omega_{CDM} \sim 0{\cdot}35$

→ The rest of the closure density → vacuum
energy → Dark energy → Acc^l expansion
of the universe.