HAWKING RADIATION FROM THE "STRANGE" RELICS OF THE COSMIC PHASE TRANSITION

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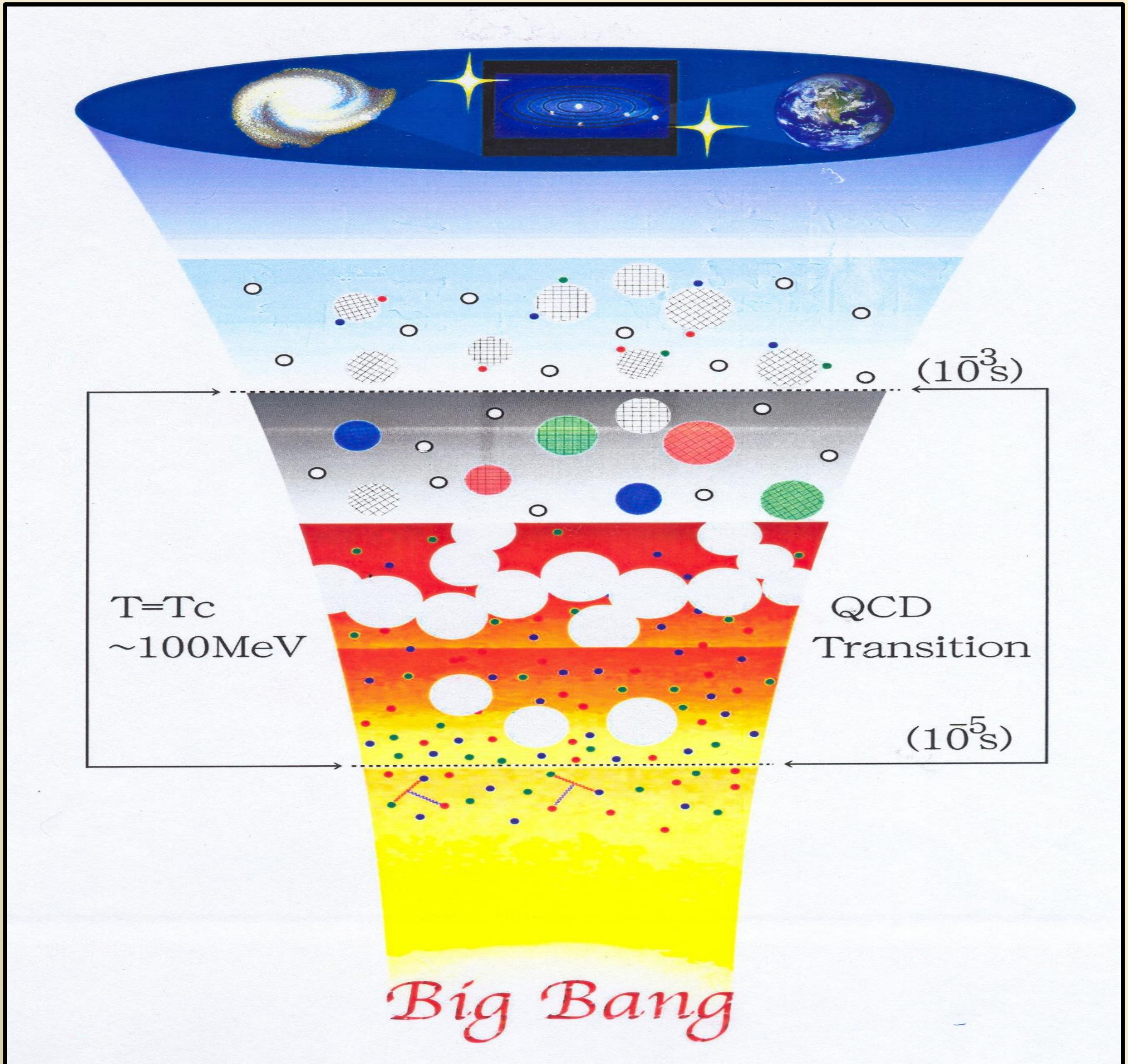

$(10^{-3}s)$
T=Tc
~100MeV
QCD
Transition
$(10^{-5}s)$
Big Bang

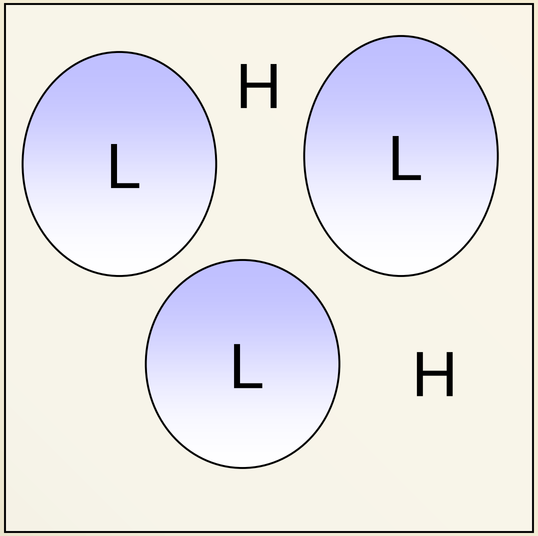
Using Roberston – Walker Metric (Einstein's eqn.)

$$t = 0.3 g^{-1/2} \frac{m_{pl}}{T^2}$$

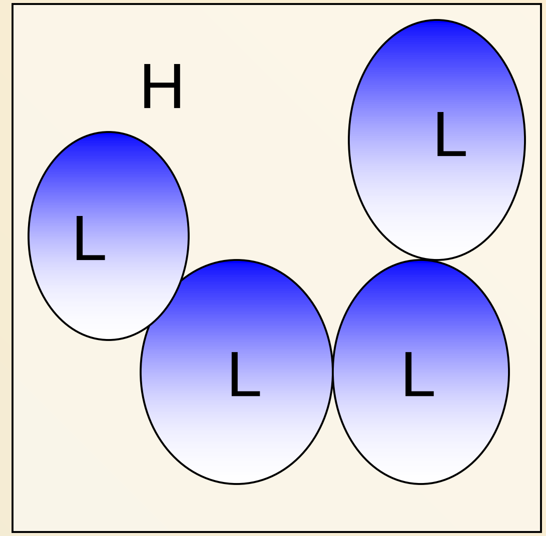
$$\underset{\sim}{t} \equiv \left(\frac{MeV}{T}\right)^2$$: Critical Temp for phase transition

from quarks – hadrons : T_c ~ 150 MeV ~ 44 μ sec

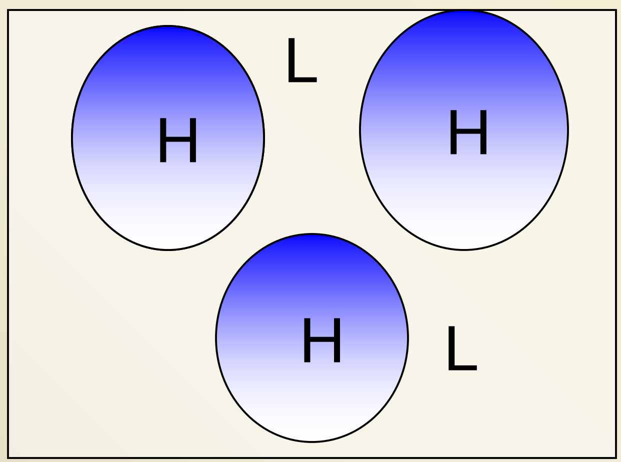
Strange quark nuggets (SQN)



Isolated expanding bubbles of low temp.
In high temp phase



Expanding bubbles meet

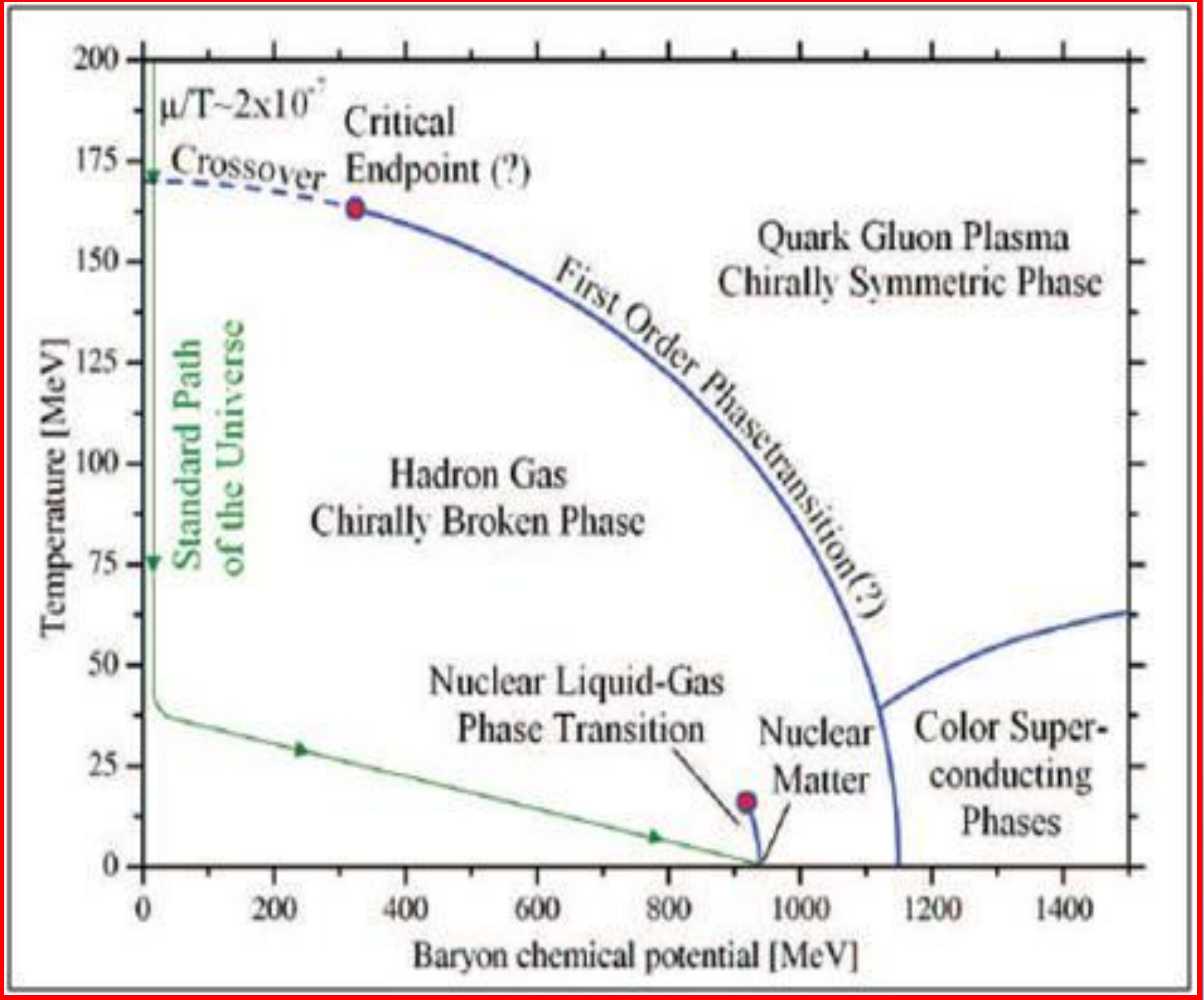


Isolated shrinking bubbles of High temp phase

E. Witten
Phys. Rev.
D 1984, 30272

The Enigma
of
Cosmic Phase Transition

Fig 2: The standard QCD phase diagram, for a transition from quarks to hadrons, in the early universe.



Boeckel T. et al., ***Phys. Rev. Lett.*** **105, 2010**

Boeckel T. et al., ***Phys Rev.*** **D 85, 2012**

The universe starts in the upper left, moves along the temperature axis from the chirally symmetric quark gluon plasma and then crosses over to chirally broken hadron gas phase. Once it reaches to 35 MeV, protons and antiprotons stop annihilating, the chemical potential then goes up rapidly from 1 eV to about the nucleon mass. In this scenario no imprint of that primordial epoch survives

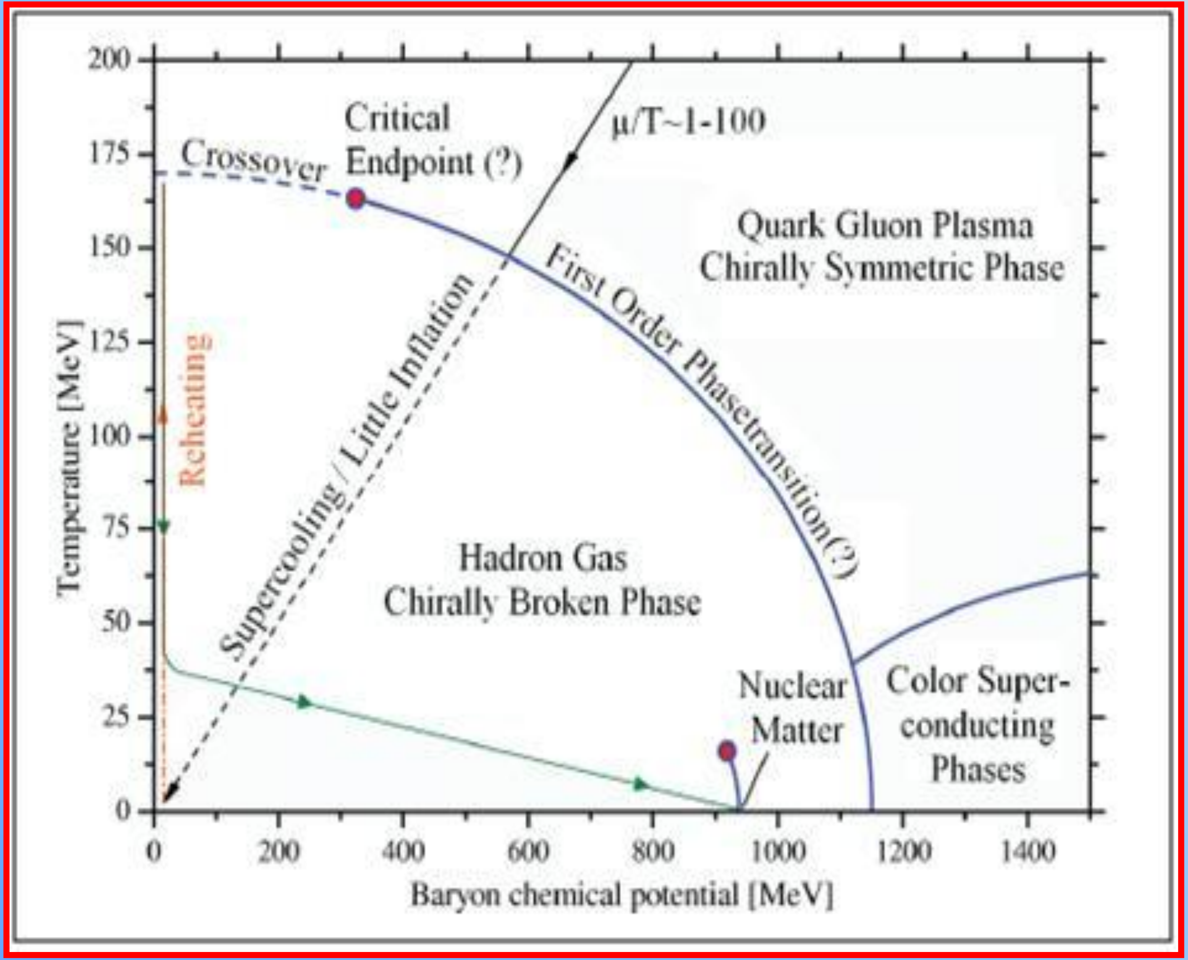
What about a first order q-h phase transition?

For a first order QCD phase transition in the early Universe to be possible a non-vanishing baryo-chemical potential $\mu_B / T \sim \mathcal{O}(1)$

The number of baryons in a comoving volume is constant and can be estimated to be $N_B \approx a_i^3 \mu_{Bi} T_i^2 \simeq a_f^3 \mu_{Bf} T_f^2$ where the index i refers to the initial values when the vacuum energy starts to dominate over the radiation energy and f to the final values after reheating. Therefore the initial ratio of the chemical potential to the temperature can be higher by $\frac{\mu_{Bi}}{T_i} \simeq \theta^3 \frac{\mu_{Bf}}{T_f} (\frac{T_f}{T_i})^3$

with $\theta = a_f/a_i$. If the time scale for the decay of the false vacuum is short compared to the Hubble time then $T_i \simeq T_f$ and already for $\theta \sim 10^3$ (corresponding to a little inflationary period with $N \approx 7$ e-foldings) the initial baryon asymmetry η_{Bi} and μ_i/T_i will be of order unity. Hence, the evolution of the early Universe could pass then through the first order chiral phase transition of QCD.

Fig 3: The path of the evolution of the universe is demonstrated in a “little inflation scenario”.



Boeckel T. et al., *Phys. Rev. Lett.* 105, 2010

Boeckel T. et al., *Phys Rev.* D 85, 2012

Driven by little inflation, the universe starts with a large baryon chemical potential, crosses the first order phase transition but stays in the deconfined chirally symmetric phase. The universe is trapped in a false QCD vacuum, undergoes a short period of inflation upto the point when delayed phase transition takes place.

The released latent heat then causes a large entropy release that dilutes the baryon asymmetry to the presently observed value - then the universe follows the same route as Fig 2.

Chromo electric Flux-tube fission

With a first – order & cosmic phase transition

P. Bhattacharya
J. Alam
S. Raha
B.S. (PRD ’93)

$$[dN_B/dt]_{abs} = -2\pi^2 \, [\, n_N \, V_N \, / \, m_N \, T^2] \exp [m_N - \mu_N^q \, / \, T \,] \, [\, dN_B \, / \, dt \,]_{ev}$$

Rate of change of baryon number of the QN is

$$dN_B /dt \; = \; [dN_B/dt \,]_{ev} \; + [dN_B/dt]_{abs}$$

QN with a baryon number N_B at the time t will stop evaporating further (thus survive) if the "time scale" of evaporation

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

>> Hubble expansion (Cooling time scale)

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

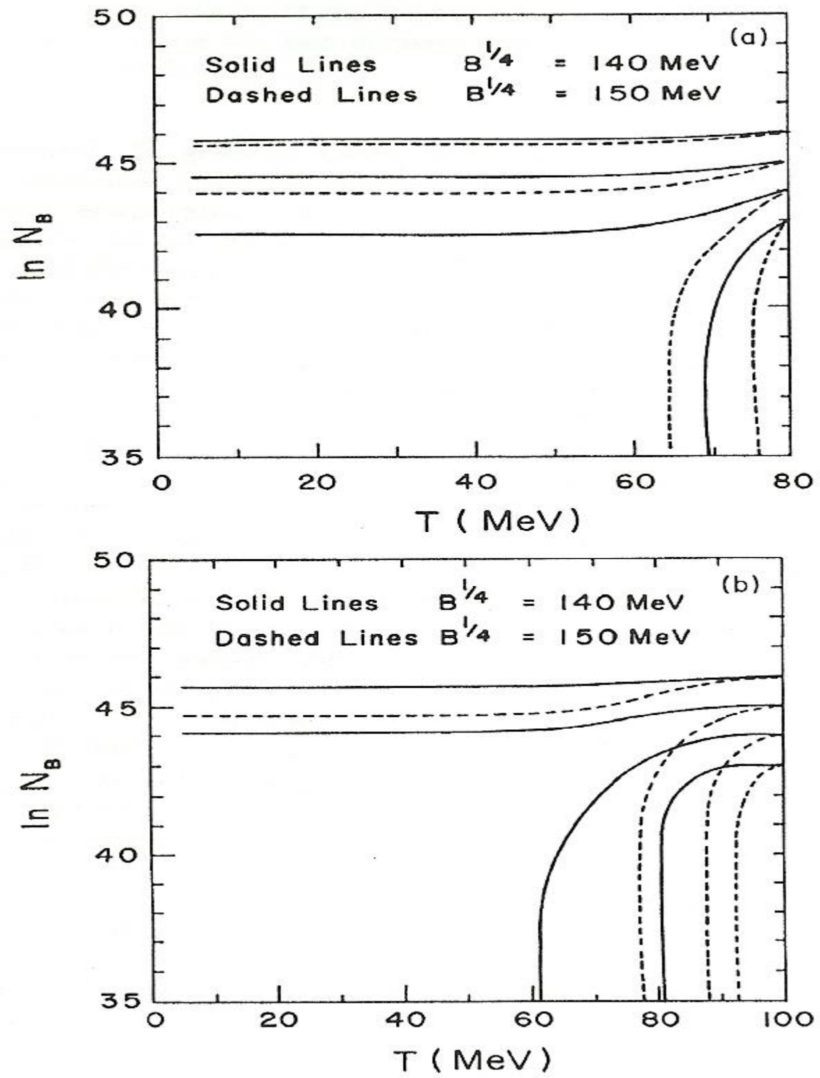


FIG. 2. (a) Evolution of the baryon number of quark nuggets with temperature for two different values of the bag constant B as indicated, for $T_{in}=80$ MeV, and $\alpha_c=2.0$. (b) Same as (a), with $T_{in}=100$ MeV.

[Source: P. Bhattacharjee, J. Alam, B. Sinha and S. Raha, 1993, Phys. Rev. D 48, 10, 4630-4638

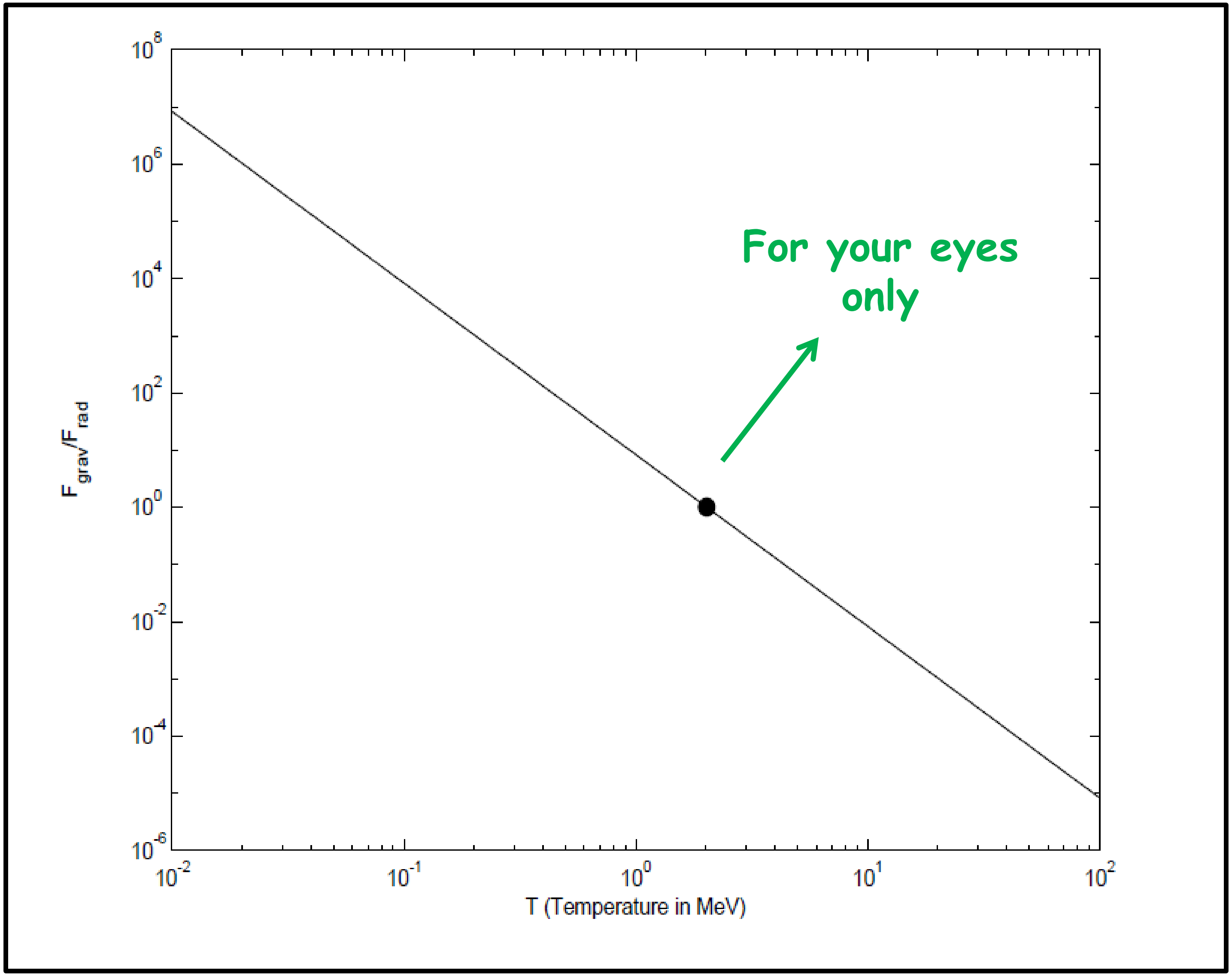
For temperature less than some critical temperature Tcl ≈ lMeV, gravity takes over, Fgrav/Frad <1, and SQN's go through gravitational clumping

These clumped SQN's are the MACHOs. Beyond a certain mass, no clumping takes place; density of such objects had become too small. For baryon number $b_N \sim 10^{42}$ at Tcl ~ 1.6 MeV, $M/M_{\odot}$ = 0.24; for $b_N \sim 10^{44}$ at Tcl ~ 4.4 MeV, $M/_{\odot}$ = 0.01

So, Quark Nuggets with $N_{B\,,\,in} \geq 10^{43.5}$ are stable and survive forever!!

Gravitational force & Radiative force

* S. Banerjee et. al. Mon. Not. R. Astron. Soc. 340, 284 (2003)



The dot represents the point where the ratio assumes the value 1.

Witten (1983) has argued quite convincingly the quark nuggets which survive are likely to be made of strange quarks (SQN), lowest state of energy.

The argument goes as follows:

(1) Addition of strangeness does not stabilize nuclear matter because strange baryons are heavier than non strange baryons, fermi momentum ~ 35 MeV or so, much less than strange quark mess.

(2) Quark Matter is very different:

For quark matter the likely Fermi momentum ~ (300 – 350) MeV, more than the strange quark mass; So for non strange quarks to transform to strange quarks energetically favoured, lowering the Fermi momentum

SQN’s are Non luminous (Dark) Baryonic Dark Matter

Candidates for MACHO

MACHO $\longrightarrow$ massive astronomical compact halo objects

Hawking – Unruh radiation from the SQNs, the relics of cosmic phase transition
Quark to hadron

BLACK HOLE ANALOGY

Quark Nugget $\Rightarrow$ Black hole

In the Hawking- Unruh radiation scenario while 'G' ensures gravitational attraction and `B' ensures confinement. Similarly, the Hawking radiation from a black hole, with its celebrated connection to entropy, has an analogous scenario to that of the quark nuggets that survive the cosmic phase transition. The strange quark nuggets radiate neutrons but remain dark and cold.

Strange Quark Nuggets are somewhat analogous to black holes, tend to absorb matter as they hurtle through the cosmos.* An attempt is being made here to find out a modified entropy "entropy equivalence" between black hole and SQNs. This was first initiated by Hawking-Unruh radiation [Castorina et al., Eur. Phys. J. C 52, 187, (2007)].* Also, S. Banerjee et. al 1999 Phys. Rev. D30 2000 Phys. Rev. Lett. 85

It is instructive to consider the Schwarzschild radius of a typical hadron, assuming a mass m ~ 1 GeV:

$$R_g^{had} \cong 1.3\ X\ 10^{-38} GeV^{-1} \cong 2.7\ X\ 10^{-39}\ fm$$

To become a gravitational black hole, the mass of the hadron would thus have to be compressed into a volume more than 10^{100} times smaller than its actual volume, with a radius of about 1 fm. On the other hand, if instead we increase the interaction strength from gravitation to strong interaction, we gain in the resulting "strong" Schwarzschild radius R_s^{had} a factor

$$\frac{\alpha_s}{Gm^2}$$

$$R_s^{had} \cong \frac{2\alpha_s}{m}$$

with the effective value of α_s ~ O(1) we thus get $R_s^{had} \sim O(1)$ fm. In other words, the confinement radius of a hadron is about the size of its “strong” Schwarzschild radius, so that we could consider quark confinement as the strong interaction analogue of the gravitational confinement in black holes

Bekenstein Hawking

Black hole $M = (1/2G)R$

$1/2G \equiv$ String Tension $= \sigma$

$GM^2 \rightarrow \alpha_s$ (Quark Sector)

$\sigma \cong m^2/2\alpha_s \sim 0.16\ \mathrm{GeV}^2$

Color confinement in QCD does not allow colored constituents to exist in the physical vacuum and thus in some sense color confinement is similar to gravitational confinement provided by black holes. Thus, while ‘G’ ensures gravitational attraction and eventually to black holes, ‘B’, the Bag pressure ensures confinement of quarks leading to colorless physical vacuum (white holes) in QCD. Physically vacuum is colourless, white. Not to confuse with the cosmological white hole.

It has been argued * that quantum tunnelling through a color event horizon is the QCD counterpart of Hawking- Unruh radiation from the gravitational black holes.

*P. Castorina et. al. Eur. Phys. JC 52, 187, (2007) Let us consider the SQNs, after the gravitational collapse as QCD white holes, with neutrons tunnelling out from the event horizon. The natural length scale for SQNs, heuristically, can be argued as $L_B = M_N/M_{\odot}(B^{1/4})^{-1}$ *, M_N being the mass of the SQN and B the Bag Pressure which keeps the color confined. So, the entropy for QCD white hole becomes

*Sinha B, 2016, JP conf. series 668, 012028

Hawking's entropy relation to the area and the length scale

$$S_{QN} = (A/4L_B^2) = \pi R^2 B^{1/2} \left({M_N}/{M_\odot} \right)^{-2}$$

The celebrated area law of Hawking entropy can be written as

$S=\pi R^2/G$; for QCD, $G\equiv 1/2\sigma$; $\sigma=0.16\ GeV^2$

σ being the string tension.

The confinement radius R of a SQN is equivalent to the “strong” Schwartzchild radius equivalent of the gravitational black hole.

P. Castorina et. al. Euro. Phys. JC 52, 187

$$S = 2\pi R^2 \sigma = \pi R^2 B^{1/2} \left({}^{M_N}/_{M_\odot} \right)^{-2}$$

thus $B^{1/2} \left({}^{M_N}/_{M_\odot} \right)^{2} = 2\sigma$, it is noted that in the final expression “strong” schwartzchild radius gets crossed out as it should”. For $B^{1/4}$=150 MeV; $(M_N/M_\odot)$=0.265 and for $B^{1/4}$=200 MeV $(M_N/M_\odot)$=0.35; the result agrees closely with the results obtained by Banerjee et al.* although derived from a very different route of arguments.

* S. *Banerjee et al*. Mon. *Not*. *R*. *Astron*. *Soc*. *340, 284* (2003)

Using the conjectured analogy between black hole thermodynamics and the thermodynamics of confined charged quarks, the SQNs, we transliterate black hole mass, charge and gravitational constant* into the mass M_N of the SQNs, baryon number B_N and the string tension σ

$$\{M, Q, G\}_{BH} \leftrightarrow \left\{M_N, B_N, {}^{1}\!/_{2\sigma}\right\}_{QN}$$

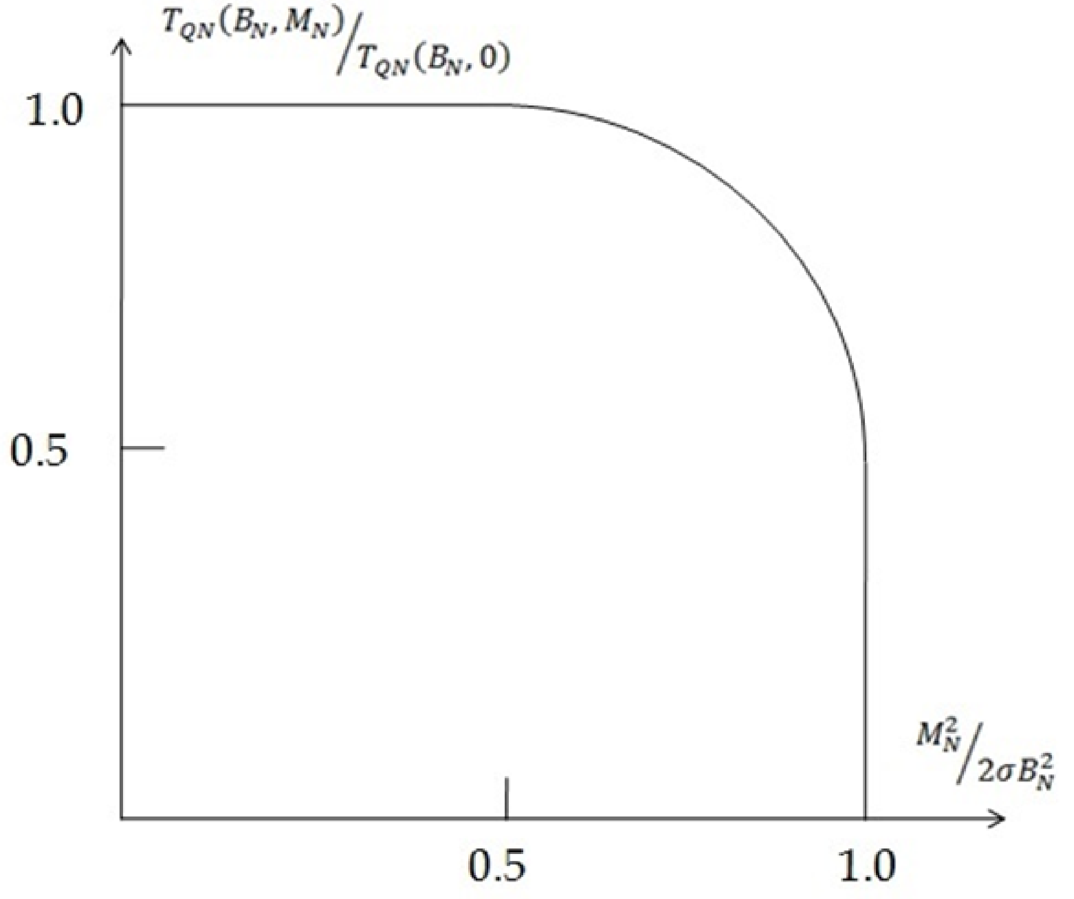
*Castorina P. et. al 2007, Eur. Phys

Such that

$$T_{QN}(B_N, M_N) = T_{QN}(B_N, M_N = 0) \times \left[\frac{4\sqrt{1 - {M_N^2}/{2\sigma B_N^2}}}{\left(1 + \sqrt{1 - {M_N^2}/{2\sigma B_N^2}}\right)^2} \right]$$

B. Sinha, arXiv: 1904.04345 physics.gen-ph, March 2019

Hawking temperature as a function of mass M_N and the baryon number B_N of the nuggets; σ is the string tension



The phase transition is not instantaneous but happens over a period of time*; for a critical temperature of transition 100 MeV, the time it takes for the phase transition ≈ $t_{ch} \sim 144$ µsec. and for a critical temperature 150 MeV $t_{ch} \equiv 64$ µsec; during this time all the quarks inside the nugget, acquires mass, as chiral symmetry gets broken.

* A. Bhattacharya et. al. 2000 Phy. Rev. D 61 083509

For the temp. from T_{QN} (B_N, O) ($\approx$ 150 MeV) to go to zero Hawking temp. takes about $\approx$ 50 μsec.

One has attempted so far utilizing the possible equivalence of gravitational black hole and QCD white hole to drive the mass of QCD white hole which survives the evolution of the universe uptill now. Using the same conceptual framework we have derived the baryon number at which evaporation or equivalently tunneling out of the QCD white hole stops. Stopping of Hawking radiation from white holes indicate the survivability of the nuggets.

Where do these SQNs go? Originally, it was proposed that these SQNs are the MACHOs, the Massive Astrophysical Compact Objects*, detected in the direction of the Large Magellanic Cloud (LMC) of mass range (0.15-0.95)$M_\odot$, with a probable mass of 0.5$M_\odot$, and the total number being $N_{macho} \approx 10^{23-24}$. These MACHOs are candidate of baryonic dark matter*.

*Mon. Not. R. Astron Soc. 340

Other Signals of

Little inflation scnario ⇒ first order QCD phase transition

i) Primordial Density fluctuation upto the dark matter mass scales of $M_{max} \sim 1 M_{\odot}$

ii) Extra Galactic magnetic fields

iii) Gravitational wave spectnum with a frequency around $V_{peak} \sim 4 \text{ X } 10^{-8}$ Hz

In galaxy formation SQNs would behave like the planetory mass black holes.