Cosmic Phase Transition- a hint of Cold Dark Matter in the Standard Model

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Why Dark Matter ???

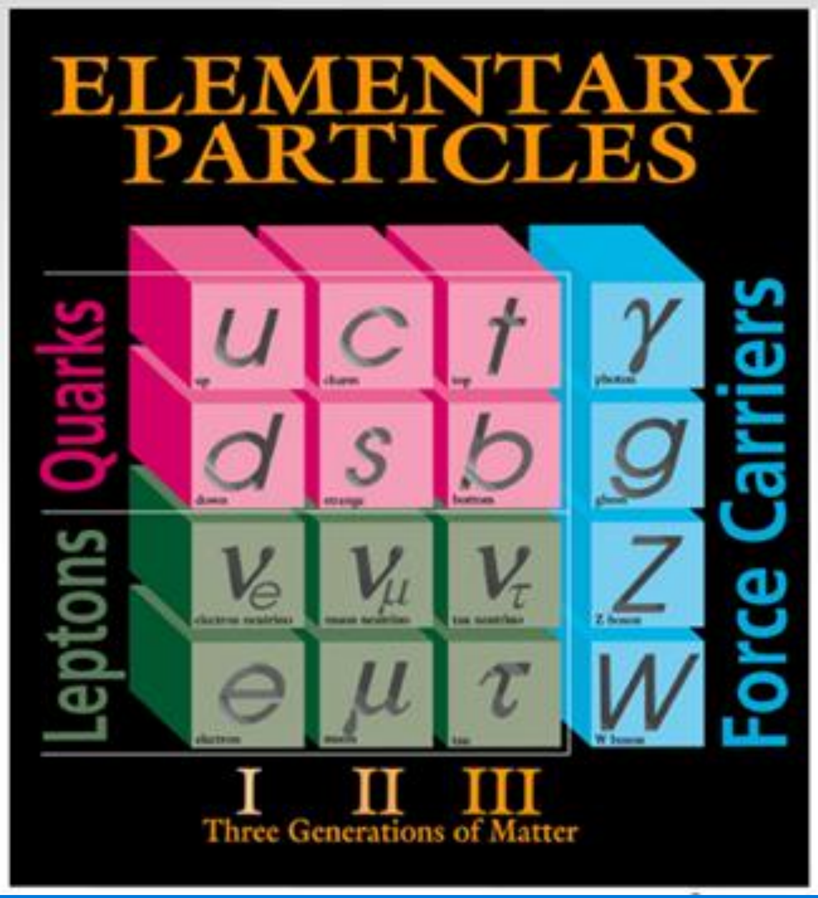
The evidence of the existence of dark matter is by and large gravitational. The discrepancy between the luminous mass and the gravitational mass gives an indication of the presence of a huge unseen mass in the universe.

In order to measure the gravitational mass of a galaxy, or galaxy cluster for that matter, one studies the motion of the galaxy and uses gravitational calculations to estimate the gravitational mass required to keep the system bound, in the same manner that the gravitation between sun and the Earth balances the motion of the sun and the earth around the sun.

The average motion of a star (say) in a spiral galaxy is however fairly circular. Thus one can consider that the velocity of this circular motion is such that it exactly balances the gravitational force of the star toward the galactic center in order to keep it in the circular motion.

General Properties of Dark Matter

- **Should be neutral**
- **Gravitationally interacting only**
- **Stable**
- **Very weak at best or Zero interaction with other particles**
- **major constituents is perhaps heavy (massive) particles (non- relativistic while decoupling)**



Spiral Galaxy

Elliptical Galaxy

For a star in such a galaxy at a distance r from the galactic center moving with a circular velocity v(r), we have the gravitational force balancing the centrifugal force given by the equation

$$\frac{mv(r)^2}{r} = \frac{GmM_{<r}}{r^2} \quad \ldots(1)$$

where $M_{<r}$ is the mass enclosed within the radius r. If the star is within the dense central region (or central hub) of the galaxy, the, $M_{<r} = \left(\frac{4\pi}{3}\right) r^3 \rho$ where ρ is the average density of the central hub. Therefore, within the central hub one expects from eq. 1

$$v(r) \sim r.$$

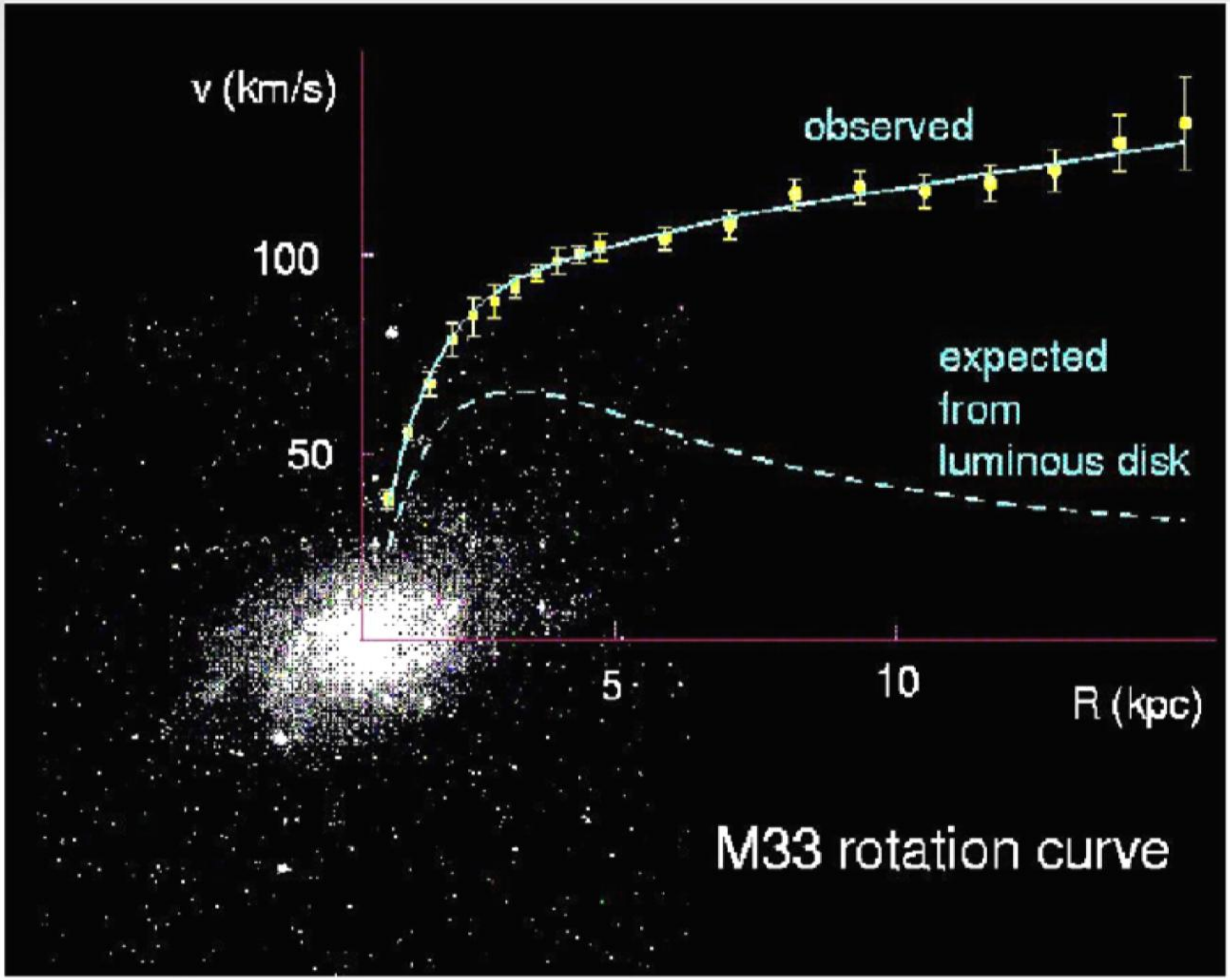
But for a star outside this dense central hub, the mass $M<r$ can be taken to be constant and then from Eq. 1 it follows that

$$v(r) \sim \frac{1}{r^{1/2}}$$

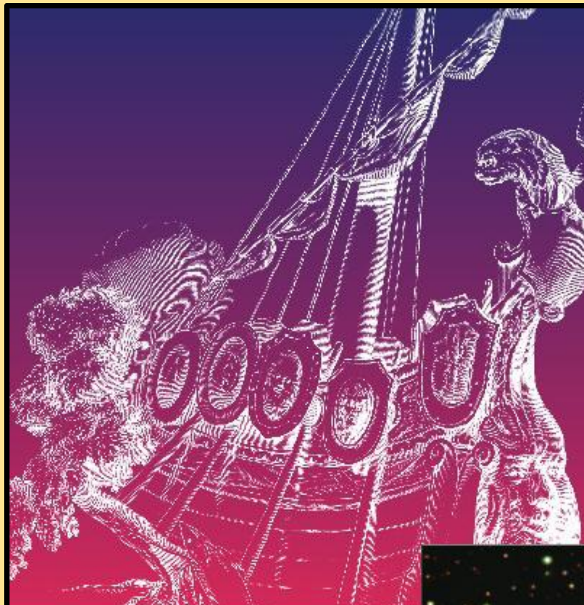
Thus the variation of v(r) with r for a spiral galaxy should show an initial increase (when $r \leq$ the radius of the central hub) and then should suffer a decline (Keplerian decline) that goes as $1/\sqrt{r}$. But the observational measurements of rotation curves for several spiral galaxies show v(r)= constant for large r. then one gets from Eq. 1 that $M_{<r} \sim r$, suggesting the presence of an enormous unseen mass in the galaxy.

This unseen matter or dark matter in fact is believed to form a “halo” of dark matter within which the galaxy is embedded. An example of such a rotation curve is given in Fig 1., which shows the features discussed above.

Flatness of Rotational Curve



G. Jungman et al., Phys Rep 267, 1996



Bullet Cluster

WHO: The "Bullet Cluster," named for its distinctive shape, is formally known as 1E 0657-56, and is the result of the collision of two enormous clusters of galaxies.

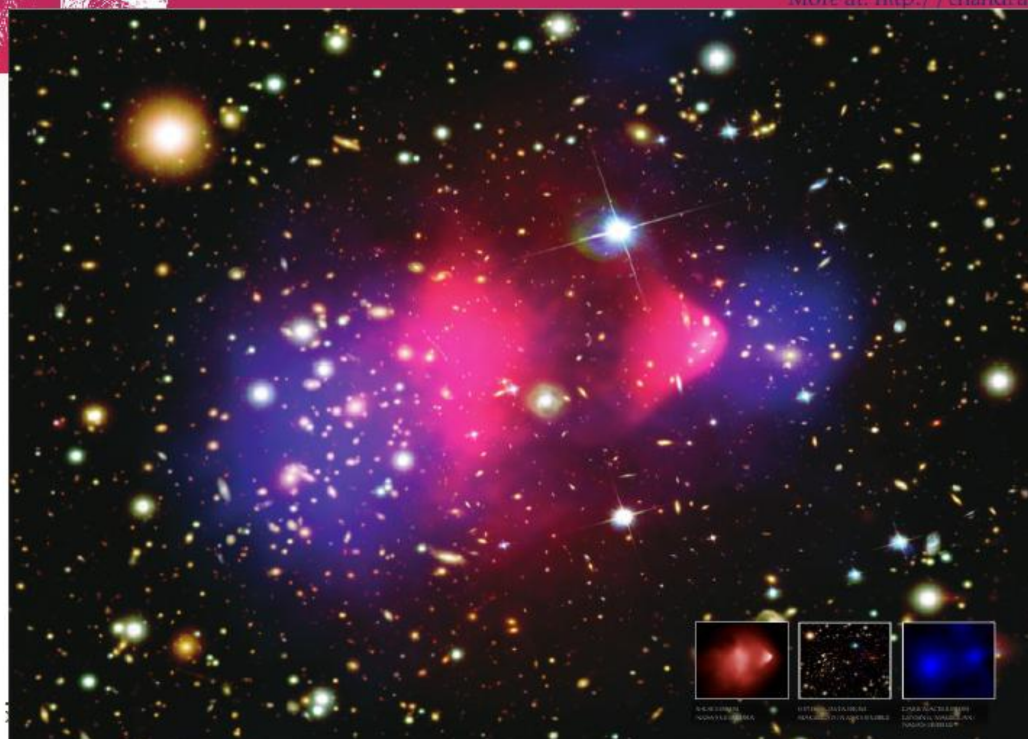
WHAT: The collision that created the Bullet Cluster was one of the most energetic events since the Big Bang.

WHERE: At a distance of nearly 4 billion light years from Earth, the Bullet Cluster is located in the constellation Carina, or the "keel" (bottom of a ship).

WHEN: The speed and shape of the bullet, and other information from various telescopes suggest that the smaller cluster passed through the core of the larger one about 150 million years earlier.

HOW: When these two enormous objects collided, they did so at speeds of several million miles an hour. The force of this event was so great that it wrenched the "normal" matter in the form of hot gas (seen in pink) away from the dark matter (blue).

WHY: The separation between the hot gas and the dark matter in this system is direct evidence that dark matter does, in fact, exist. The exact nature of dark matter remains unknown, but it is thought to account for about 25% of the matter in the Universe.
More at: http://chandra.harvard.edu



There is now abundant evidence for the presence of large quantities of unseen matter surrounding normal galaxies, including our own. The nature of this dark matter is unknown, except that it cannot be made of normal stars, dust or gas, as they would be easily detected. Exotic particles such as axions, massive neutrinos or other weakly interacting massive particles (collectively known as WIMP) has been proposed, but yet to be detected.

Alcock C. et al., Nature, 365, 1993.

A less exotic alternative is normal matter in the form of bodies with masses ranging from that of a large planet to few solar masses. Such objects, collectively known as massive astrophysical compact halo objects (MACHOs), might be brown dwarfs or "jupiters" (bodies too small to produce their own energy by fusion), neutron stars, old white dwarfs or black holes.

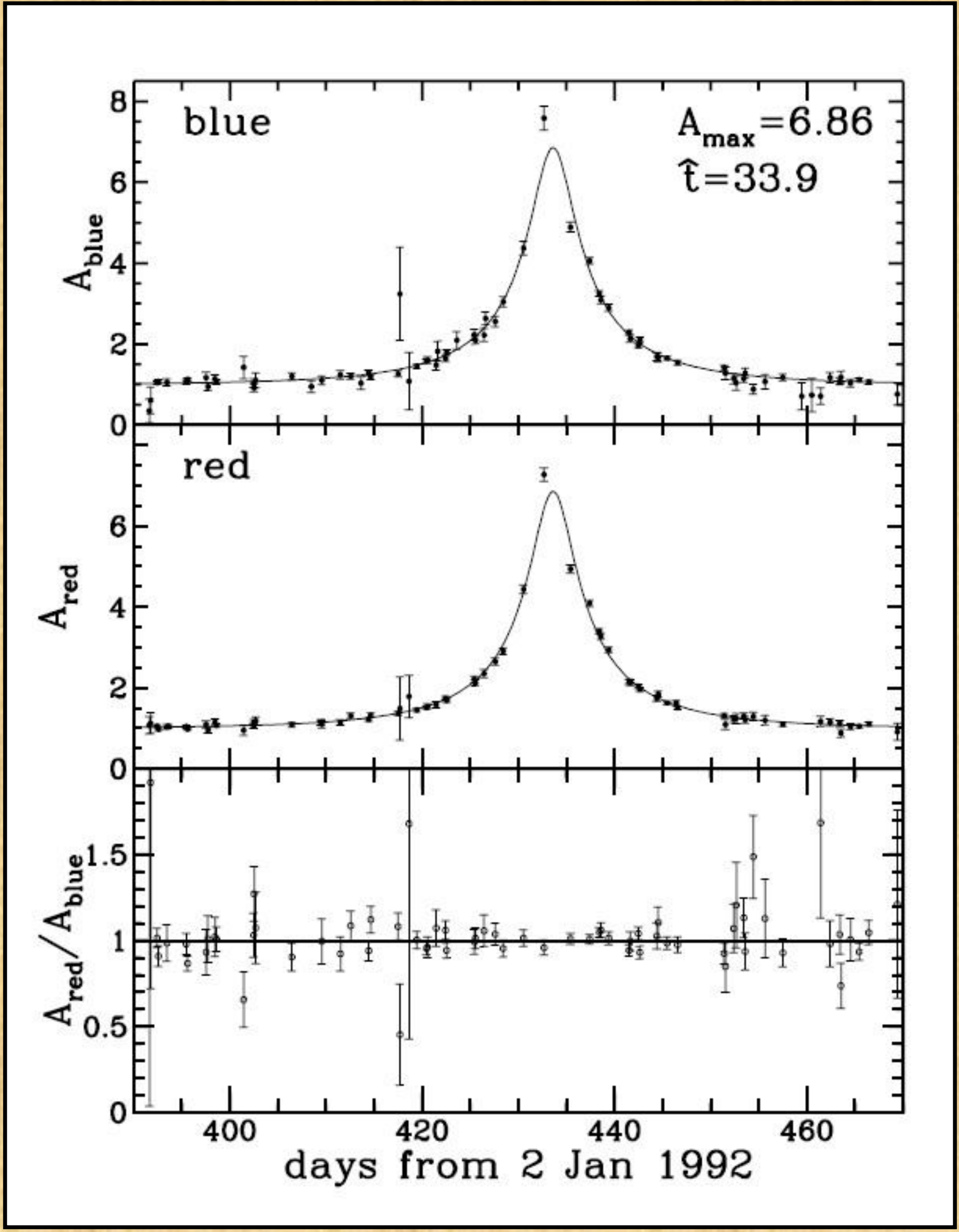
Alcock C. et al., Nature, 365, 1993.

Alcock et al., 1993 conducted a microlensing experiment suggested by Paczynski (1986) to determine whether the dark matter halo of our Galaxy is made up of MACHOs. They reported a candidate for such a microlensing event, detected by monitoring the light curves of 1.8 million stars in the Large Magellanic Cloud for one year.

Alcock C. et al., Nature, 365, 1993.

The light curve shows no variation for most of the year of data taking, and an upward excursion lasting over 1 month, with a maximum increase of ~ 2 mag. The most probable lens mass, inferred from the duration of the candidate lensing event, is ~ 0.1 solar mass.

Alcock C. et al., Nature, 365, 1993.



blue
$A_{max}=6.86$
$\hat{t}=33.9$
A_{blue}
red
A_{red}
A_{red}/A_{blue}
days from 2 Jan 1992
400
420
440
460
0
2
4
6
8
0.5
1
1.5

It has been argued by Bhattacharya et al., 1993; Banerjee et al., 2003 and Sinha B, 2014 quite exhaustively that a natural explanation will be that the MACHOs are the relics from the putative cosmic phase transition from quark to hadrons about a microsecond after the Big Bang. MACHOs, it is argued, can be the quark nuggets which survived from that primordial epoch (Bhattacharya et al., 1993).

These relic quark nuggets, it is entirely plausible are made of strange matter, the true ground state of QCD (Witten, 1984).

Aubourg et al., 1993 have been monitoring the brightness of three million stars in the large Magellanic Cloud for over three years, and here report the detection of two possible microlensing events. The brightening of the stars was symmetrical in time, achromatic and not repeated during the monitoring period. The timescale of the two events are about thirty monitoring period.

Aubourg E. et al., Nature 365, 1993

The EROS (Experience de Recherche d'Objects sombers) collaboration is searching for microlensing events using the European Southern Observatory at La Silla, Chile. We have two complementary programmes. This makes the programme primarily sensitive to lens masses in the range $10^{-4}\ M_{\odot} < M < 1M_{\odot}$.

Aubourg E. et al., Nature 365, 1993

The existence of strange quark matter (SQM), containing a large amount of strangeness, had been postulated by various authors quite a few years ago. In a seminal work in 1984, Witten (Phys Rev D 30, 272, 1984) proposed that SQM with roughly equal numbers of up, down, and strange quarks could be the *true ground state of quantum chromodynamics (QCD), the* accepted theory of strong interactions.

Banerjee S. et al., Phys Rev Lett 85 (7), 2000

Strangelets may arise from various scenarios; they could be formed in highly energetic nuclear collisions associated with the formation of quark-gluon plasma or they might be of cosmological origin, as remnants of the cosmic QCD phase transition . Collisions of strange stars could also lead to the formation of strangelets which could contribute to the cosmic ray flux.

A discerning property of such strangelets would be an unusual charge to mass ratio (*Z/A <<1*).

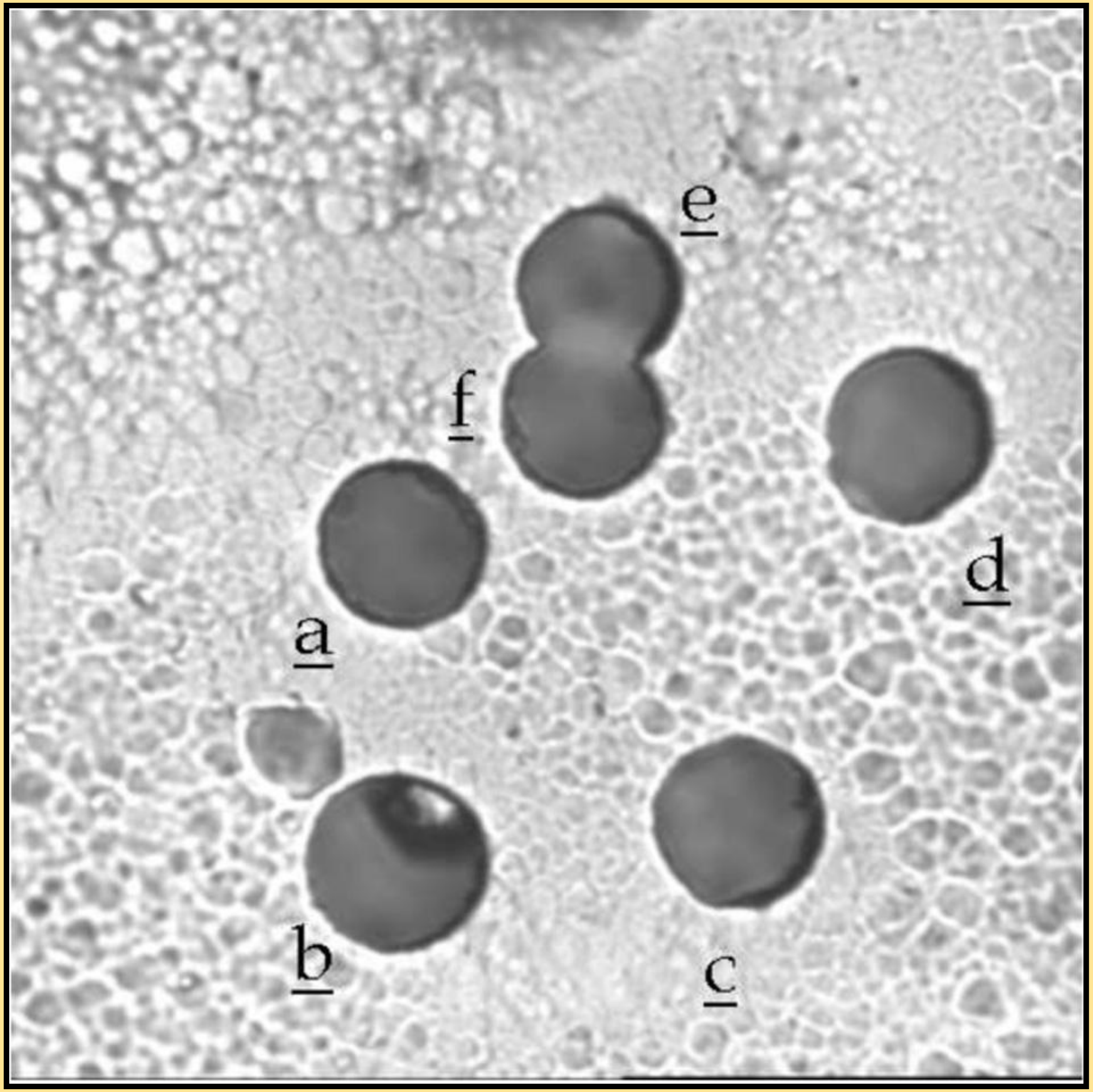
Banerjee S. et al., Phys Rev Lett 85 (7), 2000

Existence of strangelets in cosmic rays has been predicted even at mountain altitudes ~ 3-4 km with extremely low abundance. Basu et al. exposed an appropriate passive detector to cosmic rays at Darjeeling (Tea!), India, at an atmospheric pressure of 765 hPa , as a pilot study to determine its suitability for the detection of strangelets in a large area detector array through long-term exposure. (hPa ⟶ hecto Pascal)

Basu et al., Phys Rev Lett 85 (7), 2000
Basu et al., Astroparticle Physics, 61, 2015

During the analysis they found a highly unusual event consisting of a cluster of six identical nuclear tracks. They argued that even the most mundane explanation of this event requires unusual physics, the first possible observation of multi-fragmentation involving cosmic rays.

Basu et al., Astroparticle Physics, 61, 2015



The unusual event showing six similar tracks in a single image frame of the PET detector. The size of the image frame is 67 lm 67 lm

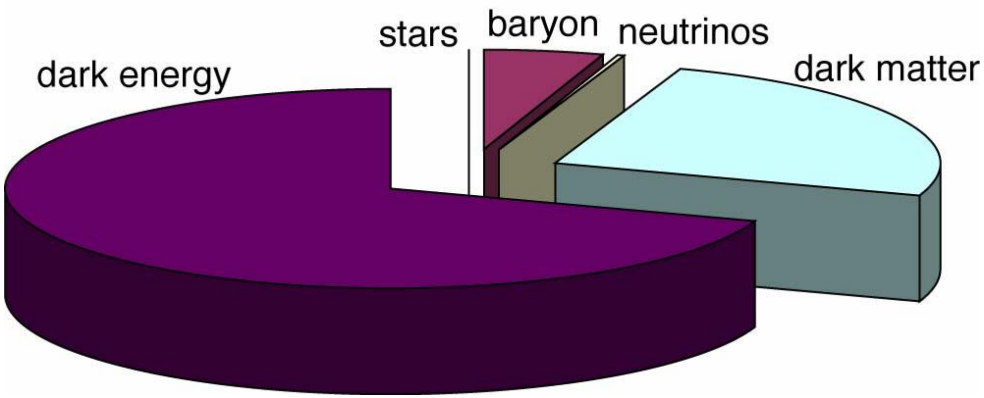
According to the analysis, a strangelet with an initial mass of ~64 amu and charge ~evolves to a mass ~340 amu or so, by the end of its journey, an altitude ~3.6 km above the sea level (typically the height of a north-east Himalayan peak in India). This mass is quite close to the few avaiable data and seems to the interpretation that exotic cosmic ray events with very small Z/A ratios could result from SQM droplets.

Banerjee S. et al., Phys Rev Lett 85 (7), 2000

Energy Budget of Universe

PLANCK's RESULTS !!!

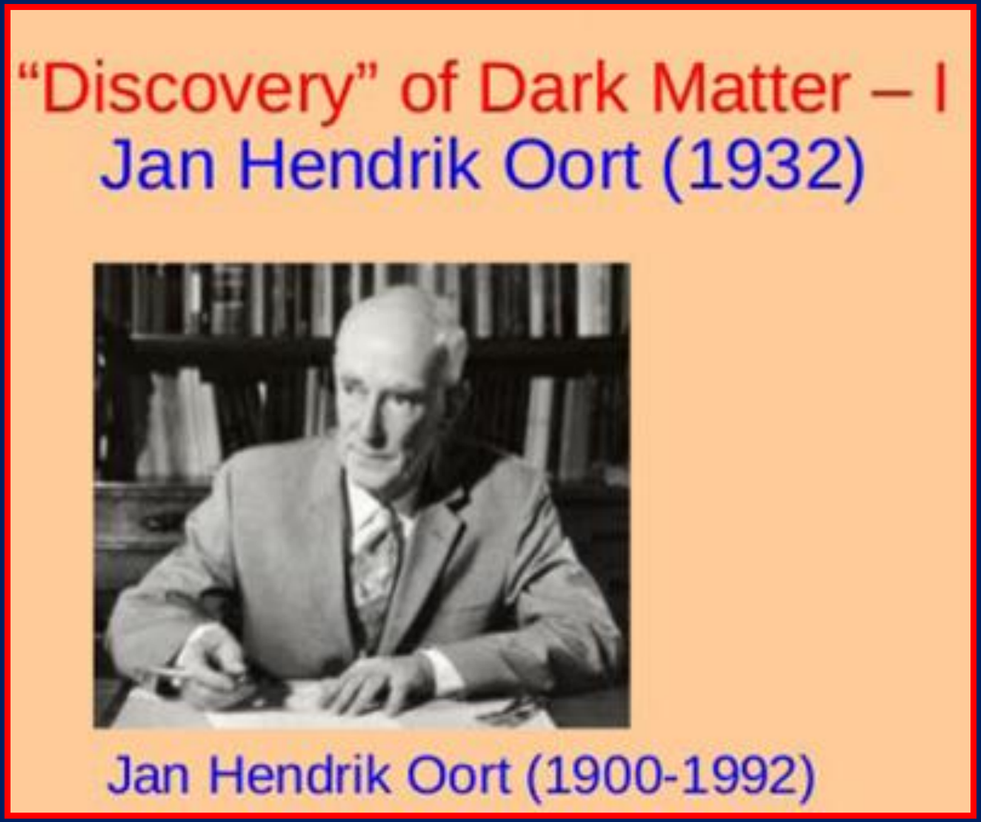
- Baryonic Matter are ~ 4.8%
- Dark Matter ~ 26.5%
- Dark Energy ~ 68.4%

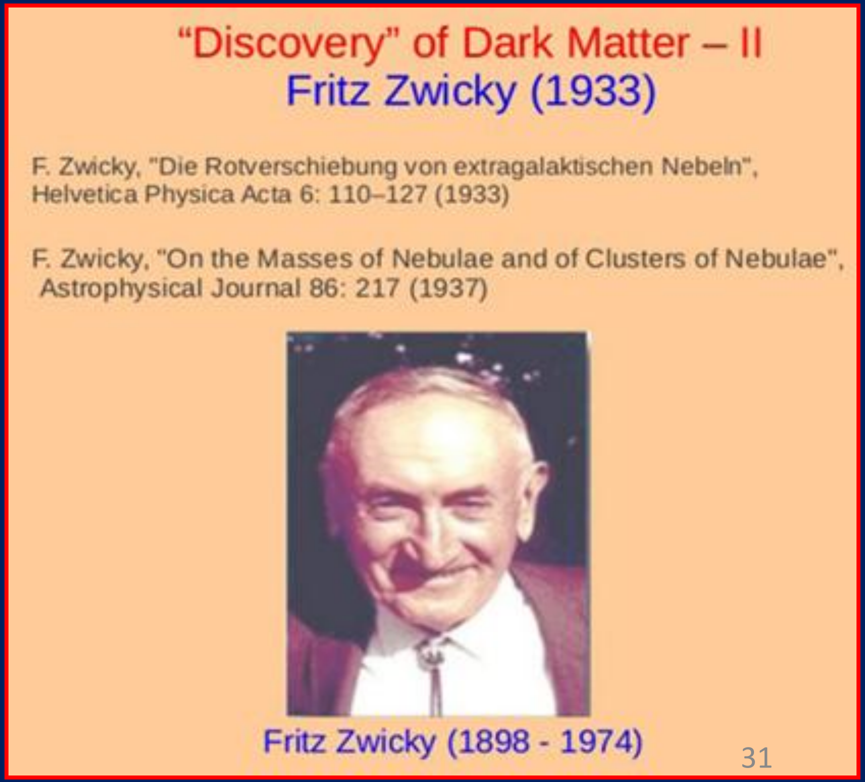


DARK HIGGS

Dark Matter Ring

An image from Hubble Space Telescope shows
ring of dark matter in a galaxy cluster. (NASA: Reuters)





F. Zwicky, "Die Rotverschiebung von extragalaktischen Nebeln", Helvetica Physica Acta 6: 110- 127 (1933)

F. Zwicky, "On the masses of Nebulae and of Clusters of Nebulae", Astophysical Journal 86: 217 (1937)

Survivability of Cosmological Quark Nuggets: (Chromoelectric flux-tube fission model):

First order phase transition (q-h)

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

P. Bhattacharya, J. Alam, B.Sinha,

Sibaji Raha: Phys Rev.D 48 (1993)

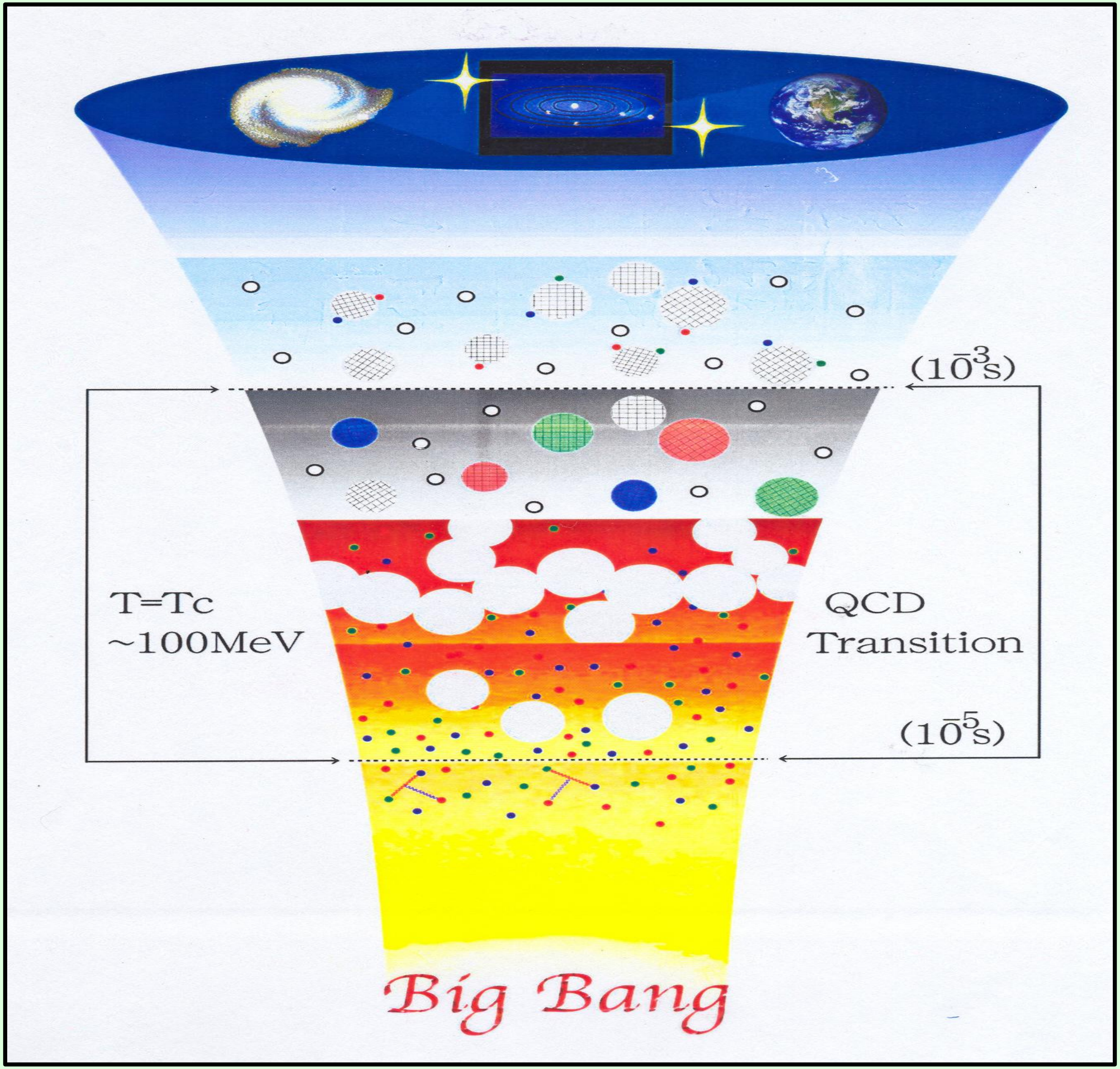
Chromo electric Flux-tube fission

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

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

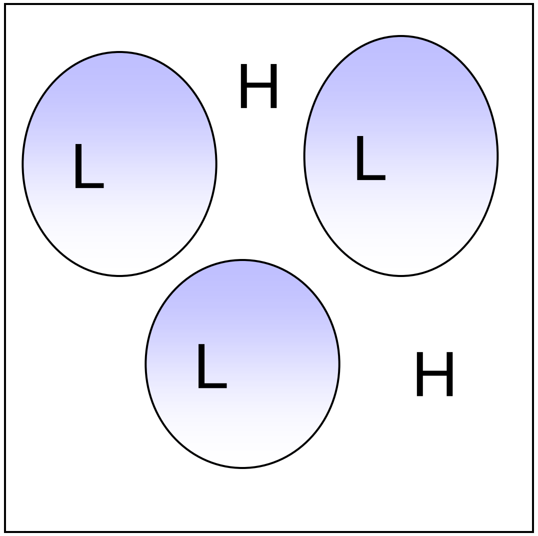
The net charge of baryon number of the QN is

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

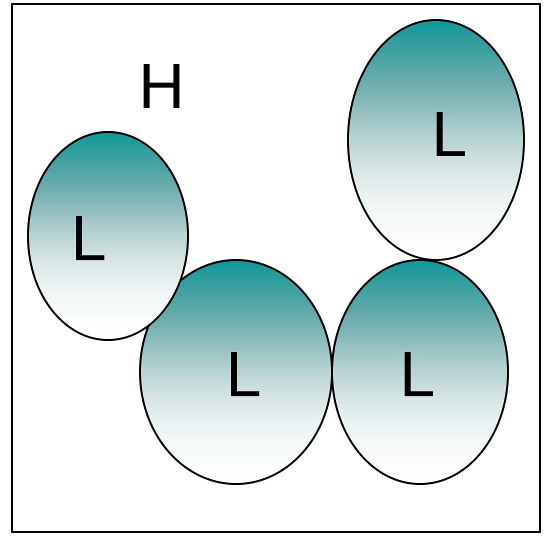


(10^{-3}s)
T=Tc
~100MeV
QCD
Transition
(10^{-5}s)
Big Bang

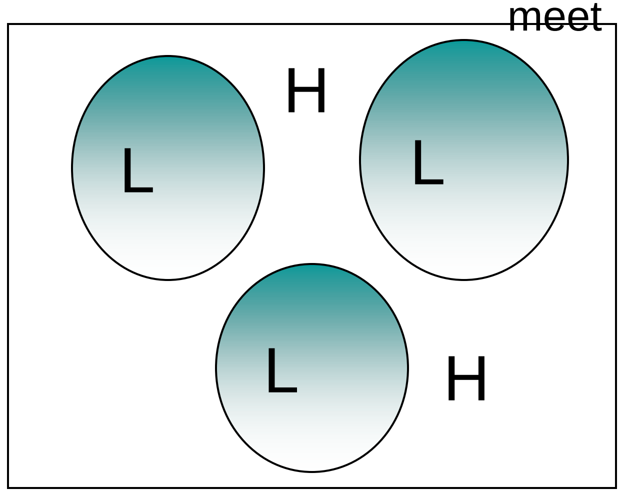
Strange quark nuggets (SQN)



Isolated expanding bubbles of low temp
In high temp phase



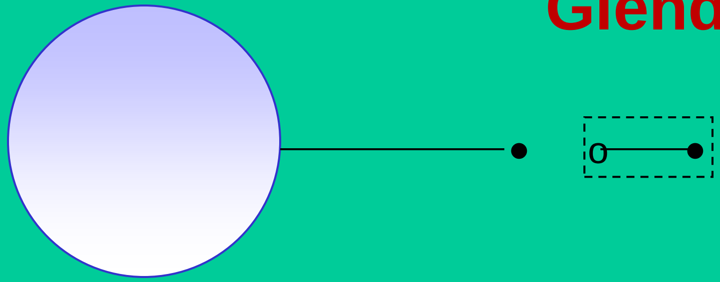
Expanding bubbles meet



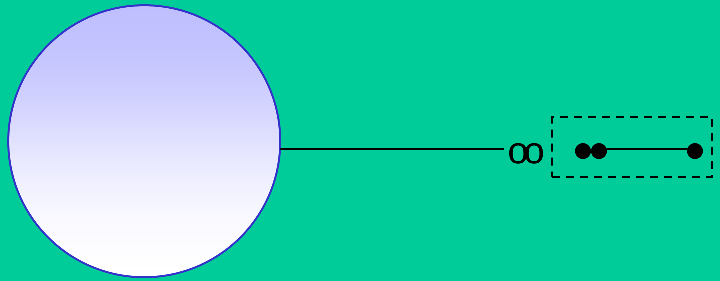
Isolated shrinking bubbles of High temp phase

CEFT MODEL

Glendenning & matsui -1983



meson evaporation



Sumiyoshi et al 1990

Baryon evaporation

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)

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

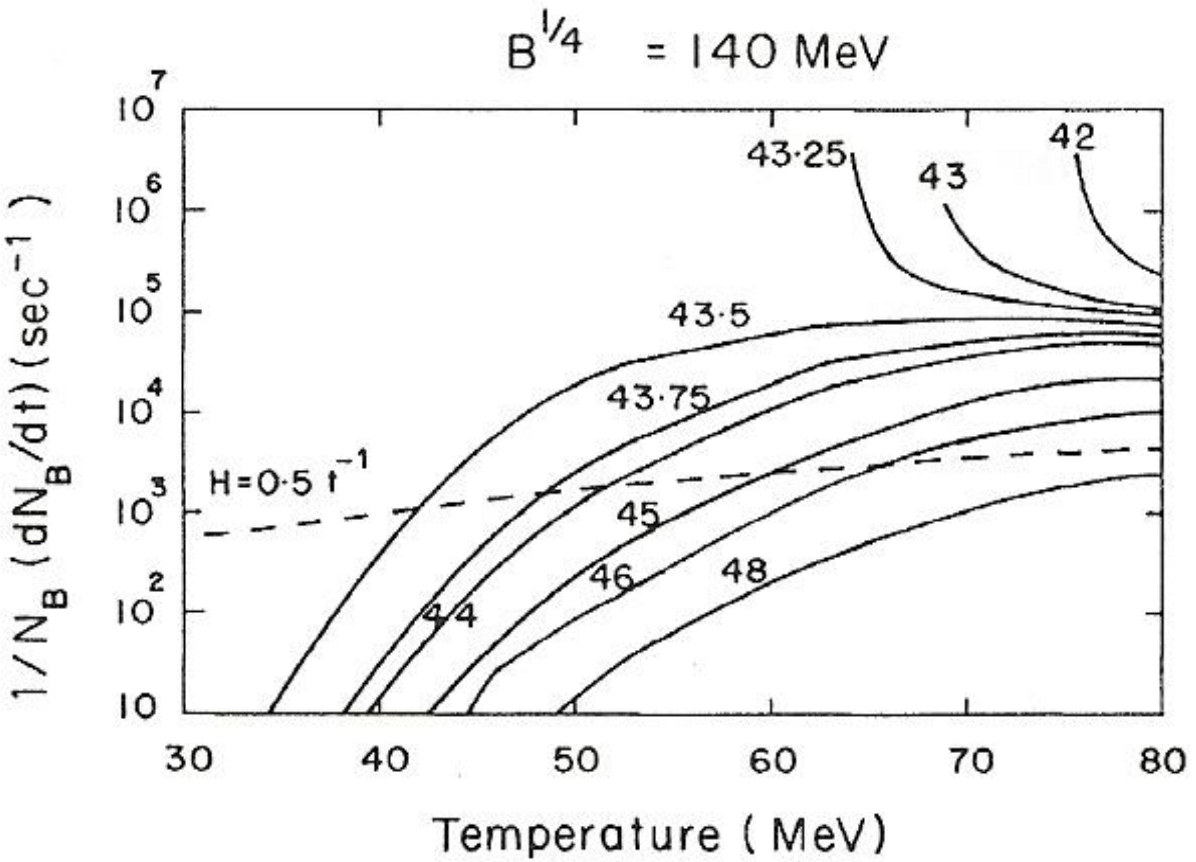


FIG. 1. The inverse of the baryon evaporation time scale as a function of temperature for nuggets with different values of initial baryon number ($\ln N_{B,\text{in}}=42$, 43, 43.25, and so on as indicated). The bag constant is $B^{1/4}=140$ MeV, and $\alpha_c=2.0$. The dashed curve is the Hubble constant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

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

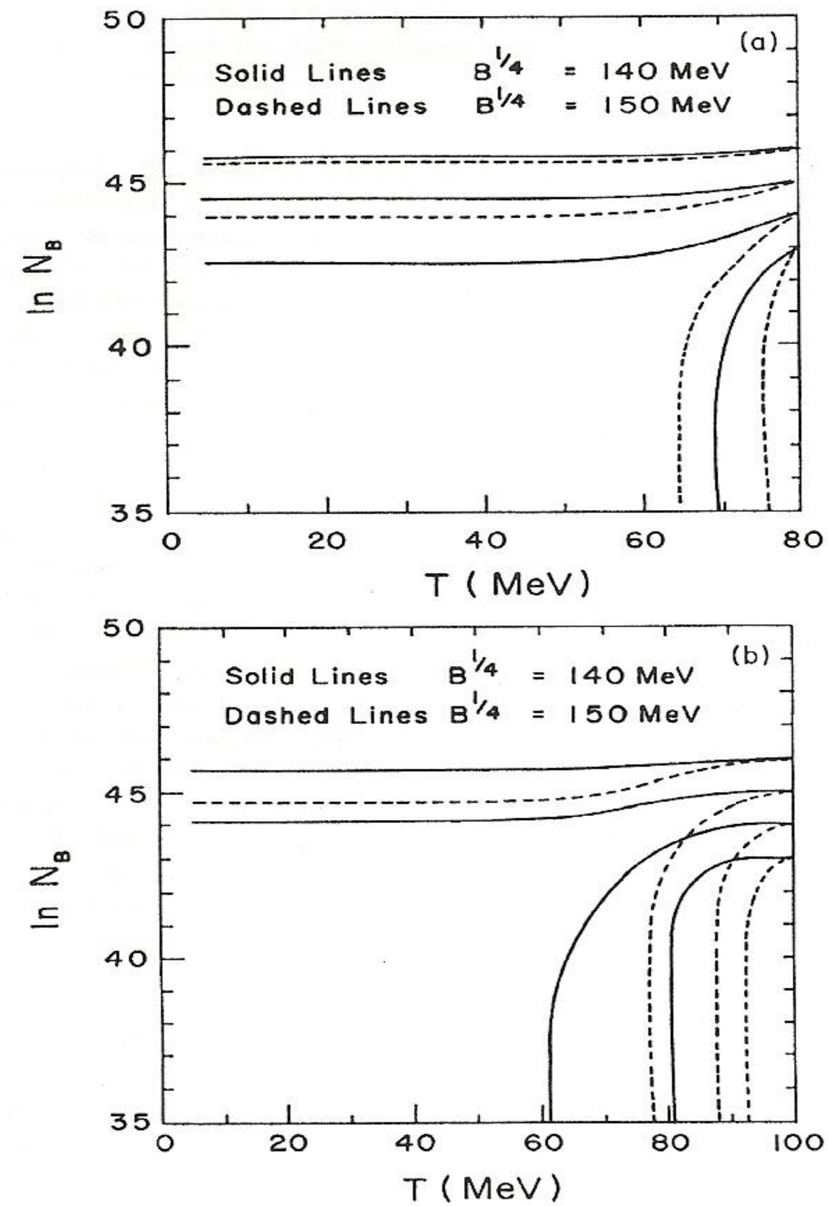


FIG. 2. (a) Evolution of the baryon number of quark nuggets with temperature for two different values of the bag constant B as indicated, for $T_{in} = 80$ MeV, and $\alpha_c = 2.0$. (b) Same as (a), with $T_{in} = 100$ MeV.

[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!!

MACHO , Relics of Q-H phase transition

Sibaji Banerjee

A. Bhattacharya

S. Ghose

S. Raha, B.Sinha

Mon. Not. R. Astronomical Society (2002)

Gravitational Lensing :

(13-17) Milky Way halo MACHOs, detected in the direction of Large Magellanic cloud

Mass range (0.15-0.95) Mo

Most probable ~ 0.5 Mo

Sutttherland (1999)

Alocock (2000)

Above the threshold for Nuclear fusion => evolution of metastable (TFVD)

(Strange Quark Nuggets, SQN)

Entire Cold Dark Matter (CDM)

(Ω_{CDM}~0.3-0.35) can be comfortably explained by stable SQN's

Alam, Raha & B.S. Astrophysical journal (1999)

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

Nucl. Phys A774(2006)

After some algebra it can be shown that if all the cold dark matter (CDM) is believed to arise from SQNs, then their size distribution peaks, for reasonable nucleation rates, at baryon number ~ $10^{42\text{-}44}$, evidently in the stable sector.

It was also seen that there were almost no SQNs with baryon number exceeding 10^{46-47}, comfortably lower than the horizon limit of ~ 10^{50} baryons at the time. Since Ω_B is only about 0.04 from BBN, Ω_{CDM} in the form of SQNs would correspond to ~ 10^{51} baryon so that there should be 10^{7-9} such nuggets within the horizon limit at the microsecond epoch, just after the QCD phase transition (Alam et al., 1998; 1999).

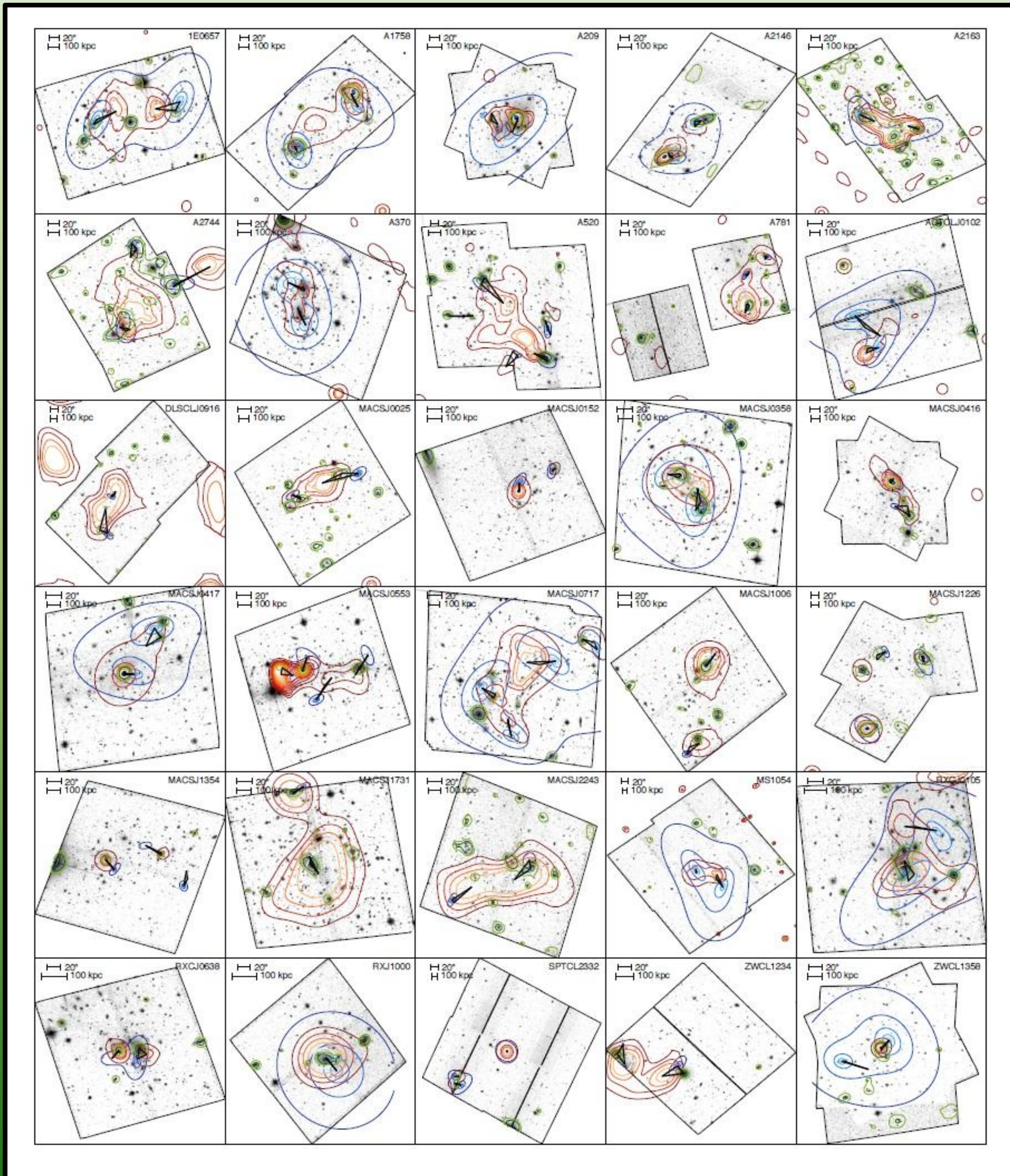
Collisions between galaxy clusters provide a test of the non-gravitational forces acting on dark matter. Dark matter's lack of deceleration in the "bullet cluster collision" constrained its self- interaction cross- section $\sigma_{DM}/m<1.25\ cm^2/g$ (68% confidence limit) for long ranged forces. Using the Chandra and Hubble Space Telescopes Harvey et al. observed 72 collisions, including both "major" and "minor" mergers.

Harvey et al., arXiv:1503.07675v2[astro-ph.CO]

Combining these measurements statistically, we detect the existence of dark mass at 7.6σ significance. The position of the dark mass has remained closely aligned within 5.8σ± 8.2 kpc of associated stars: implying a self- interaction cross-section $\sigma_{DM}/m<0.47\ cm^2/g$ (95% CL) and *<u>disfavoring some proposed extensions to the standard model.</u>*

Harvey et al., arXiv:1503.07675v2[astro-ph.CO]

Colliding galaxies…



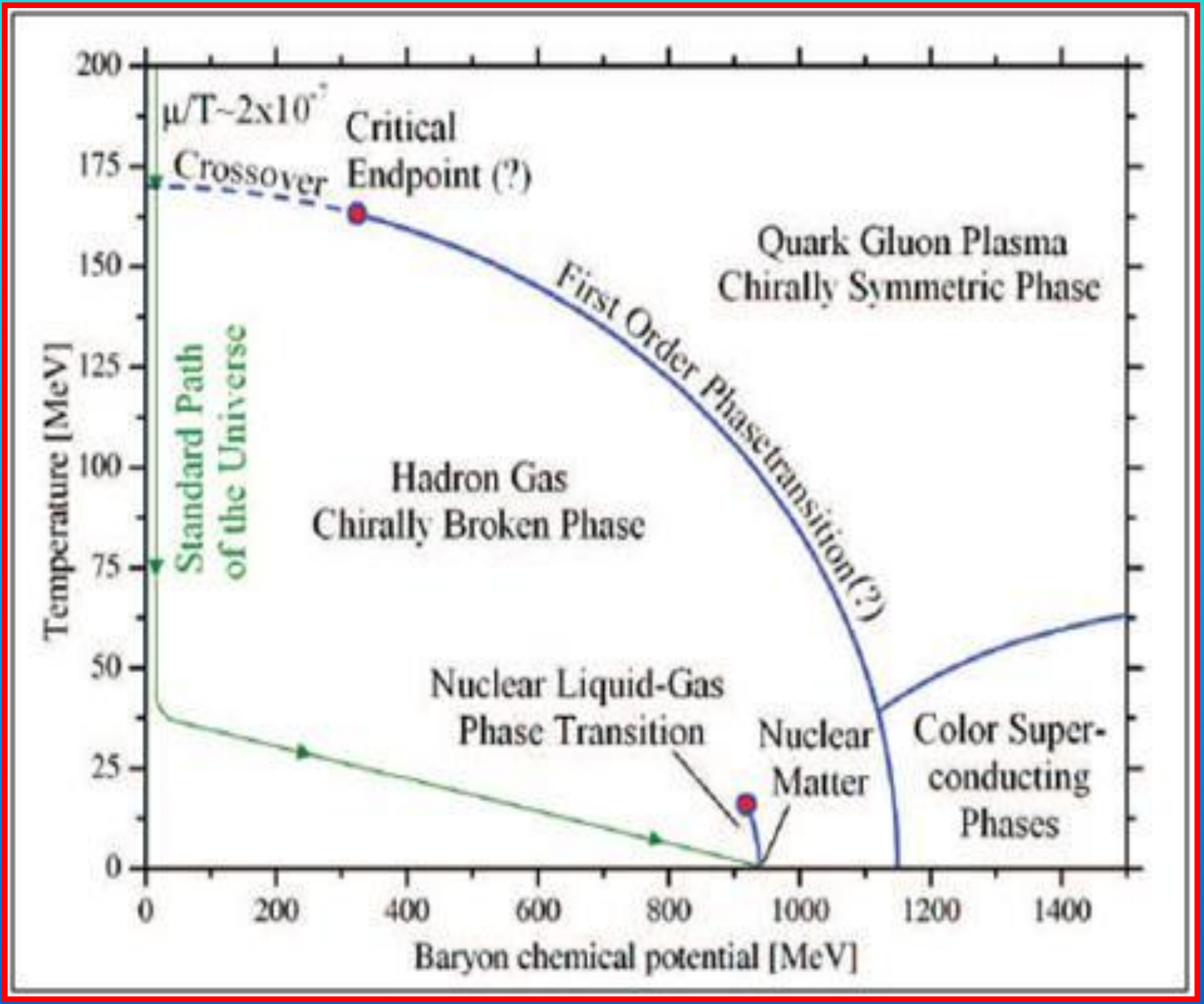
arXiv:1503.07675v2 [astro-ph.CO] 13 Apr 2015

P3… Primordial Painting of Picasso

The Enigma
of
Cosmic Phase Transition

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. Please note that everyone expects a critical end point at $\mu_c \approx \mathcal{O}(1) T_c$, but convincing experimental evidence still remains an enigma.

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



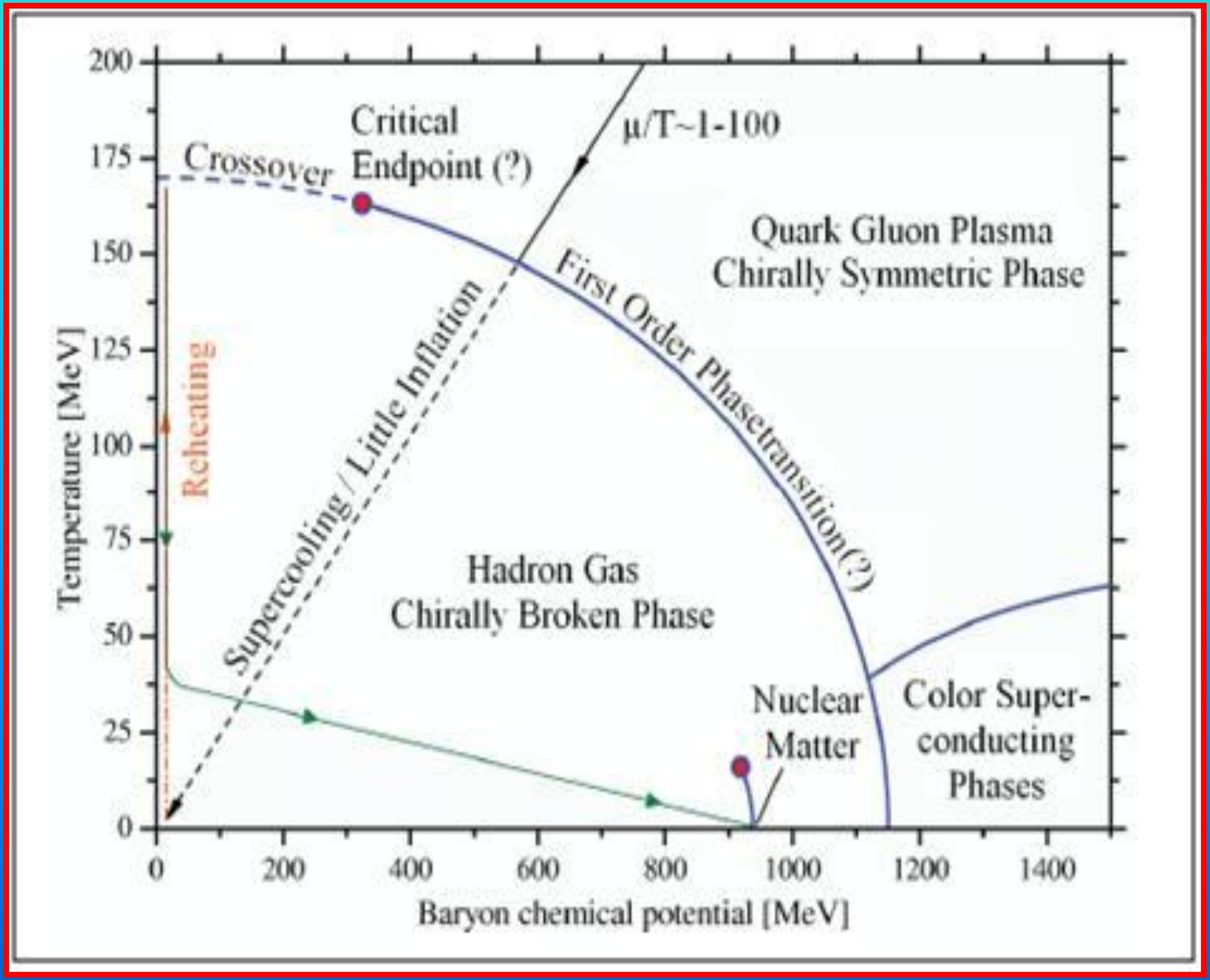
Boeckel T. et al., ***Phys. Rev. Lett.*** **105, 2010**

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

QCD phase diagramme still is Terra incognita; the validity of lattice for an expanding universe with chemical potential as a function of time is somewhat questionable.

Now we come to the "little inflation" scenario introduced by Boeckel and Schaffner- Bielch (Phys. Rev. Lett. 2010, 105, 041306). We shall go into why and how shortly.

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 3.

The increase in entropy changes n_q/n_γ radically. Whereas, the quark number density decreases as $n_q \sim R^{-3}$ and $n_\gamma \sim T^3$, the ratio $n_q/n_\gamma \sim (RT)^{-3}$, is proportional to the inverse of entropy. This immediately implies that if at the end of the transition $n_q/n_\gamma \sim 10^{-10}$ as dictated by primordial nucleosynthesis at $T \approx T_c$, $n_B/n_\gamma \sim \mathcal{O}(1)$. This result is in sharp contrast with normal adiabatic expansion in which the baryon asymmetry will not change [Borghini et al, 2000].

Witten, 1984; Bhattacharya et al., 1993 & Boeckel T. and Schaffner-Bielich, 2012 have argued that a first order phase transition is plausible with a “small” supercooling which would imply that the transition occurs effectively at a temperature at which most of the latent heat between the two phases still remains, so that phase coexistence can be established after nucleation.

In a ***recent private communication*** **Witten further asserted that if $\eta_B = n_B/\gamma$ remains 10^{-10} as it is in the current universe, then supercooling is implausible. However, he also points out that if the baryon to photon ratio is not small during the QCD phase transition and become small because of some phenomena at later times, then supercooling is plausible in principle.**

This is the central issue, the relevance of baryon asymmetry at that primordial epoch.

The Affleck-Dine mechanism [Affleck I. and Dine M., 1985] has the potential to produce a baryon asymmetry of $\mathcal{O}(1)$ without requiring superhigh temperatures. However, the observed baryon asymmetry of (10^{-10}) at CMB temperatures needs to emerge naturally from such a scenario. This is what is achieved through a 'little inflation' of about 7 e-folding occurring at a lower temperature which may be identified with the QCD phase transition thought of as a first order phase transition [Boeckel T. and schaffner- Bielich, 2010].

Such an inflation naturally dilutes the baryon photon ratio to the observed range, even though the baryon potential before the first order phase transition may have been high (of $\mathcal{O}(1)$ in photon units).

The possibility and the criterion of a mini-inflationary epoch can be demonstrated in a simple way within the Friedman model of a spatially flat universe which is homogeneous and isotropic along with an appropriate equation of state (EOS).

The Friedman equation reads

$$\dot{R} - CR\sqrt{\epsilon} = 0$$

$$\dot{\epsilon} - 3\left(\dot{R}/R\right)(\epsilon + P) = 0$$

Boyko et al., 1990: Sinha, 2015… to be published

The corresponding equation of state, relating energy density ϵ and the pressure p using the bag model reads for QGP

$$\epsilon_{qg} = (37\pi^2/90)T^4 - B, \quad p_{qg} = \big(\epsilon_{qq} - 4B\big)/3$$

$$p = p_{qg} + p_{bg} : \epsilon = \epsilon_{qg} + \epsilon_{bg} : \epsilon_{bg} = p_{bg}/3$$

$$p_{bg} = 14.25\pi^2 T^4/90$$

….(2)

The cosmic evolution will be an inflationary one if the expansion is accelerated, $\ddot{R} \geq 0$ which leads to

$$\ddot{R} = -C^2 R(\epsilon + p)/2 \geq 0$$

….(3)

and $3p+\epsilon<0$

with the solution $\epsilon = Bcth^2\left[2C\sqrt{B}(t-t_c) + arcth\left(\sqrt{\epsilon_c/B}\right)\right]$

$$R = sh^{1/2}\left[2C\sqrt{B}(t-t_c) + arcth\left(\sqrt{\epsilon_c/B}\right)sh^{-1/2}\left(arcth\sqrt{\epsilon_c/B}\right)\right]$$

$$t \gg t_{exp} = (2C\sqrt{B})^{-1}$$

clearly the space expansion proceed exponentially, $R \propto exp(C\sqrt{B}t)$

2 & 3 are satisfied for $T<T_i$ with $T_i \cong 0.5B^{1/4}$

For temperature below T_0= $0.65B^{1/4}$, the pressure becomes negative leading to acceleration of the universe. This is exactly what is achieved by the “mini inflation”

To recapitulate, the universe is assumed to begin with a large baryon chemical potential acquired through an Affleck- Dine [Nucl. Phys. B 249, 1985] type of mechanism. It then undergoes a period of inflation, Fig 3 crossing the QCD first order phase transition line, while remaining in a deconfined and in a chirally symmetric phase. The universe is then trapped in a false metastable QCD vacuum state.

The existence of compact gravitational lenses, with masses around 0.5 $M_\odot$, has been reported in the halo Milky Way. The nature of these dark lenses is as yet obscure, particularly because these objects have masses well above the threshold for nuclear fusion. In this work, we show that they find a natural explanation as being the evolutionary product of the metastable false vacuum domains (the so- called strange quark nuggets) formed in a first order cosmic quark- hadron transition.

Banerjee et al., Mon. Not. R. Astron. Soc. 340, 2003

In a recent paper, Harvey et al. (arXiv:1503.07675v2) rather categorically demonstrate that dark matter self- interaction cross section $\sigma_{DM}/ m < 0.47\ cm^2/g$ and disfavoring some proposed extensions to the standard model.

SQN's, even after clumping, only feel gravitation and the pressure of radiation and no other interactive force, as was pointed out, in agreement with the observation of Harvey et al.

For SQNs of baryon number b_N each, the number of SQNs within the horizon at that time would be just $(10^{51}/b_N)$. Now, in the radiation dominated era the temperature dependence of density $n_N \sim T^3$, horizon volume V_H varies with time as t^3, ie. $V_H \sim T^{-6}$ and hence the variation of total number inside the horizon volume will be $N_N \sim T^{-3}$.

It can be shown that the number of SQNs within the horizon (N_N) and their density (n_N) as a function of temperature would be given by :

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

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

where the time t and the temperature T are related in the radiation dominated era by the relation :

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

with g_* being ~ 17.25 after the QCD transition (Alam et al.1999)

The expression for the gravitational force as a function of temperature T can written as :

$$F_{\text{grav}} = \frac{G {b_N}^2 {m_n}^2}{\bar{r}_{nn}(T)^2}$$

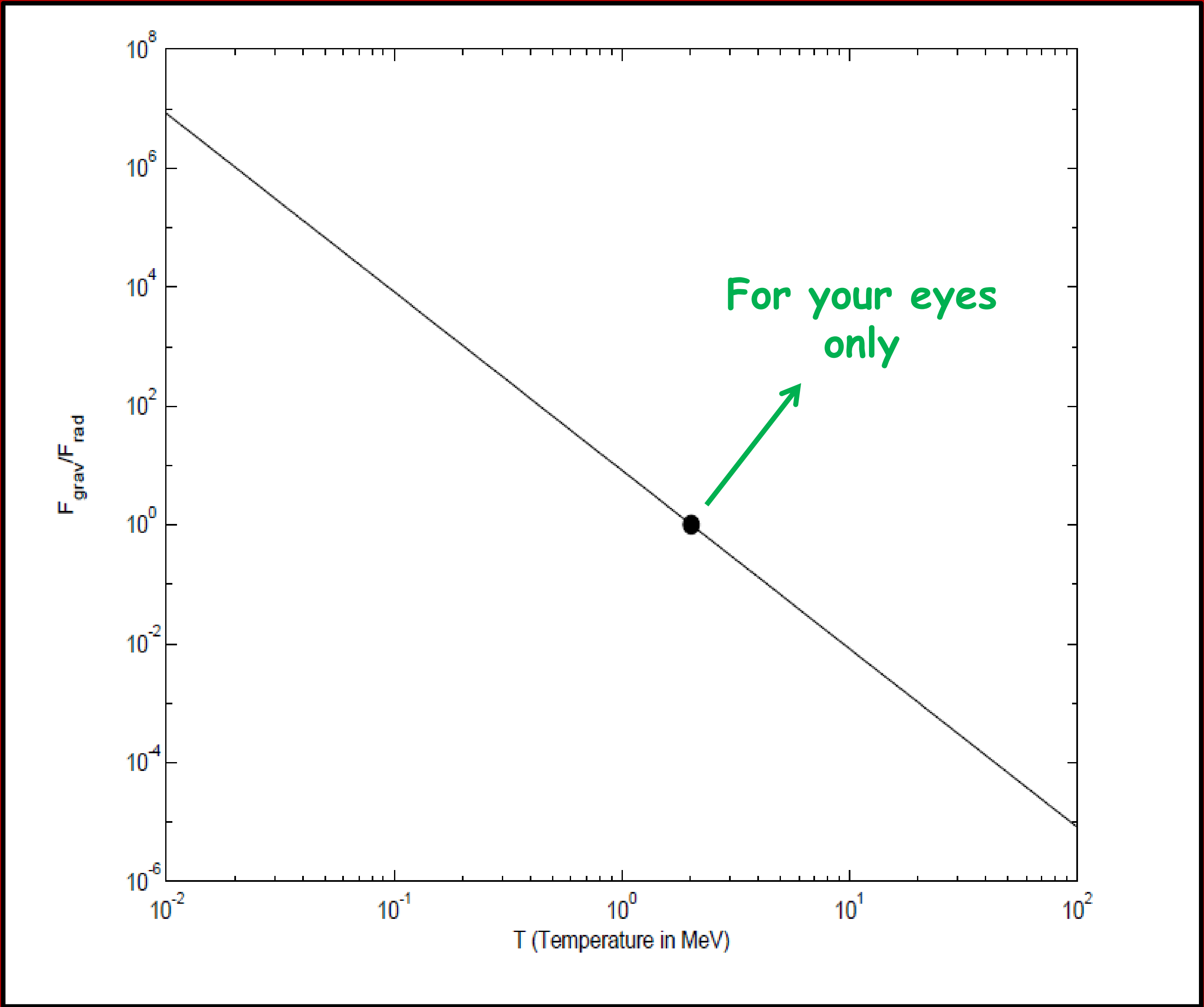
where b_N is the baryon number of each SQN and m_n is the baryon mass. $\bar{r}_{nn}(T)$ is the mean separation between two nuggets and is given by the cube root of the ratio κ of total volume available and the total number of nuggets

$$\kappa = \frac{1.114 \times 10^{-12} c^3}{T^3}$$

The total radiation force resisting the motion of SQNs is

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

where $\rho_{\rm rad}$ is the total energy density at temperature T, $v_{\rm fall}$ or βc is the velocity of SQNs determined by mutual gravitational field and γ is $1/\sqrt{1-\beta^2}$. The quantities $F_{\rm rad}$, β and γ all depend on the temperature of the epoch under consideration. (It is worth mentioning at this point that the t dependence of $F_{\rm rad}$ is actually $t^{-5/2}$, sharper than the t^{-2} estimated above, because of the $v_{\rm fall}$, which goes as $t^{-1/4}$.)



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

Critical temperatures (T_{cl}) of SQNs of different initial sizes b_N, the total number N_N of SQNs that coalesce together and their total final mass in solar mass units.

b_N	T_{cl} (MeV)	N_N	$M/M_\odot$
10^{42}	1.6	2.44×10^{14}	0.24
10^{44}	4.45	1.13×10^{11}	0.01
10^{46}	20.6	1.1×10^{7}	0.0001

It is obvious that there can be no further clumping of these already clumped SQNs; the density of such objects would be too small within the horizon for further clumping. Thus these objects would survive till today and perhaps manifest themselves as MACHOs.

We now recapitulate some interesting and crucial points mostly a lâ *Witten (1984); Bhattacharya et al. (1993)* and *Banerjee et al., (2003)*.

We can thus reasonably expect that for a time comparable to the Hubble time, there will be co-existing phase on a scale R_1 – 1cm < R_1 < 10^4 cm (Witten, 1984).

The density of baryons in the low temperature phase may therefore be less than the density in the high temperature phase by a large factor: in either phase, the baryon density

$$\langle B \rangle = \frac{1}{V} \langle B e^{-\mu_B / T} \rangle$$

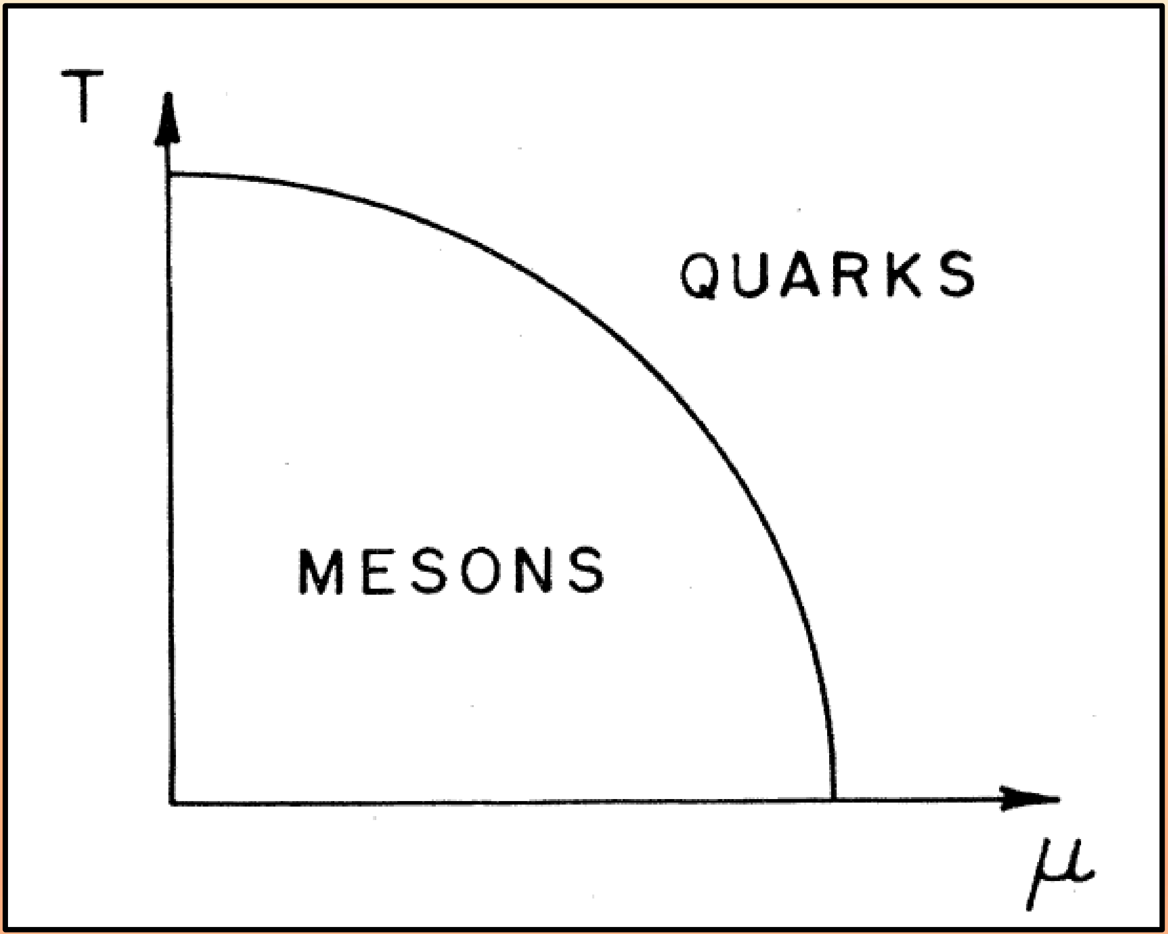
$$\langle B \rangle = -\frac{\mu}{TV} \langle B^2 \rangle_{\mu=0}$$

Let's define $\epsilon = \langle B \rangle^L / B^H = \langle B^2 \rangle_0^L / \langle B^2 \rangle_0^H$

ϵ is much less than 1, even$\epsilon \sim 10^{-2}$ is possible

The baryon- to- entropy ratio $\sim \mathcal{O}$ (1) when $\mu \sim T$; at this point T is comparable to but significantly less than T_c; (say) $T \simeq \frac{1}{2} T_c$

The temperature as a function of μ at which the two phases exert equal pressure (Witten 1984).



A rough sketch of the coexistence temperature for quark matter of chemical potential μ coexisting with the meson- baryon phase of μ=0

High temperature phase begin to detach themselves and shrink- the radius is R_1~ (1-10^4 cm), they fill roughly 50% of the total volume and they may contain a fraction as high as $1/(1+\epsilon)$ or about 80%-90% of all the baryons in the universe.

The dense region now occupy a tiny fraction of the total volume but contain 80-99% of the baryon excess. How large are they?? Let *f* be the primordial baryon to entropy ratio (so $10^{-8} \leq f \leq 10^{-10}$, experimentally). The baryon to photon ratio of the dense regions when they have radius R_1 is *f*, so this ratio becomes 1 when the radius shrinks to $r=R_1 f^{-1/3}$. If, for instance, $f \simeq 10^{-8}$, and 1 cm $\leq R_1 < 10^4$ cm, then r is between 10^{-2} and 10 cm.

Because of the extreme large inertia they would not have been incorporated in stars and planets and would be floating in interstellar space, affected significantly only by gravity. The baryons they contain would not participate in nucleosynthesis, so one could assume a closure density of baryons without disturbing the successes of the big bang nucleosynthesis.

In galaxy formation they would behave like the planetary mass black holes. It might account for the "missing mass" in the universe if $\epsilon \sim 10^{-2}$.

Taking the analogy of black hole entropy [Hawking 1974, Misner, Thorne, Wheeler 1973, Beckenstein (1972, 73, 2008)] one can argue the entropy of a Quark Nugget (QN),

$$S_{QN} = \frac{A}{4L_B^2}$$

A is the surface area of QN

And L_B is the natural length of a QN

$A=4\pi R^2$ (R is the radius of the QN)

$\sigma^2=8B$

And the natural length $L_B = \left(B^{1/4}\right)^{-1}$ where B is the Bag pressure: $B^{1/4} \approx 150$ MeV

$$S^{(B)}_{QN} = \pi R^2 B^{1/2}$$

Thus $$S^{(\sigma)}_{QN} = \pi R^2 \sigma / \sqrt{8}$$

bounds

Whereas : $\frac{S}{N_{QN}} \sim \mathcal{O}(1)/10^{-8}$ When QN's are formed $S/N_{QN} \approx \mathcal{O}(1)$

Epilogue

Driven by the familiar standard model and introducing a “mini inflation” at the cosmic quark hadron phase transition one can precipitate a first order phase transition from quarks to hadrons.

Contd.

It has been argued in this paper that it does not introduce any non standard cosmological scenario and indeed this mini inflation come in quite naturally; raising the value of $\eta = n_B/n_\gamma$ substantially. It is argued that the MACHOs will survive the cosmological time scale and beyond a critical baryon number window of ~ 10^{40} are the candidates of cold dark matter observed some years ago and rather more recently.

Contd.

The interestingly satisfying thought lingers that we can accommodate all this in the framework of standard model without invoking yet unobserved exotic physics.

Outlook

To look for more such candidates

Weakly Interacting Massive Particles
WIMP

The Quark Nuggets

Not WIMMP