The Cosmic Quarks

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There are at least three sources of cosmic quarks in the universe. One, the quark nuggets which may survive beyond a certain baryon number during the phase transition from quarks to hadrons microsecond after the big bang.

For a cross-over there will be no relic. We shall demonstrate that a mini inflation 7-e folding accompanied by super cooling lead to a first order phase transition.

These quark nuggets can very well be a candidate of cold dark matter and these nuggets consists of strange quark.

P. Bhattacharya et. al., Phys. Rev. D48 4630
B. S. Int. JMP A29 1432004

Second, the interior of the neutron star may well be made of quarks due to very very high pressure. It is further shown that the interior of heavy neutron star, recently discovered $\approx 2M_{\odot}$, with an appropriate equation of state, can also be made of quark core.

B.Sinha, Int. J Phys Conf. Series 668 (2016)

Finally, using the property of colour entanglement among quarks it is entirely possible to have free orphan quarks roaming around the cosmos.

S. Banerjee et. al., Phys. Letts B 611 (2005)

Quark- Hadron Phase transition
Massive Compact Halo Objects (MACHO)

C. Alcock et. al. Nature 365 621 (1993)

WIMPS
Brown Dwarfs
Jupiter like Objects
Neutron Stars/ Even Black Holes

Primordial Quark Nuggets
Strange Quark Nuggets are the WIMPS

B. S. Int. JMP A29
Witten 1984, Phys Rev D 30

Bose Institute Group

Banerjee S. et. al., 1999 Phys Rev D 30
Banerjee S. et. al., Phys Rev Lett 85 (2000)

Initial mass ~ 64 amu and charge ~ 2 acquires mass and goes upto mass ~ 340 amu ~ 3.6km above the sea level, typically at Darjeeling height in the Himalayas.

Strange Quark Matter

(a) Formation of QN’s
(b) Survival

Wisdom of lattice cross over
$q \longrightarrow h$: no relic

Lattice Calculation with bare quarks in an expanding universe??

$\eta = (n_B - n_{\bar{B}})/\gamma$ same order $\eta \sim 10^{-10}$

But at that primordial epoch, with mini inflation $\eta \sim \mathcal{O}(1)$

Then after the phase transition $\rightarrow 10^{-10}$

Witten: small amount of super cooling

Pvt. Comm.: If $\eta \sim 10^{-10}$ supercooling is impossible : Large $\rightarrow$ small

Super cooling is plausible

Affleck Dine mechanism Nucl Phys B 249 361 (1985)

Produces baryon asymmetry $\mathcal{O}(1)$ without superhigh temperatures → η=10^{-10} later at CMB temp. must come naturally: Little Inflation

Boeckel T and Schaffner- Bielich
Phys Rev Lett 105 041301
Phys Rev D 85 2012

The entropy in the standard Guth inflation is conserved during the exponential expansion: In the present case of "mini inflation" the entropy is continuously increasing.

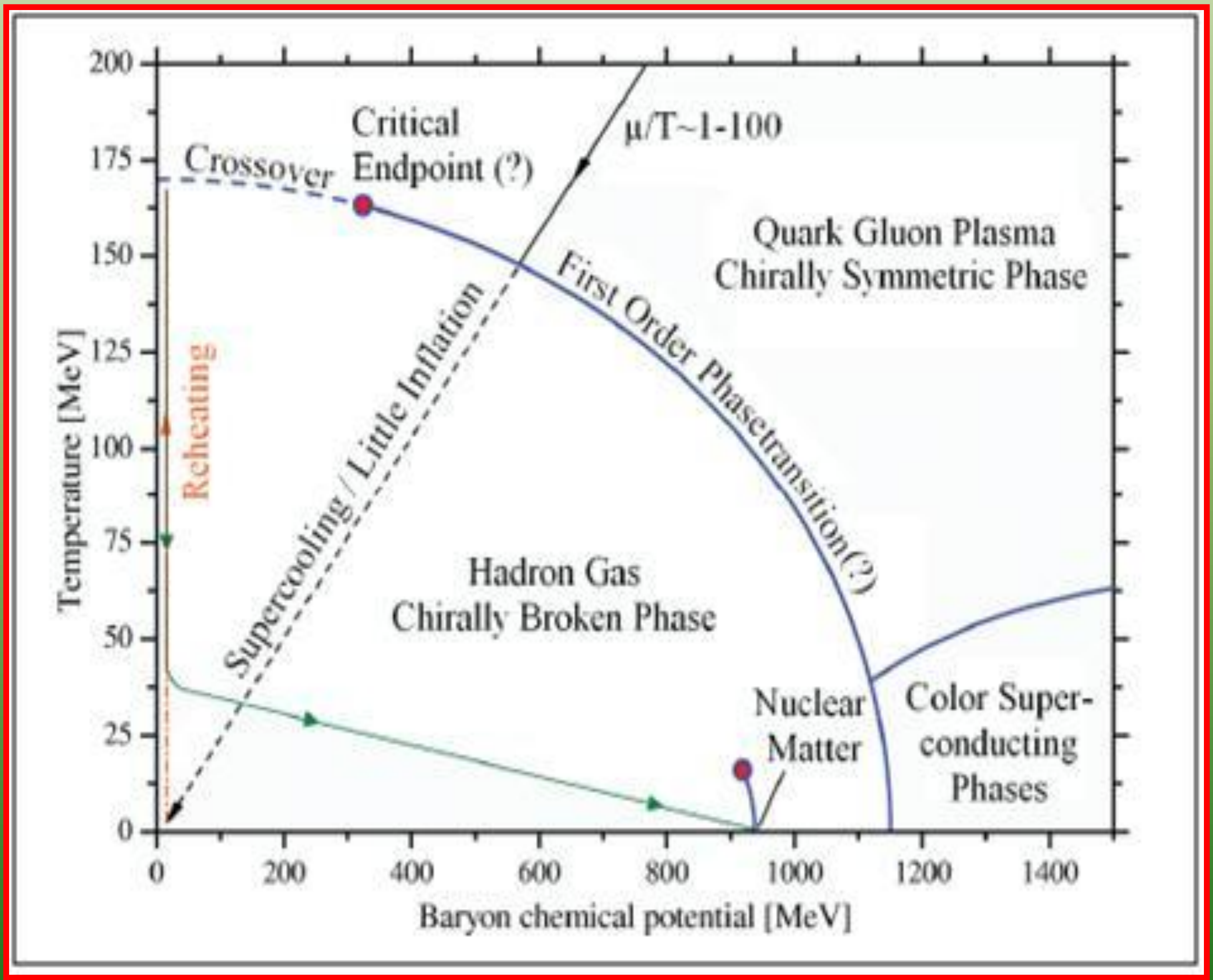
In the mini inflation scenario

$$R_{infl} \sim exp(c\sqrt{B}t) \qquad c = (8\pi/3)^{1/2}/M_P$$

$$R_{Guth} \sim \exp(\chi t) \qquad \chi = \sqrt{8\pi/_{3G\rho_0}}$$

ρ_0 **is energy density of the universe**

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

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)

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

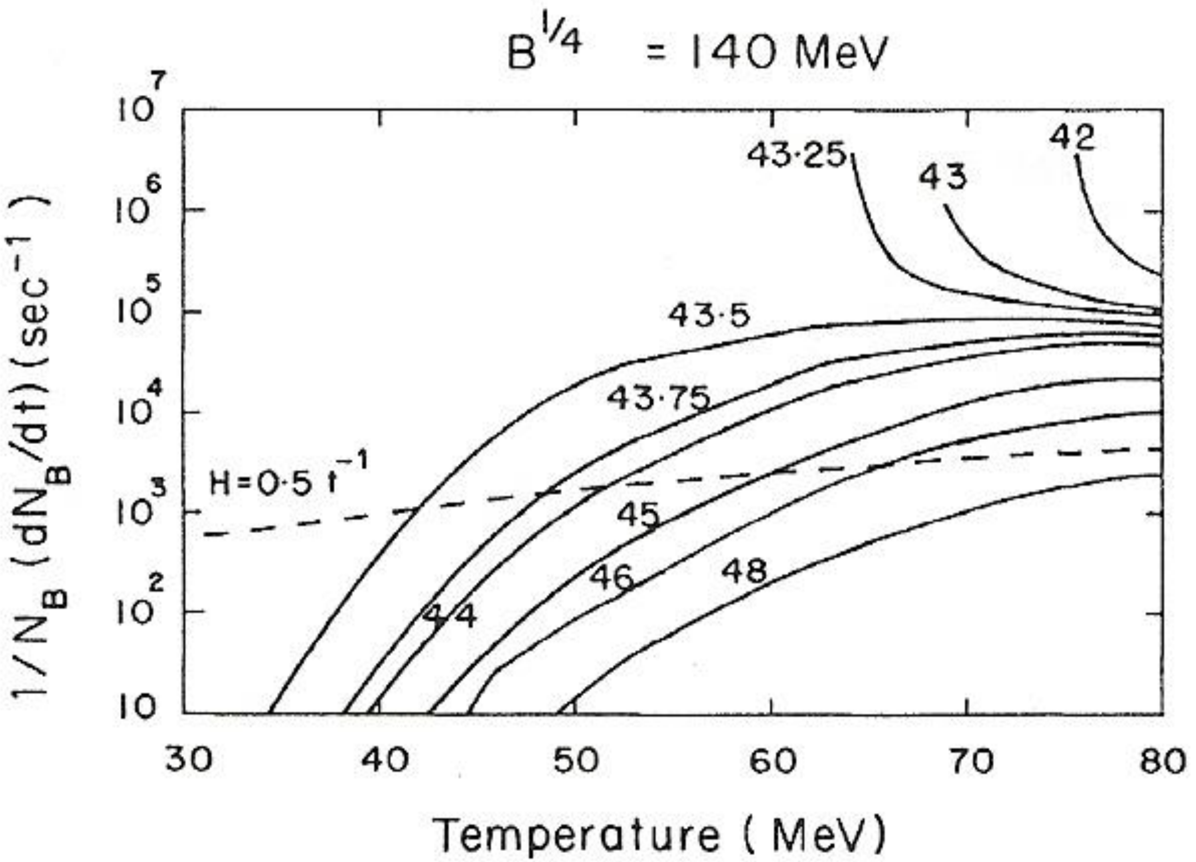


FIG. 1. The inverse of the baryon evaporation time scale as a function of temperature for nuggets with different values of initial baryon number ($\ln N_{B,\mathrm{in}}=42$, 43, 43.25, and so on as indicated). The bag constant is $B^{1/4}=140$ MeV, and $\alpha_c=2.0$. The dashed curve is the Hubble constant whose present epoch value is taken to be 75 km $\sec^{-1}\mathrm{Mpc}^{-1}$.

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

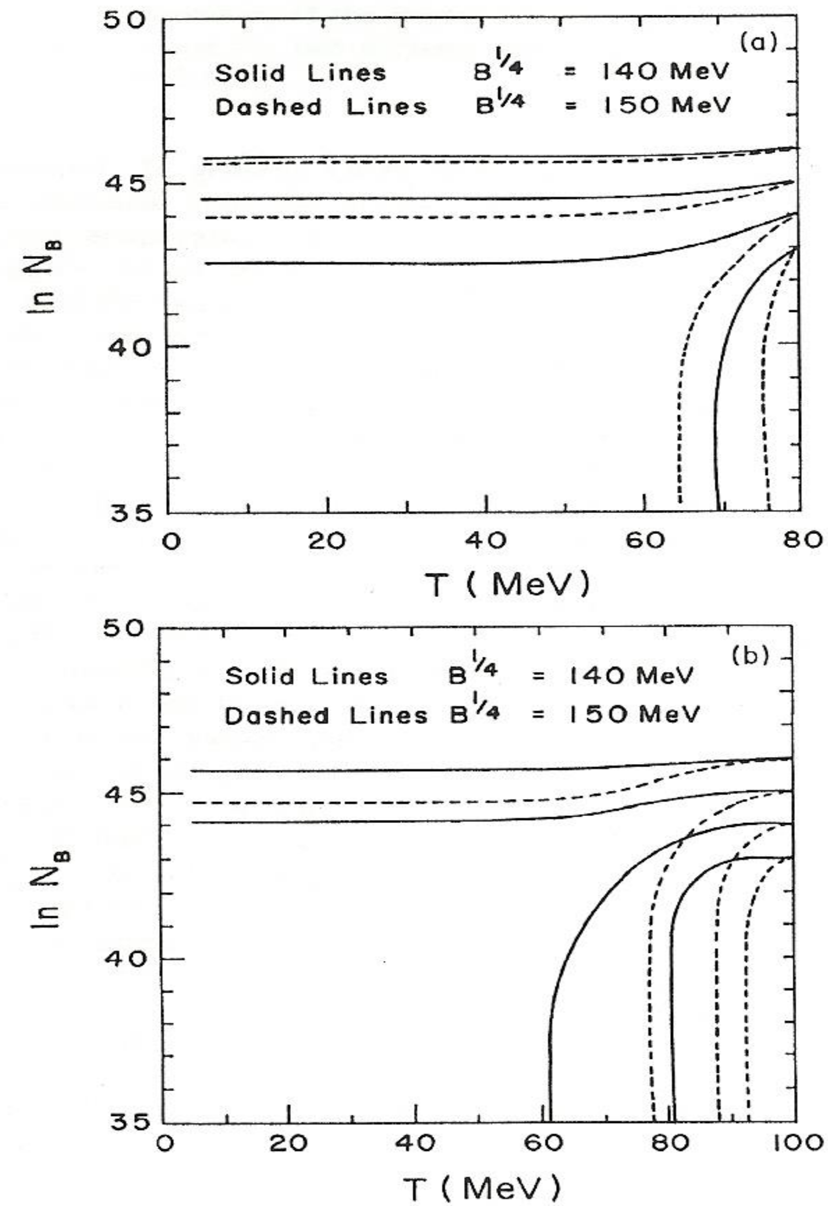


FIG. 2. (a) Evolution of the baryon number of quark nuggets with temperature for two different values of the bag constant B as indicated, for $T_{in}=80$ MeV, and $\alpha_c=2.0$. (b) Same as (a), with $T_{in}=100$ MeV.

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

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

The mini-bang between two nuclei, although mimicing the big bang of the universe, is somewhat different.

It is clear however, that the role played by the Newtonian constant of Gravity, G, in the big bang is somewhat analogous to the role played by the vacuum energy density often referred to as the bag constant, B. The Big Bang is a display of gravity, space, and time, whereas the little bang is essentially dealing with confinement and subsequently deconfinement in extreme conditions.

On the other extreme end of the phase diagram lies a domain of very high baryon density at rather low temperature, the scenario of neutron star matter, of compressed baryonic matter (CBM) at almost zero temperature. It will be of some interest to compare and contrast the “perfect fluid” property of the quark matter in the microsecond universe with the “perfect fluid” of the core of the neutron star.

It is clear however that for the early universe, we have depleting quark matter as hadronisation progresses and the universe expands in space and time. From the canonical value of η/s≤ ¼π, for quarks with hadronisation, η/s will go on increasing as pointed at Lacey et. al.

Eventually, the SQNs will be floating in a dilute hadronic fluid, which is not so perfect, facing more viscous drag than its quark matter counter part.

In the case of the neutron star, however, the scenario is opposite; more hadrons will be transformed to quarks, so η/s will decrease towards the canonical value η/s≤ ¼π. For the neutron star, an approximate estimate of $\eta/s \sim T\lambda_F c_p$ will indicate that with very low value of $\lambda_F \equiv (\rho\sigma)^{-1}$, a very high ρ and an extremely low temperature η/s for the quark core of the star (with $c_p \sim 1/\sqrt{3}$ (say)) may well go down below the generic value ¼π, close to zero, making the core, a perfect fluid splashing on the membrane of hybrid hadronic matter and quark core.

The recent observation of two massive neutron stars $M=1.97\pm\ 0.04$, $M_\odot$ and $M=2.01\pm\ 0.04M_\odot$ ($M_\odot$ solar mass) indicates that equation of state of dense cold matter must be rather stiff and, that immediately raises the question quark matter, can it be stiff enough to support such massive stars?

As shown by Kojo, Hatsuda and others that with reasonable strength of the vector repulsion between quarks and the diquark pairing interaction can readily support high mass neutron star. This scenario is consistent with other neutron stars of radii 10-12 kms. It should be noted that dense nuclear matter with three- body forces and so on do not quite describe these massive stars. How far this scenario is consistent with lattice calculations is yet to be seen.

Gilden and Shapiro made a numerical study of a head- on collision of two neutron stars at moderately relativistic velocities. They found that about 13% of the mass was ejected from the star system. If quark matter is stable, this 13% would probably escape as lumps of quark matter of various sizes.

Head on neutron star collisions may be rare events. However, neutron star collisions of some kind are almost certainly not rare. Of less than 10^3 known pulsars, there seems to be one known binary neutron star system, the binary pulsar PSR 1913+16. The gravitational radiation from this system gives it a lifetime of 10^8 yr; in that time- short compared to the age of the Galaxy- the two neutron stars will spiral inward and collide. Naively, extrapolating from one known example out of 10^3, it is likely that 10^6-10^7 of the 10^9-10^{10} neutron stars in our galaxy have undergone this fate.

BLACK HOLE ANALOGY

Quark Matter Nugget $\leftrightarrow$ 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 also 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)].

For SQNs, the deciding role is played by the Bag Pressure, B, making the SQNs dark, veiled to an exterior observer. The natural length scale for SQNs, heuristically, can be argued as $L_B = M/M_{\odot}(B^{1/4})^{-1}$, so that the entropy of SQNs is $S_{QN} = A/(4L_B^2) = \pi R^2 B^{1/2}(M_N/M_{\odot})^{-2}$, M_N being the mass of the quark nugget and $M_{\odot}$ is the solar mass, whereas, for the black hole, $S_{BH} \equiv A/(4L_p^2) = (c^3 A)/(4G\hbar)$: $A = 16\pi\ (GM/c^2)^2$, where M is the mass of the black hole. At this preliminary stage, the above ansa̎tz of SQNs' entropy seem to broadly agree with other result.

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 version of the gravitational confinement in black holes.

Bekenstein Hawking

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

$1/2G \equiv$ String Tension

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

$$T_{BH} = \frac{1}{8\pi GM} \leq 2 \times 10^{-8}\ {}^{0}K$$

$$T_\theta \sim \sqrt{\frac{\sigma}{2\pi}} \qquad R_g \approx 1.3 \times 10^{-38}\ \ GeV^{-1}$$

for a hadron compressed by 10^{100} times radius of 1 fm

From gravitation → strong interaction

$$R_s^{had} \sim 2\alpha_s/m \rightarrow \sim \mathcal{O}(1) \text{ fm}$$

$B^{1/4}$ (MeV)	R_N (m)	M_N	M_B	S_{BH}	S_{QN}
140	1	$0.5\ M_\odot$	$M_\odot$	1.06×10^{77}	6.35×10^{30}
140	0.2	$0.5\ M_\odot$	$M_\odot$	1.06×10^{77}	2.54×10^{29}
200	1	$0.5\ M_\odot$	$M_\odot$	1.06×10^{77}	1.30×10^{31}

Colour entangled orphan Quarks for QCD epoch in the Universe:

we assume a first order cosmic QCD phase transition as has been already shown. Other crucial ansaẗze in our scenario include that the universe is overall colour neutral at all times, baryogenesis is complete substantially before the QCD transition epoch and that the baryon number is an integer.

At temperatures higher than the critical temperature T_c, the coloured quarks and gluons are in a thermally equilibrated state in the perturbative vacuum (the quark gluon plasma). The total colour of the universe is neutral (i.e., the total colour wave function of the universe is a singlet). Then, as T_c is reached and the phase transition starts, bubbles of the hadronic phase, begin to appear in the quark-gluon plasma, grow in size and form an infinite chain of connected bubbles (the percolation process).

Within this hadronic phase, the remaining high temperature quark phase gets trapped in large bubbles. As is well known, this process is associated with a fluctuation in the temperature around T_c; the bubbles of the hadronic phase can nucleate only when the temperature falls slightly below T_c. The released latent heat raises the temperature again and so on. It is thus fair to assume that the temperature of the universe remains around T_c at least upto percolation.

The net baryon number contained in these Trapped False Vacuum Domains (TFVD) could be many orders of magnitude larger than that in the normal hadronic phase and they could constitute the absolute ground state of strongly interacting matter as has been argued by Witten. In all these considerations, it has been tacitly assumed that in a many-body system of quarks and gluons, colour is averaged over, leaving only a statistical degeneracy factor for thermodynamic quantities.

Here we argue that such simplification may have led us to overlook a fundamentally important aspect of strong interaction physics in cosmology, that is of quantum colour entanglement, still in an emergent state.

Let us now elaborate on the situation in some detail. In the QGP, all colour charges are neutralised within the corresponding Debye length, which turns out to be $\sim 1/gs(T)T$, where gs is the strong coupling constant. For Debye length smaller than a typical hadronic radius, hadrons cannot exist as bound states of coloured objects. The lifetime of the QGP may be roughly estimated by the temperature when the Debye screening length becomes larger than the typical hadronic radius, and formation of hadrons as bound states of coloured objects becomes possible.

As the phase transition proceeds, locally colour neutral configurations (hadrons) arise, resulting in gradual decoherence of the entangled colour wave function of the entire universe. This amounts to a proportionate reduction in the perturbative vacuum energy density, which goes into providing the latent heat of the transition, or in other words, the mass and the kinetic energy of the particles in the nonperturbative (hadronic) phase (the vacuum energy of the non-perturbative phase of QCD is taken to be zero). In the quantum mechanical sense of entangled wave functions, the end of the quark-hadron transition would correspond to complete decoherence of the colour wave function of the universe; the entire vacuum energy would disappear as the perturbative vacuum would be replaced by the nonperturbative vacuum.

The earlier discussions imply that in order for the TFVDs to be stable physical objects, they must be colour neutral. This is synonymous with the requirement that they all have integer baryon numbers, i.e., at the moment of formation each TFVD has net quark numbers in exact multiples of 3. For a statistical process, this is, obviously, most unlikely and consequently, most of the TFVDs would have some residual colour at the percolation time. Then, on the way to becoming colour singlet they would each have to shed (leave behind) one or two coloured quarks. This is the inherent picture of orphan quarks.

Thus, at the end of the cosmic QCD phase transition there would be a few coloured quarks, separated by spacelike distances. Such a large separation, apparently against the dictates of QCD, is by no means unphysical in this case. The separation of coloured TFVDs occurs at the temperature T_c, when the effective string tension is zero, so that there does not exist any long range force. By the time the TFVDs have evolved into colour neutral configurations, releasing the few orphan coloured quarks in their immediate vicinity, the spatial separation between these quarks is already too large to allow strings to develop between them; see below.

Such a situation could not occur in the laboratory searches for quark-gluon plasma through energetic heavy ion collisions as the spatial extent of the system is ~ few fermi and the reaction takes place on strong interaction time scales. Therefore, the orphan quarks must remain in isolation. In terms of the quantum entanglement and decoherence of the colour wave function, this would then mean that their colour wave functions must still remain entangled and *a corresponding amount of the perturbative vacuum energy would persist in the universe.*

$$\mathbf{f_q \equiv V_{color}/V_{total}}$$

$f_{q,o} \equiv$ orphan quarks

Perturbative vacuum energy density $Bf_{q,0}$
Residual PQCD vacuum energy 10^{-46} – 10^{-48} GeV^{4}.

Banerjee S et al., PLB 611 (2005) 27

Thousands of stars blink away forever.

In the backdrop,

Nataraj is alone and silent.

नित्याय त्रिगुणात्मने पुरजिते कात्यायनी-श्रेयसे
सत्यायादिकुटुंबिने मुनिमनः प्रत्यक्ष-चिन्मूर्तये ।
मायासृष्ट-जगत्त्रयाय सकलाम्नायान्त-संचारिणे
सायं ताण्डव-संभ्रमाय जटिने सेयं नतिश्शंभवे ॥ ५६ ॥

"O Omnipresent, the embodiment of all virtues, the creator of this cosmic universe, the king of dancers, who dances the *Ananda Tandava* in the twilight, I salute thee."

(Source: Verse No. 56, Sivanandalahari by Sri Adi Sankara)

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